Gothenburg: 2013-10-18

Report draft from project Phase 1

**Slide-in Electric Road System**

*Inductive project report*

This report is compiled and edited by Viktoria Swedish ICT on behalf of Volvo GTT and Scania CV and is partly financed by the:

In this project, the following companies and organizations are participating:

![Companies and Organizations Logos]
SAMMANFATTNING


ABSTRACT
Electrifying vehicles is seen by many as a possible solution to reduce environmental emissions and the dependence on fossil fuel. Unfortunately, most environmentally friendly energy storage systems, such as batteries, have less energy density compared to fossil fuel, which will have a negative impact on the vehicle range. A battery with enough capacity for long distance transports will therefore often imply a substantial increase in cost and weight, and reduced transport volume. An alternative would be to continuously transfer energy from the road to the vehicle both for propulsion and charging. A development of an electrified road system (ERS) between cities would mean that most of the route could be driven on electricity from the road and the remaining distance can be driven on energy from potentially smaller batteries optimized for city routes.

This is a progress report in the Slide-in project where the final objective is to evaluate the technology to inductively transfer energy from the road to the vehicle based on cost, efficiency and feasibility. The report includes both a background with a business model as well as a description of the technology that would be required on the vehicles, in road and in the surrounding infrastructure for a large-scale implementation. The report also includes a cost estimate for a full deployment of a road between Stockholm and Gothenburg and an assessment of how implementation should be carried out.
VOCABULARY AND ABBREVIATIONS

AC       Alternating current
DC       Direct current
ERS      Electric Road System
EMF      Electromagnetic field
HMI      Human-machine interface
ICE      Internal combustion engine
primove  Bombardier’s contactless power transfer system
Prox Sensor Proximity sensor, for sensing the distance to another object
RFID     Radio-frequency identification device
VDSC     Vehicle detection and segment control (system)
WPC      Wayside power converter

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Chapter 4. Generic scenario description. Scania CV and Volvo GTT
Chapter 5. Details of inductive system. Bombardier
Chapter 6. Details of vehicle. Scania CV
Chapter 7. Details of power supply system from energy provider to the inductive system. Vattenfall
Chapter 8. Implementation concept. The Swedish Transport Administration
Chapter 11. ERS reference case based on overhead lines. Svenska Elvägar

In this report 1 Euro corresponds to 8.63 Swedish kronor.
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1 AN ELECTRIC ROAD SYSTEM

A brief background description of an Electric Road System and the purpose, goal and participants of this project.

1.1 Background

Increasing global pollution and with Peak-oil approaching or possibly even reached calls for new means of transport, non-dependent on fossil fuels. The huge power capacity, enabled by the energy density in the oil, has accustomed and spoiled the automotive-world and raised the competition for new competing technologies, such as the Electric Vehicle (EV).

There is a major challenge to meet the demands placed on a new vehicle such as regarding cost, efficiency, range, and functionality. Great resources are spent to increase the EV range by increasing the vehicle efficiencies and the battery capabilities. Despite this, the energy storage capacity of the batteries is not enough for long-distance transport of EVs and even output power could be a limiting factor. Larger batteries are not necessarily the solution since they require a longer time to recharge or access to charging stations with extreme charge capabilities. Moreover, the battery is a substantial part of the total cost and weight of the EV, which reduces the cargo load capacity, and thereby also the monetary gain for the otherwise less energy-demanding vehicle. To make the EV less dependent on the battery, especially for long distance heavy transport, and at the same time reduce the vehicle cost, a possible solution could be to transfer power to the vehicle from the roadway.

Electric Road Systems (ERS) can be defined as roads supporting dynamic power transfer to the vehicles from the roads they are driving on. An ERS could connect cities and allow the bulk distance to be driven on external electric power instead of using fossil fuels. The propulsion of the short remaining distance outside the ERS network could either be based on internal combustion engine (ICE), or on energy stored in small, on-board batteries optimized for city routes. With this solution, both the costs and the weight of the batteries can be kept small. In addition, there is no need to stop and recharge since this is possible while driving.

Theoretically, ERS could be based on energy transmission to the vehicle from above, from the side, or from under the vehicles. The idea of transmitting energy from above is the most mature technology, it has been used in e.g. trolley buses for many decades. Such a solution is suitable for the heavy transport segment but it excludes passenger vehicles since the current collector would be unrealistically long. Transmitting energy from the side of the road would be suitable for most kinds of vehicles but the potential number of lanes to be electrified would be limited. Electricity transferred from the roadside would also cause increased danger to vehicles in an accident or to people and animals on the side of the road. Consequently, this report addresses the solution of transmitting energy from the road below the vehicle. This solution could have a high potential, as it could be viable for both heavy duty and passenger vehicles and thus sharing infrastructure costs.

Furthermore, there are different ways to transmit energy from an ERS to the vehicles and two of the more commonly discussed solutions are conductively and inductively. In a conductive system, energy is transferred by establishing a physical contact between the vehicle and a conductor built into the road. Consequently, the technology requires a current collector, also known as a pick-up, which follows the electrified road and acts as the interface between the road and the vehicle. With the flexible highway vehicles, unlike trains that are bound to follow the rails, the pick-up needs to be active and capable of following the ERS with the ability to connect and disconnect depending on the driving behaviour and road conditions. With inductive technology, the energy is transferred wireless through a magnetic field and no physical connection between the road and the vehicle is required. Instead of rails in the road, a conductor (comparable to the primary side of a transformer) inside the road generates a magnetic field that
can be obtained in the vehicle and converted into electrical current. To enable the transmission also this solution requires a type of pick-up, corresponding to the second side of the transformer. To ensure high energy efficiency, the transmission distance and flexibility to follow the road collector are important issues.

From an industrial perspective, the transition towards ERS will significantly affect the business models of most stakeholders involved in road transportation. The existing road transportation system has evolved organically over the last Century, and is today constituted by actors developing technologies and operation subsystems according to an overall technological system logic. Since ERS constitutes a completely new technological system, it entails no predefined interfaces between actors or existing standards between technological subsystems. Compared to the conventional road system, the subsystems of ERS are closely integrated, which affects both future industry structure and future business models. How the technological development of ERS affect business models has to be investigated further to ensure the viability of ERS.

Solving the energy transfer to the EV, an EV has a “tank-to-wheel” efficiency that is significantly higher than a vehicle with an internal combustion engine. From the energy used, there are also no tailpipe emissions or emissions from the energy generation as long as the energy come from renewable energy sources and no energy is wasted when the vehicle is stationary and the engine is idling. Furthermore, an ERS based on a fixed grid for power supply could entail a simplified and more effective way to use renewable energy sources. The energy could also be transferred directly from an efficient large-scale power grid through the road directly to the vehicle engine without passing though the battery and thereby avoid the battery wear and losses.

Despite the increased efficiency of the EV, an increased number of vehicles abandoning fossil fuels for electricity as energy source require increased energy to be generated. If all vehicles in Sweden were electrified it would result in an increase of Sweden’s total electricity consumption. Today, Sweden has relatively low CO₂ emissions from energy generation due to usage of nuclear-, hydro- and wind-power plants. To avoid emissions worse than today’s fossil fuels it is important that the generated power comes from renewable resources. If the energy is originally generated from coal or oil, emissions from the vehicle is indeed avoided but the problem is moved elsewhere.

Vehicle emissions affect globally but roads with heavy traffic are in general also a dangerous place to visit. Adopting an ERS should not make it even more dangerous for people and animals on the road regarding road properties and from an electrical point of view. For example both friction properties and driving behaviour due to a rail in the centre of the road and electric magnetic field due to the high voltages in the road must be monitored and considered. It is also of importance that the ERS is not affected or does not negatively affect the roads ability to withstand the prevailing weather conditions.

1.2 Project goals

The experience of continuously transmit electrical energy from a highway road to a vehicle is limited. The project aims to fill this lack of knowledge and experience, especially when it comes to energy efficiencies, installation costs, maintenance costs and safety.

1.3 Project objectives and scope

The project is managed by Volvo GTT and partly financed by the Swedish Energy Agency through the program Fordonsstrategisk Forskning och Innovation (FFI). Volvo GTT is also together with Alstom responsible for the development of a conductive energy transfer solution while Scania and Bombardier together are responsible for the development of the inductive energy transfer solution. Additional partners in the project are Vattenfall, the Swedish
Both solutions are to be demonstrated and compared in full-scale tests in a realistic environment why two test tracks are being built. In order for the solutions to be comparable, measurements are made during similar conditions and with settings from a common scenario. As no solutions for ERS with energy transmitted from the road are commercially available, similar existing solutions used within other transport sections, such as the tram industry, has been adapted for road vehicles. Most of the adaptations concern the pick-ups, which are specially designed within the project. Also the vehicles have been adapted to be able to connect to the ERS and utilize the energy transferred. A description including cost figures for an ERS with energy transmitted from above the vehicle are included in the report as a reference case.

An increased proportion of vehicles utilizing an ERS would demand new infrastructure to supply the electricity. Computer models have therefore been made by the Lund University to simulate the energy demand for a technical solution and thus being able to estimate cost of the extending infrastructure required. Vattenfall has also analysed and proposed a solution for the distribution grid connection of a “Slide-in road” between Stockholm and Gothenburg and together with the project partners estimated the total investment cost for the required grid infrastructure. KTH has furthermore studied how business models and stakeholders are affected by the ERS.

The proposed solutions are also discussed with the Swedish Transport Administration and other relevant administrative authorities, to jointly reach a solution that to a least possible extent affect the road’s function and durability, and also meet the future requirements that will be placed on an ERS.

### 1.4 Project participants and responsibilities

<table>
<thead>
<tr>
<th>Organization</th>
<th>Person</th>
<th>Title</th>
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<tbody>
<tr>
<td>Volvo GTT</td>
<td>Richard Sebestyén</td>
<td>Project leader and project leader of the conductive subproject</td>
</tr>
<tr>
<td>Scania</td>
<td>Håkan Gustavsson</td>
<td>Project leader of the inductive subproject</td>
</tr>
<tr>
<td>Bombardier</td>
<td>Bjarke Sonnesen</td>
<td>Project Manager primove</td>
</tr>
<tr>
<td>Vattenfall</td>
<td>Lennart Spante</td>
<td>Project manager Vattenfall</td>
</tr>
<tr>
<td>Swedish Transport Administration</td>
<td>Mats Andersson</td>
<td></td>
</tr>
<tr>
<td>Projektengagemang (Svenska Elvägar AB)</td>
<td>Per Ranch</td>
<td>Project leader of overhead line subproject</td>
</tr>
<tr>
<td>Lund University</td>
<td>Mats Alaküla</td>
<td>Professor</td>
</tr>
<tr>
<td>KTH Royal Institute of Technology</td>
<td>Mats Engwall</td>
<td>Professor</td>
</tr>
<tr>
<td>Chalmers</td>
<td>Jonas Sjöberg</td>
<td>Professor</td>
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<table>
<thead>
<tr>
<th>Organization</th>
<th>Person</th>
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<tbody>
<tr>
<td>Alstom</td>
<td>Patrick Duprat</td>
</tr>
<tr>
<td>Bombardier</td>
<td>Christian Köbel</td>
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<tr>
<td>Chalmers</td>
<td>Jonas Sjöberg</td>
</tr>
<tr>
<td>KTH</td>
<td>Mats Engwall</td>
</tr>
<tr>
<td>Lund</td>
<td>Olof Samuelsson</td>
</tr>
<tr>
<td>Scania CV</td>
<td>Nils-Gunnar Vägestedt</td>
</tr>
<tr>
<td>Svenska Elvägar</td>
<td>Anders Nordqvist</td>
</tr>
<tr>
<td>Swedish Transport Administration</td>
<td>Mats Andersson</td>
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<tr>
<td>Vattenfall</td>
<td>Johan Tollin</td>
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<tr>
<td>Volvo GTT</td>
<td>Henrik Svenningstorp</td>
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Table 3 Responsibility areas and commitments

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Responsibility</th>
</tr>
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<tbody>
<tr>
<td>Concept developer and test track provider for inductive energy transfer</td>
<td>Support with knowledge within inductive power transfer. Developing and optimizing concept for inductive power transfer. Providing key figures for technical performance and costing.</td>
<td>Bombardier</td>
</tr>
<tr>
<td>Vehicle movement simulations</td>
<td>Requirements of how a vehicle movement behaves in comparison to road surface lane.</td>
<td>Chalmers</td>
</tr>
<tr>
<td>Business model and stakeholders</td>
<td>Defining and analysing the transition to the ERS from a business model and stakeholder perspective.</td>
<td>KTH Royal Institute of Technology</td>
</tr>
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<td>Generic ERS-simulation</td>
<td>Simulation of a generic ERS involving distribution network power flow and thermal loading of network components, all based on a detailed time domain traffic model.</td>
<td>Lund University</td>
</tr>
<tr>
<td>Vehicle adaption, inductive</td>
<td>Scania is responsible for develop and test a vehicle equipped with a Bombardier inductive power transfer system.</td>
<td>Scania</td>
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<td>Reference case for an ERS</td>
<td>Description of a reference case for an ERS with energy transmitted from above the vehicle</td>
<td>Svenska Elvägar AB</td>
</tr>
<tr>
<td>Road construction, maintenance and standards</td>
<td>Specifications of a highway between Stockholm and Gothenburg and the requirements demands on an ERS. Development of an ERS future implementation concept.</td>
<td>Swedish Transport Administration</td>
</tr>
<tr>
<td>Road energy supply (e.g. transformer stations and rectifiers)</td>
<td>Technical requirements for the &quot;Slide-in road&quot; power supply system (Stockholm-Gothenburg); analyses of needed power supply, system design and cost analyses for the total electrical distribution system.</td>
<td>Vattenfall</td>
</tr>
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</table>

1.5 Targeted audience

This report intends to describe a technology that enables continuous wireless energy transfer from the road to the vehicles thus allow for a fossil independent transport system. Vehicles intended to utilize this technology ranges from heavy-duty timber transport to lighter personal vehicles and building this system concerns both road constructors, power suppliers and the community structure.

Targeted audience therefore includes both decision-makers within these fields as well as the general public interested in the discussion about creating an ERS that is available for the majority of vehicles.

1.6 Time plan

Project start: October 4, 2010

Delivery of the first edition of the report for the first phase of the project: October 18th, 2013

Delivery of the final edition of the report for the first phase of the project: December 2013
2 ERS – A NEW TECHNOLOGICAL PARADIGM

This chapter describes the transition to the ERS as a new technological paradigm. It defines the general principle of ERS, different ongoing ERS initiatives and the barriers for the implementation of ERS.

Electric Road Systems (ERS) can be described as electrified roads that support dynamic power transfer to the vehicles from the roads they are driving on. The basic principle is to power an electric engine within the vehicle from an external power source that is built into the road infrastructure, see Figure 1. The electrical power is transmitted while the vehicle is in motion, through a pick-up assembled to the vehicle in a similar way as for a trolley bus. The roads would be accessible for both vehicles with ERS-propulsion as well as conventional fossil fuelled vehicles. Further on, the ERS-vehicles would be equipped with a small battery and a potentially smaller internal combustion engine (ICE), which allows the vehicles to drive also on conventional roads outside the ERS network.

![Figure 1 Principal design of an Electric Road System (ERS)](image)

Today, there is a common notion among key actors in the industry that ERS technology is technologically feasible and a way to reduce fossil fuel dependency and emissions in the road system (in spite of huge infrastructure investments required for the technology). There are disagreements among the experts whether the transformation from the diesel engine regime to ERS will be realized within 10, 20 or 50 years, but there is a consensus that this transition is possible to come. However, the change is expected to take place gradually, from smaller demonstrations and systems, via closed systems (e.g. mining transportation or city bus loops), to major networks of regional and international highways. Hence, there are several ERS-projects going on around the world at the moment, exploring and evaluating the technology and the possibilities of deploying this prospective system on commercial basis (e.g. Pajala (Trafikverket, 2012); Los Angeles and Long Beach, California (Green Car Congress [1], 2012); Arlanda, Sweden (Elways, 2012); Bordeaux, France; McAllen, Texas (OLEV Technologies, 2011); Lommel, Belgium (Bombardier Transportation, 2012); and Stanford University, California (Green Car Congress [2], 2012)).

Originally, it was actors from the railway industry who developed the ERS based technologies. There are different technological solutions available; the power could be transferred to the vehicle by overhead transmissions or through power sources built into the ground (road). The overhead transmission technology is conductive-based and the vehicle connects to the transmission lines by a type of pantograph, see Figure 2. The ground-based solution could be
either conductive or inductive. If conductive, the vehicle uses a physical pick-up to connect to an electrified rail in the road; if inductive, there is a wireless power transfer from a coil in the road to a pick-up in the vehicle. Technologically, the overhead line solution is a more mature than the ground-based alternatives.

ERS technology is already feasible for railroad applications. Deployment on road transportation requires huge investments in the physical infrastructure, but if implemented on full scale, it has significant potential advantages in relation to the existing fossil dependent transportation system; it is fossil independent and emission free\(^1\); it is more energy efficient and reduces operation costs (electricity is cheaper than fossil fuel); it reduces noise problems allowing vehicle operations at off-traffic hours, which decreases congestion and even out the energy demands. In addition, it has the potential to reduce vehicle maintenance costs since an electric engine is simpler and lighter than a traditional internal combustion engine although this might not be the case in the short term with different powertrains.

However, the main barriers for implementation of an ERS are related to increased complexities on the system level. The conventional transportation system has evolved organically over more than 100 years and constitutes today an open socio-technological system with different standards and regulations and constituted by different, more or less, autonomous and complementary subsystem. These subsystems – the truck, road, and fuel – are today produced and operated autonomously by different actors, e.g. truck manufacturers, construction companies, road authorities, and oil companies. Initially at least, the ERS-technology requires a more closed system-design, where the subsystems are tightly coupled together. The power train of the ERS-truck needs to be tightly integrated with the power transfer technology, which needs to be integrated with the electric road design, which in its turn needs to be integrated with the regional power grid.

Consequently, there are a number of actors from different industries owning strong interests in the different ERS-technologies, e.g. manufacturers concerning the vehicle and its power-train; railroad manufacturers concerning the power transfer technology and electric roads technology; construction firms concerning the physical infrastructure; and power utilities concerning the electric power supply and operations of the power grid. In addition, there are several new services required in order to manage ERS, e.g. payment systems, logistics, driver management, electricity metering, and safety. Furthermore, software management services are needed to reduce the complexities of the technological interfaces between ERS and its customers.

\(^1\) Depending on the energy balance, electricity is not necessary always to prefer from an environmental perspective. However, by pushing for more sustainable technologies in the vehicles, actors of public policy try to increase demand in order to create a pull for greener produced electricity.
2.1 Stakeholder implications

Based on the observations from the Slide-In project, the primary subsystems of ERS will probably be delivered by firms mainly coming from railway manufacturing industry and by electric utilities that could produce, distribute, and sell electricity. In the following sections, the different actors will be discussed in terms of their role in the conventional road system compared to in the ERS. A comparison could be seen in Figure 3.

For the **truck manufacturers**, power electrification could be seen as a body builder (building application on the truck chassis). This means that the truck should manage electrification independent of which power transfer technology that becomes the standard. However the vehicle will be more integrated with the infrastructure in the new system compared to the conventional road system, as it needs to be developed and connected with the other subsystems. In the beginning of the ERS deployment, ERS could mature in a niche market for different applications (such as mining and bus system). However, in the long term, ERS could come in to mainstream markets of the truck manufacturers (such as long haulage). The role and value of the core competence for the truck manufacturers, currently being the diesel engine, could change with a switch to the ERS. This would also affect the customer value and service network. Thus, a shift to ERS would require the truck manufacturers to acquire new competencies and new business models.

**Petroleum firms** will most probably continue to play a significant role with ERS (electrified roads and batteries would not be able to supply the whole road transportation system). The role of these firms could however change, from being the dominating fuel supplier, to a secondary fuel supplier. If vehicles do not need to tank as frequently as today, petroleum companies will lose their sale volumes and the number of customers would decrease. This might turn the petroleum firms into new businesses, and the established tank-station networks might complement their current businesses with new applications, such as quick charging and battery swapping.

One of the main implications for **construction firms** is to ensure safety and durance in controlling the construction and properties of the electric roads. As an actor with experience of large projects, construction firms could take the role of integrating the transfer technologies as well as the electric grid into the road construction. Furthermore, the issue of financing new ERS projects might open a new market for public-private partnerships, where construction firms (or
other private real estate owners), build and operate electric roads on contracts for public agencies.

The main motivations behind the ERS for the state and agencies is to reduce environmental impacts, oil imports and increase energy efficiency by switching from fossil to electric fuel. All other stakeholders have pointed out that the state and agencies have a key role as facilitators when it comes to investing in infrastructure. The loss in oil taxes and currency savings from oil imports could require new national and international policies. The transition to the ERS might change the financing and owning structure of these roads in order to share the risks and opportunities with private actors that will benefit of new system. The ERS could also be developed as a new export industry in countries that have come far in their development of this technology, such as Sweden, Germany and Korea. Hence, investing in the development of the ERS could result in a new market and thus increased income for states and agencies.

The users of the ERS could benefit from higher energy efficiency in the vehicles compared to diesel engine trucks and thus potentially lower fuel costs (although the electricity prices are expected to rise). ERS could also constitute an image and brand value to be more environmental friendly than other alternatives. Despite this, cargo firms might be reluctant to change to ERS vehicles if the infrastructure is undeveloped in the sense that flexibility and uptime is still better in the conventional road system. It is yet unclear how much the vehicle prices could be affected due to the ERS equipment and new powertrain technology. There are also uncertainties concerning how and to whom the customer should pay for the usage of the ERS.

Road power technology firms could be firms in the railway industry or entrepreneurs. Railway companies have long experience of designing, producing and delivering complete railway systems, including infrastructure and intelligence. Trams in urban transportation are one of the main markets for these firms. Since the past couple of years railway companies have introduced different technologies for power transfer from roads to vehicles. These firms are now trying to broaden the scope for respective technology, to include urban transportation such as busses and cars, but also trucks and cars on highways. This creates a situation were different technologies are competing with each other. Proponents of the inductive and conductive technologies are pushing for their solution and it is uncertain which solution that will win in the end. In addition, there are several unclear issues concerning how the system will evolve: Will these actors become systems or component providers? Will they sell licenses of their components to other actors or will it be exclusive roads? Will they develop alliances with partners to deliver a complete ERS or will they provide generic technologies? And how should the revenues within the new value network be shared?

Power companies produce electricity through different energy sources, e.g. fossil fuels, nuclear and renewables. The traditional way of making money is to sell electric power per kWh to households and companies. In the ERS scenario, electricity will be the new primary vehicle fuel, which opens a new market for the power companies. Designing and delivering power station in connection to the power transfer technology and the road is a potential business of the power companies. The power grid and stations need to be dimensioned based on the amount of power required for the vehicles at the particular road section. The main question for the power companies is: Who will finance the investments in the power subsystem and how should the revenues from the vehicle’s electricity consumption be captured?
2.2 A Business model Perspective

In Figure 4 the issues related to the transformation to ERS are summarized from a business model perspective. The model is constituted by the three main business model components *Value Proposition* (what the selling points are for the actor to its customer/user), *Value Creation* (technologies, core competencies, alliances, etc), and *Value Capture* (how to charge for the value provided). As shown in the figure, the most significant barriers holding back a systemic change to ERS are institutional, rather than purely technological, and related to issues such as standardization, competition, core competencies, infrastructure deployment, financing, and solutions for value capture for the different stakeholders.

![Figure 4 Business model for an ERS](image)
3 SIMULATION OF GENERIC ERS

In order to understand the effects and requirements from an ERS, an ERS simulation system has been developed at Lund University within the project. The system simulates a simple road with no intersections and is implemented in MATLAB. Three different types of simulations are integrated into the system:

1. Traffic simulation
2. Electric simulation of the power system
3. Thermal simulation of the power system

An illustrative animation tool has also been developed to conveniently visualize the results from the simulations. The core is the traffic simulation, which has explicit representation of all vehicles and uses a fixed time step of one second. To illustrate general behaviour of the system and the capability of the software tools, an ERS example has also been composed at Lund University.

3.1 Simulated ERS example

The illustrations hereon are all based on a synthetic road example with information from a Nordic road. It is a two-lane highway with a length of 20 km and altitude profile as shown in Figure 5, with a maximum slope of 7 %.

![Figure 5 The relative altitudes along the road.](image)

The simulated traffic is about 1450 cars and 230 trucks per hour. This is a realistic dimensioning traffic for an average daily traffic of 16000 cars and 3500 trucks. (Hydén, 2008) (Vägverket, 1998) (Vägverket, 2004). Four different vehicle types are defined; car, distribution truck, light loaded long haul truck and heavy loaded long haul truck, see Table 4.

<table>
<thead>
<tr>
<th>Specifications for the different vehicle classes.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>Vehicles/km</td>
</tr>
<tr>
<td>Mass (kg)</td>
</tr>
<tr>
<td>Max power (kW)</td>
</tr>
<tr>
<td>V max (km/h)</td>
</tr>
<tr>
<td>V max std. dev. (km/h)</td>
</tr>
</tbody>
</table>

The cars have an average power consumption of approximately 20 kW while the trucks consume approximately 120 kW on average. All vehicles are assumed to use the ERS if available; otherwise they run on battery power. Regenerative braking charges the battery, but power flow from vehicle to the ERS is not allowed. When running on ERS the battery is charged or discharged with a proportional controller to keep the battery’s state of charge close to the optimal level. The initial states of charge are chosen so that no significant net battery charging or discharging occurs when averaged over all vehicles.

The road is electrified in 100 m segments in the right lane in each direction. An overview of the power distribution system is shown in Figure 6. It is assumed that the thermal behaviour of all
components can be modelled as a first order time constant of 1800 seconds and that the losses at 100 % load rises the temperature to the rated temperature in steady state, see section 3.4.

Figure 6 An overview of the simulated power system. All components are three phase components.

3.2 Traffic simulation

The main goal of the traffic simulation is to properly reflect how the ERS loads the power system. This load needs to have realistic correlations in time and space along the road. The load profile for the synthetic road example is given in Figure 7. The color of each pixel in this image represents the power drawn from a 100 m section of the road in both travel directions. The higher power levels indicated by red or yellow are often the result of one or more heavy vehicles. The inclined lines indicate one or more vehicle moving along the road. More inclined lines indicate slower moving vehicles, this is for instance seen around the 11 km mark where heavy vehicles slow down in the steep hill. The higher power levels indicated by red or yellow are often the result of one or more heavy vehicle. The cars show up as less inclined light blue lines if at all. Vehicles moving uphill uses more power and are most clearly visible. Some vehicles moving downhill do not use any power from the road at all and are therefore not visible. The bunching of lines indicates some level of traffic congestion. Vehicles in the left lane of each direction do not show up at all since they have no access to power from the road. The parts of the road with higher inclination and higher altitude compared to the surrounding parts of the road are heavier loaded than average. The increased load at the tops of the hills is due to less charged batteries and acceleration after slowing down in the up hills. This would probably change if the vehicles had more intelligent battery charging control that took the expected regenerative braking on the approaching downhill slope into consideration.

Figure 7 The power consumption per segment as a function of time and position along the road. The road is divided in to 100 m sections that include the right lane of both travel directions.
The traffic model is based on the intelligent driver model (IDM) and the Lane-change Model MOBIL. (Treiber, Hennecke, & Helbing, 2000), (Helberg & Treiber, 2002), (Treiber M., 2011) These have been adapted to fit the simple fixed step solver used in this simulation. A typical traffic situation is shown in Figure 8.

![Figure 8 A typical traffic situation on 2 km of the road. The road has four lanes. The larger rectangles represent trucks and the rest represent cars.](image)

### 3.3 Electric power system simulation

The main goal of the electric power system simulation is to calculate the voltage drops and the losses in the different components. The electric simulation consists of calculating a static power flow for each time step. The power system used is shown in Figure 6 and the resulting voltages to the ERS can be seen in Figure 9.

The voltages are given in per unit (p.u.), where nominal voltage is 1 p.u. Normally in industrial applications the voltage level should be kept above 0.85 p.u. This level is violated here for short periods at specific locations. What voltage levels that will be acceptable in the respective system solution need to be specified. A control system that slightly reduces the load at low voltages could be part of the solution. The spacing of the transformers along the road could also be adjusted to better match the average local power consumption of the traffic.

![Figure 9 The voltage in the low voltage system along the road over time in per unit. The position of the feeding transformers can clearly be seen. The lowest voltage is 0.81 p.u. The 99 % percentile of the voltages is 0.93 p.u.](image)

### 3.4 Thermal power system simulation

An ERS gives a very fluctuating load locally, and in order to get an optimized power distribution system this must be taken into consideration. The main limiting factor for the current capability of electrical components is overheating. Therefore a very simple thermal simulation of the power system has been implemented. Each component is modelled by a single
thermal mass with a cooling time constant of 1800 seconds. This can be described by the equation:

$$\frac{dT(t)}{dt} = \frac{1}{t_c} \left( \frac{P_{loss}(t)}{P_{loss\_rated}} - T(t) \right)$$

Where $t$ is the time, $T(t)$ is normalised temperature of the component at time $t$, $t_c$ is the time constant of 1800 seconds, $P_{loss}(t)$ is the losses in the component at time $t$ and $P_{loss\_rated}$ is the losses in the component at rated power. The behaviour of the thermal model can be seen in Figure 10.

![Figure 10](image10.png)

*Figure 10* The blue line shows the cooling of an unloaded component. The green line shows the temperature of a component that is unloaded until $t=900$ s and then loaded at rated power. The red line shows the temperature of a component loaded at 71 % of rated power.

This is a very conservative thermal model. It is assumed that the steady state temperature of the components at rated current and voltage will be the rated temperature. The temperatures are initiated to the worst possible valid value, which is 100 % of rated temperature for each component; this ensures that the temperatures are not underestimated. The result from such a simulation can be seen in Figure 11. The transformers around the 10 km mark need reinforcements the other transformers are able to handle the load. Similar calculations are done for all cables as well; the result for the 400 V cables can be seen in Figure 12.

![Figure 11](image11.png)

*Figure 11* Temperatures of the 22/0.4 kV transformers along the road over time. Temperatures are given as percent of the allowed temperature rise. Ambient temperature corresponds to 0 % and rated temperature corresponds to 100%. Observe that the time axis start 900 seconds after the simulation starts. The components are initiated at 100 % temperature at the beginning of the simulation.
3.5 Result summary

The total average power consumed was 14 MW or 700 kW/km. The losses in the system are given in the Table 5 below:

Table 5 The losses in different classes of components as percent of the total power consumption.

<table>
<thead>
<tr>
<th>Losses</th>
<th>Total</th>
<th>130/22 kV transformer</th>
<th>22/0.4 kV transformers</th>
<th>22 kV cables</th>
<th>0.4 kV cables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>6.4 %</td>
<td>0.4 %</td>
<td>1.3 %</td>
<td>2.0 %</td>
<td>2.7 %</td>
</tr>
</tbody>
</table>

Statistics for simulated temperatures are given in Table 6. The values are given for the last 900 seconds of the simulation. As noted before, temperatures are given as percent of the allowed temperature rise. Ambient temperature corresponds to 0 % and rated temperature corresponds to 100%.

The 130/22 kV transformer is slightly overloaded in this scenario, the rest of the components are below rated temperatures.

Table 6 The average and maximum temperatures for different classes of components as percent of the rated temperature rise.

<table>
<thead>
<tr>
<th>Component category</th>
<th>Average temperature</th>
<th>Max Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>130/22 kV transformer</td>
<td>100 %</td>
<td>103 %</td>
</tr>
<tr>
<td>22/0.4 kV transformers</td>
<td>81 %</td>
<td>103 %</td>
</tr>
<tr>
<td>22 kV cables</td>
<td>61 %</td>
<td>90 %</td>
</tr>
<tr>
<td>0.4 kV cables</td>
<td>56 %</td>
<td>91 %</td>
</tr>
</tbody>
</table>

When interpreting these values it is important to remember that the system is initiated to 100 % and a component with no losses will have an average temperature of 48 % and a max temperature of 61 % since the simulation does not run to a (quasi) steady state.

3.6 Recommendations

The developed simulation tool is useful when investigating different design rules for the power distribution system for an ERS and is a good starting point for developing a simulation tool for actual roads with intersections and so on. The simulation routines can thus serve as a starting point for future development.
4 GENERIC SCENARIO DESCRIPTION

A fixed generic scenario was defined within the project in order to allow calculations and demonstration to be comparable both within the project and for other system solutions. The figures used below were also used to estimate the requirements for the ERS infrastructure, maintenance and also the total cost of ownership.

The generic scenario description includes the main parameters required to calculate or simulate the:

- Energy demand per road km,
- Infrastructure required to supply the demanded energy,
- Energy transfer efficiency from road to vehicle,
- ERS construction and safety
- Vehicle demands required to be able to utilize the ERS and
- Total ERS solution costs.

Described below are the values for the vehicles, route, route topology, environmental conditions and traffic conditions.

4.1 Heavy Vehicle definitions:
Length: 16,5 m
Weight: 40 tons
Front size: 10 m² (0.53 drag coefficient)
Rolling resistance coefficient: 0.5
Diesel engine power: 500 hp / 368 kW
Diesel engine efficiency: 42 %
Diesel engine characteristics: See reference: (Scania, 2012)
Electric motor power: 120 kW continuous. Battery charging is included.
Electric motor efficiency: 95 %
Energy storage capacity: 250 kWh
Auxiliary's power: None
Back charging to battery: Yes

4.2 Passenger car definitions:
Length: 4.6 m
Weight: 1.65 tons
Front size: 2.28 m² (0.29 drag coefficient)
Diesel engine power: 215 hp / 158 kW
Diesel engine efficiency: 42 %
Diesel engine characteristics: See reference: (Polestar, 2012)
Electric motor power: 20 kW continuous
Electric motor efficiency: 95 %
Energy storage capacity: 11.2 kWh
Auxiliary's power: None
Back charging to battery: Yes
Vehicle lateral behaviour: The vehicles are assumed not to deviate more than 50 cm from the middle of the lane. During 90% of the time they are assumed not to deviate more than 20 cm from the middle of the lane.

For simplification of the simulations all vehicle components are 20 °C at start of the route and the energy storage is fully charged.

### 4.3 Route topology

The highway, Figure 14, between Stockholm and Gothenburg via Jönköping is used as the reference distance.

![Figure 14 The highway from Stockholm to Gothenburg via Jönköping.](image)

**Distance:** 447 km  
**Inclination:** 0-1 % = 57.5 % of the distance  
1-2 % = 22.5 % of the distance  
> 2 % = 20 % of the distance  
**Speed:** 90 km/h  

Figure 15 below describes the topology of the route.

![Figure 15 The topology of the road between Stockholm and Gothenburg.](image)
4.4  Road and embankment parameters:
Type of road: Swedish highway, see Figure 5.1 in (Vägverket, 2004) and Figure 16 below.
Emergency lanes: No
Number of electrified lanes: 1 in each direction
Distance to embankment from road: 10, 9 or 6 m depending on the speed limit 110, 90 or 70 km/h. See chapter 7 in (Vägverket, 2001).
Depth of roadside equipment: Unlimited
Underground conditions: Dirt
Level of exposure to frost damage: 2 on a scale 1-4 see (Statens geotekniska intitut, 2008)
Estimates of construction and design methods are based on the information in Figure 16.

<table>
<thead>
<tr>
<th>Roadside</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wearing course (Slitlager)</td>
<td>40 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Asphalt bound gravel (Asfaltsbundet grus, AG)</td>
<td>150 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Unbound base material Gravel size 0-45 mm</td>
<td>80 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Reinforcing layer Gravel size 0-90 mm</td>
<td>480 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Road</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Wearing course (Slitlager)</td>
<td>40 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Asphalt bound gravel (Asfaltsbundet grus, AG)</td>
<td>100 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Unbound base material Gravel size 0-45 mm</td>
<td>130 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Reinforcing layer Gravel size 0-90 mm</td>
<td>480 mm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 16 Cross section of a typical Swedish highway construction.

4.5  Environmental conditions:
The ERS must withstand the Nordic weather conditions, which are described in average in Table 7 and along the defined route between Stockholm and Gothenburg, Table 8. The average humidity fluctuations in Sweden used as reference in this report are presented in Table 9.

Table 7 Average monthly surface temperatures.

<table>
<thead>
<tr>
<th></th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max.</td>
<td>-1</td>
<td>0</td>
<td>3</td>
<td>9</td>
<td>15</td>
<td>20</td>
<td>21</td>
<td>20</td>
<td>15</td>
<td>10</td>
<td>4</td>
<td>-1</td>
</tr>
<tr>
<td>Min.</td>
<td>-6</td>
<td>-7</td>
<td>-4</td>
<td>-1</td>
<td>4</td>
<td>8</td>
<td>6</td>
<td>9</td>
<td>15</td>
<td>4</td>
<td>0</td>
<td>-5</td>
</tr>
</tbody>
</table>

Table 8 Road surface temperature variation over the year.

<table>
<thead>
<tr>
<th></th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gothenburg</td>
<td>-1.1</td>
<td>-1.2</td>
<td>1.6</td>
<td>5.8</td>
<td>11.6</td>
<td>15.6</td>
<td>17</td>
<td>16.2</td>
<td>12.7</td>
<td>8.9</td>
<td>4.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Jönköping</td>
<td>-2.6</td>
<td>-2.7</td>
<td>0.3</td>
<td>4.7</td>
<td>10</td>
<td>14.5</td>
<td>15.9</td>
<td>15</td>
<td>11.3</td>
<td>7.5</td>
<td>2.8</td>
<td>-0.7</td>
</tr>
<tr>
<td>Stockholm</td>
<td>-2.8</td>
<td>-3</td>
<td>0.1</td>
<td>4.6</td>
<td>10.7</td>
<td>15.6</td>
<td>17.2</td>
<td>16.2</td>
<td>11.9</td>
<td>7.5</td>
<td>2.6</td>
<td>-1</td>
</tr>
</tbody>
</table>
Table 9 Humidity variation over the year.

<table>
<thead>
<tr>
<th></th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Göteborg</td>
<td>85</td>
<td>82</td>
<td>77</td>
<td>71</td>
<td>66</td>
<td>69</td>
<td>73</td>
<td>74</td>
<td>79</td>
<td>81</td>
<td>86</td>
<td>86</td>
</tr>
<tr>
<td>Jönköping</td>
<td>84</td>
<td>80</td>
<td>71</td>
<td>62</td>
<td>59</td>
<td>60</td>
<td>65</td>
<td>66</td>
<td>70</td>
<td>73</td>
<td>83</td>
<td>86</td>
</tr>
<tr>
<td>Stockholm</td>
<td>85</td>
<td>81</td>
<td>78</td>
<td>72</td>
<td>65</td>
<td>66</td>
<td>72</td>
<td>75</td>
<td>81</td>
<td>84</td>
<td>88</td>
<td>87</td>
</tr>
</tbody>
</table>

Increased level of road surface due to frost: Between 10 mm to 80 mm, see Table A4-11 in chapter A4.5.3 in (Vägverket, 2009).

4.6 Traffic conditions in the electric lane

Figures of traffic intensity in both driving directions are measured with hourly resolution provided to the project by the Swedish Transport Administration at two points, one east of Jönköping and one west of Jönköping. Roughly 21 500 vehicles travel on the road each day east of Jönköping and around 12 800 vehicles travel on the road west of Jönköping. An example of the measurements is seen in Table 10 from the city of Rångedala near Borås.

Table 10 The mean traffic flow in the city of Rångedala, Monday-Friday 2012-01-01 to 2012-10-23 (Vehicles per hour)

<table>
<thead>
<tr>
<th>Time</th>
<th>Westward</th>
<th></th>
<th>Eastward</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Trucks</td>
<td>Small vehicles</td>
<td>Total</td>
<td>Trucks</td>
</tr>
<tr>
<td>01:00</td>
<td>20</td>
<td>24</td>
<td>44</td>
<td>14</td>
</tr>
<tr>
<td>02:00</td>
<td>16</td>
<td>14</td>
<td>30</td>
<td>8</td>
</tr>
<tr>
<td>03:00</td>
<td>11</td>
<td>11</td>
<td>22</td>
<td>7</td>
</tr>
<tr>
<td>04:00</td>
<td>12</td>
<td>17</td>
<td>29</td>
<td>7</td>
</tr>
<tr>
<td>05:00</td>
<td>13</td>
<td>42</td>
<td>55</td>
<td>7</td>
</tr>
<tr>
<td>06:00</td>
<td>22</td>
<td>104</td>
<td>126</td>
<td>16</td>
</tr>
<tr>
<td>07:00</td>
<td>36</td>
<td>330</td>
<td>366</td>
<td>37</td>
</tr>
<tr>
<td>08:00</td>
<td>40</td>
<td>443</td>
<td>483</td>
<td>54</td>
</tr>
<tr>
<td>09:00</td>
<td>46</td>
<td>330</td>
<td>376</td>
<td>71</td>
</tr>
<tr>
<td>10:00</td>
<td>49</td>
<td>277</td>
<td>326</td>
<td>64</td>
</tr>
<tr>
<td>11:00</td>
<td>52</td>
<td>260</td>
<td>312</td>
<td>64</td>
</tr>
<tr>
<td>12:00</td>
<td>60</td>
<td>260</td>
<td>320</td>
<td>63</td>
</tr>
<tr>
<td>13:00</td>
<td>68</td>
<td>273</td>
<td>341</td>
<td>58</td>
</tr>
<tr>
<td>14:00</td>
<td>74</td>
<td>314</td>
<td>388</td>
<td>56</td>
</tr>
<tr>
<td>15:00</td>
<td>75</td>
<td>358</td>
<td>433</td>
<td>57</td>
</tr>
<tr>
<td>16:00</td>
<td>77</td>
<td>410</td>
<td>487</td>
<td>63</td>
</tr>
<tr>
<td>17:00</td>
<td>72</td>
<td>492</td>
<td>564</td>
<td>64</td>
</tr>
<tr>
<td>18:00</td>
<td>63</td>
<td>414</td>
<td>477</td>
<td>63</td>
</tr>
<tr>
<td>19:00</td>
<td>48</td>
<td>311</td>
<td>359</td>
<td>60</td>
</tr>
<tr>
<td>20:00</td>
<td>41</td>
<td>215</td>
<td>256</td>
<td>58</td>
</tr>
<tr>
<td>21:00</td>
<td>32</td>
<td>177</td>
<td>209</td>
<td>50</td>
</tr>
<tr>
<td>22:00</td>
<td>27</td>
<td>128</td>
<td>155</td>
<td>24</td>
</tr>
<tr>
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<tr>
<td>Total number</td>
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<td>5342</td>
<td>6341</td>
<td>1013</td>
</tr>
</tbody>
</table>

Time between vehicles at flat road: 1s, measured back to front
Time between vehicles going uphill: 1s, measured back to front
5 DETAILS OF INDUCTIVE SYSTEM

The chapter describes and discusses the “primove Highway” inductive power transfer solution for electrifying highways, using the specific example of transport truck application on the E4 highway between Stockholm and Jönköping then highway 40 to Gothenburg, as described in the Chapter 4 Scenario description. It includes the general concept, technology readiness, safety, availability, and projected cost.

5.1 System Overview

The primove Highway system is inductive charging with primary windings installed in 20 m segments. Segments are powered when an authorized and primove-equipped vehicle is over the segment, is able to accept energy, and is moving 50 km/h or faster. If another vehicle covers part of the segment then the segment will not be energized (as indicated by proximity sensors on the primove vehicle). A secondary winding within a pickup on the vehicle will provide power to run the electric motor and charge the on-board battery. Segments can be placed all along the roadway or just in clusters or “islands” of many segments with gaps between islands where the battery energy is used to move the vehicle. The islands are located as necessary to maintain the state of charge of the battery. The diesel engine on the truck will be off during normal cruising but will start and assist the electric motor when more power is needed for instance during acceleration, passing, and climbing hills. The diesel will also provide power when the battery is depleted for some reason, for instance when the truck is not on the primove Highway and far from a charging point.

The permission to use primove and collecting fees for receiving primove energy will be regulated by transponders on primove vehicles, similar to systems commonly used on toll highways in many countries. Upon entering the primove Highway the transponder will interact with the electronic toll station and negotiate clearance for use between the truck driver and the primove service provider. If both sides agree then a one-time code is given to the primove controller on the truck that the controller will send to each primove segment along the route to switch it on and transmit energy (as needed). Energy delivery will be tracked and payment calculated via the transponder when the truck exits the primove Highway.

5.2 Concepts and Scaling

In this chapter of the paper the concept for the generic scenario is discussed as well as an alternative scenario called Opportunity charging. Later, in chapter 0, the consequences of the different traffic load cases (Maximum and Average load case) are discussed. Figure 17 below explains the three concepts discussed in this report.

![Figure 17 The three scenarios which are discussed in this report](image-url)
It is essential to understand how concept changes are affecting the dimensioning of the subsystems. Please find below some rules:

The number of primove components in the road (e.g. cables) and next to the road (inverters) does not increase if the traffic load increases in the case there are installed inductive charging all over the distance Stockholm-Gothenburg. Each vehicle is only able to absorb the same power per meter road, no matter the density of the traffic, and the primove components are from the beginning dimensioned according to the energy needed in average of the full stretch.

It makes sense to increase the power per meter of road if the vehicles can draw a higher power and the vehicles can absorb the transferred energy. If e.g. only a part of the full distance Stockholm-Gothenburg are covered with primove, it requires a higher power transfer rate per meter, to transfer the required energy.

The vehicle in the generic scenario can draw a higher power than the electric engine can absorb. The transferred energy can be divided between the battery and to the electric engine. The energy absorbed by the battery can be stored and later utilized at stretches where no primove is installed.

The substations shall supply more power if the traffic load increases as described in Figure 18.

![Diagram of power supply dependency on traffic load](image)

Figure 18 The number and size of primove components are independent of the density of the traffic

### 5.3 System Technology

The fundamental primove Highway technology is transfer of energy from the roadway to the vehicle using the well-known AC transformer principle. As shown Figure 19, the typical AC transformer (as used in a power distribution system for example) has a laminated iron core that directs the magnetic flux from the primary winding through the secondary winding with very little leakage or loss. For primove the core is split, allowing the primary to be in the road and the secondary on the vehicle. Then the primary is elongated so flux can be transferred as the vehicle moves. For better power transfer efficiency the AC frequency is 20 kHz and the iron is either removed or exchanged for ferrite (a magnetic ceramic material).

The primary winding is embedded in the road and covered with asphalt so there are no exposed cables or connections. The primary windings are installed in segments of 20 m each, as shown in Figure 20. The segments are energised only when the primove vehicle transmits the proper code. Substations with rectifiers (rectifier stations) are connected to the medium voltage power grid at regular intervals in segment equipped regions of the primove highway, and the DC power is distributed to the WPC inverters to generate the 20 kHz AC needed to energise segments. In the event of a loss of a single station on the line that rectifier station can be isolated and the remaining stations can power WPC’s on the line.
5.4 Test track facility

The primove Highway test track has been installed to test the functionality of dynamic power transmission for road vehicles. The test facility was originally prepared for the application of busses and trams, and was part of funded project by the German federal ministry of transport, building and urban development. The use of the test facility for further testing of applications such as trucks has been in particular foreseen.

The test track facility has got a total length of 300m of which 4 highway segments of 20m each have been build for dynamic transmission.

The power supply for the system is an available substation with a lower voltage of standard 400 V AC, see Figure 20. To feed the inductive system an active front end is used.

The setup of only 4 segments has been chosen to test the functionality of driving into the segments and out of the segments and see the behavior of the system.
The facility includes next to the inductive road a stretch with gravel and bumpy road surface to test the shock and vibration behavior of the system in real life environment, Figure 21.

5.5 System Operating Modes

In all modes of operation vehicles will enter the primove Highway through a gateway across the highway, similar to that shown in Figure 22. Transponders in primove equipped transport trucks will notify the driver and obtain clearance to supply power. If primove mode (for energy transfer) is desired then a code is given to the truck that will be used to energize primove segments. The power pickup deploys to power transfer height and power is transferred as desired by the truck to keep the battery charged.

Drivers will have the option of accepting or refusing primove energy at entrance gates along the route.

Upon leaving the primove Highway an exit gateway on the exit ramp (or end of the highway) will obtain the energy consumed by the vehicle, compare it to the values tracked by the system for that specific code, and either debit the credit card on file or record the charges to the pre-arranged account for later billing. The pickup will be raised to “parked” position when not in primove mode.

5.5.1 System Normal Operation

In normal operation trucks are travelling 90 km/h and are separated by at least 20 m. Upon reaching a primove segment the code sent by the VDSC transmitter on the truck will be detected by the VDSC antenna on the roadway and the WPC will energize the segment. If another vehicle is closer than 20 m to the front of the truck the VDSC transmission will be halted and the segment will switch off, preventing a non-primove vehicle from driving on an energized segment. A second proximity sensor on the back will switch off the primove segment if a vehicle is following too close (so there is no risk of driving on an energized segment). Even at high speed the segment will switch on fast enough to be ready when the pickup reaches it.

There is an indicator in the cab telling the driver when primove power is transferring, but no special actions by the driver will be required. If the truck strays too far laterally or changes to the non-primove lane then VDSC transmitter will no longer be detected and the segment will be de-energized. Figure 22 Shows the primove highway architecture and Figure 23 is displaying the primove test track.
5.5.2 Degraded Operation

In times of high congestion the vehicles may bunch together and primove power transfer is largely suspended due to the lack of 20 m spacing between vehicles. The diesel engine alone will move the truck once the battery is discharged. In bad weather conditions vehicles should leave more space and hence primove operation will not be affected.

If a single rectifier station fails the system operation will not be affected. If two or more consecutive rectifier stations fail then the voltage may be too low to sustain power transfer in that section. Similarly if more than 1/3 of rectifier substations fail in random locations then power transfer will be affected at least in some areas. Again the diesel engines will be employed.

The system will operate if any number of WPC’s fail, however sufficient energy transfer to keep the battery charged may not be available.
5.5.3 Emergency Operation

In case of an emergency due to a collision the system operation may reduce to degraded operation due to congestion or may be completely stopped. There is no primove hazard to persons leaving their vehicles and helping others, as the VDSC signal to energize segments are disabled when the vehicle speed is below 50 km/h.

If a traffic accident damages primove wayside equipment or involves destruction of the highway surface (say due to fire) then built-in protections will engage. An operator may elect to power down the primove system for added safety. The equipment will be installed so that emergency personnel such as firefighters and crews will follow normal local procedures for switching off electrical equipment from the electric power utility.

5.6 System Efficiency

Primove systems will typically perform at 90% power transfer efficiency or higher, measured from and including WPC to vehicle onboard rectifiers.

5.7 Road and vehicle requirements

The primove highway solution can be applied to any highway alignment. The topology chosen in the generic scenario between Stockholm and Gothenburg via Jönköping, Chapter 4.3 and Figure 15, is used here for easy comparison and demonstration.

The primove Highway vehicle is any road vehicle equipped with the primove vehicle equipment. A specific example is the heavy transport truck described in the generic scenario description, reproduced in Chapter 4.1.

5.7.1 Primove Vehicle Equipment

The primove equipment added to the truck includes pickup, pickup lifter, rectifier, VDSC antennae, primove controls, HMI, distance (prox) sensors, payment transponder, and shielding as needed. The truck with primove equipment is shown graphically in Figure 24. Primove equipment will add up to 500 kg to the vehicle in the scenario.

5.7.2 Primove Vehicle Controls

The vehicle control architecture is shown in Figure 25. The primove power receiver is capable of delivering 200 kW continuous power to the DC bus on the vehicle. The receiver includes the primove power pickup, a rectifier to convert the 20 kHz, 3-phase AC power from the pickup to DC voltage, and a lifting device to raise the pickup into a locked position when the vehicle is not using the primove highway. The pickup has a linear 3-phase winding with taps to allow for wide gap and alignment variations.

The lifting device lowers the pickup to a large gap value from the upper, locked position at the entrance to the primove Highway. When primove power transfer is detected the lifting device adjusts the pickup position to obtain nominal voltage. The lifting device continues to adjust the position to maintain nominal voltage while primove power is transferring, however returns to the large gap value when primove power transfer stops. The time constant of the lifting device is very long to avoid hunting. The pickup lifting device also has a barrier built in to sweep debris aside and protect the pickup from impacts.

The acceptable DC voltage variation is 550 to 950 Volts. Should the pickup voltage be too low for compensation by lowering the pickup further then the primove controller will direct the rectifier to switch to a higher tap on the pickup, employing more turns and producing higher voltage. When primove power transfer stops the rectifier returns to the lowest voltage tap.
The **primove** controller coordinates with the vehicle controls to ensure smooth operation. The current from the **primove** system is regulated by the battery management system under the direction of the vehicle controller. The battery management system will adjust the voltage from the battery around the **primove** voltage to limit the current from **primove** and either charge or discharge the battery to meet the traction motor and battery requirements. When the truck speed is below 50 km/h the **primove** controller will hold the VDSC transmitters off.

![Figure 24](image)

**Figure 24** Generic heavy-duty truck with **primove** equipment.

![Figure 25](image)

**Figure 25** **primove** vehicle control architecture. 1: Electric traction motor. 2: Traction motor control inverter. 3: Traction battery. 4: Battery Management System. 5: Vehicle control system. 6: pickup. 7: Pickup lifting device. 8: Rectifier with tap change switch. 9: **primove** vehicle controls. 10: VDSC transmitters. 11: Prox sensor(s). 12: MMI & transponder.

### 5.8 Primove Highway System Roadway Equipment

The 20 m primary winding segments are embedded 40 mm under the highway surface, in a special form that holds the shape of the windings while the asphalt is applied. Similarly the VDSC antenna loops are installed in a form to allow paving over top. All **primove** windings, antennae, starpoint junctions, and connector leads are installed prior to the final paving step. In areas where utilities run under the road a layer of aluminum is required between the **primove** winding and the utilities.

To install **primove** windings only the top 200 mm of asphalt road surface must be ground away in a strip 800 mm wide. The **primove** winding is installed in a carrier to maintain the winding shape. The carrier is fixed to the roadbed and the cable ends routed to the WPC. Finally the topcoat of concrete is applied to complete the segments installation. The procedure is similar to installing snow melting cables, as shown in Figure 26.
5.9 Primove Highway System Wayside Equipment

The primary winding segments are driven by WPC’s located along the wayside beside the highway and above grade. These power inverters are small, air-cooled units with a minimum number of passive components and a maximum of software control. They incorporate the VDSC function of receiving the code from the vehicle, validating it against information from the central controller, switching on as directed, monitoring the energy consumption, and reporting it. Each WPC employs feedback to ensure a constant current output of 400 Amperes per phase, and will detect a cable breakage and shut off.

Power is supplied to the WPC’s over a DC distribution system powered by rectifier substations connected to the 30 kV medium voltage power grid. The size and spacing of the rectifier substations depends on the load, the size of the DC distribution cable, and the allowable voltage drop between the substations and the WPC’s.

The load is estimated based on simulations of the energy required for a vehicle to traverse the entire route and of driving patterns on the highway. Simulations based on the truck, equipment, and alignment of the road show that a truck will use approximately 700 kWh of energy travelling from Stockholm to Gothenburg, provided that the electric motor delivers no more than 125 kW and regenerative braking is used. At 90 km/h the average continuous power needed is 110 kW. Data provided by the Swedish Transport Administration indicates that the maximum flow is 140 trucks per hour (both directions), as shown in Table 10 or 1.55 trucks per kilometre at 90 km/h (if they were evenly spaced). The result is quite a low power per kilometre, 170 kW/km. However if all vehicles on the highway were primove equipped, including cars, and a safety factor for growth and bunching is included, we arrive at 1.4 MW/km.

The allowable voltage range from primove operation is 750VDC ± 20%. The trade-off between conductor size and rectifier substation space is shown in Table 11. The properties of the cables are given in the Table 12.
Table 11 Spacing of rectifier substations and conductor size.

<table>
<thead>
<tr>
<th>Substation Spacing (km)</th>
<th>Rectifier Substation Rating (MW)</th>
<th>Main DC Distribution Feeder [ # Cables x Conductor Size (mm²) ] per polarity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>1.5</td>
<td>2 x 240</td>
</tr>
<tr>
<td>2.0</td>
<td>3.0</td>
<td>3 x 300</td>
</tr>
<tr>
<td>3.0</td>
<td>4.5</td>
<td>4 x 400</td>
</tr>
</tbody>
</table>

Table 12 Capacity and Resistance of Cables

<table>
<thead>
<tr>
<th>Conductor (Single Conductor Insulated Cable – Stranded Copper)</th>
<th>Current Carrying Capacity² (A)</th>
<th>Resistance³ (Mohms/conductor @ 20 degC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>240mm²</td>
<td>~570</td>
<td>75.4</td>
</tr>
<tr>
<td>300mm²</td>
<td>~650</td>
<td>60.1</td>
</tr>
<tr>
<td>400mm²</td>
<td>~760</td>
<td>47.0</td>
</tr>
</tbody>
</table>

Although it is most cost effective to use as few rectifier substations as possible, the conductor size rapidly becomes unmanageable as the spacing increases. Rectifier substation spacing of 3 km is a practical limit for the primove Highway. The layout of the DC distribution is shown in Figure 27. Each rectifier substation is fed from redundant 30 kV power lines, and supplies the DC distribution system through circuit breakers and disconnects. A rectifier substation will continue to function even if one 30 kV supply is lost. If a rectifier substation should fail it can be isolated and the DC distribution load is assumed by the remaining substations.

² Current carrying capacity taken from cable manufacturer specifications (Philips Cables) for copper cable in duct.
³ IEC 60288 Table 2
5.9.1 Full Inductive Charging

In accordance with the generic scenario of the Slide-in project stated in chapter 0, primove segments are installed on 100% of the highway to ensure uninterrupted flow of primove energy. In this case the power supplied to each WPC need to be only 130 kW, and the pickup on the vehicle need only deliver 120 kW power (the motor load). The onboard battery serves only a power smoothing function and can be replaced by a larger DC link capacitor in the rectifier. In this case the DC distribution must supply the entire highway, which requires 2000 km of 240 mm$^2$ cable (2x240m$^2$, positive and negative, 500 km). It will also require 2260 km of 200 mm$^2$ cable with 448, 1.5 MW substations spaced 1 km apart, or 4500 km of 400 mm$^2$ cable with 149, 4.5 MW substations spaced 3 km apart.

5.9.2 Opportunity Charging

The battery on the vehicle can easily supply the needed energy to power the vehicle for many kilometers. Simulation was used to determine the placement of primove segments, given the energy required to move the generic truck and the size of the battery. It was determined that only 35% coverage of the road is required to maintain the charge in a 100 kWh battery if the motor is used to brake the vehicle and the regenerated energy is returned to the battery. In this case the primove pickup on the truck delivers 200 kW to power the motor and charge the battery. Primove segments are arranged in 10 clusters or islands each typically 16 km long, and the islands are separated by 30 km. Two of the islands need to be somewhat longer to maintain a good state of charge. Figure 28 shows the arrangement of the primove charging islands both Westbound to Gothenburg and Eastbound to Stockholm. The islands are aligned or at least contiguous one side to the other to optimize the power supply and distribution. Figure 29 and Figure 30 show the state of charge from Stockholm to Gothenburg and Gothenburg to Stockholm, respectively. The state of charge of the 100 kWh battery does not go below 40% and the truck leaves the highway with a fully charged battery. It was assumed that the battery was charged 50% at the entrance to the primove Highway. Each island will require 5 rectifier substations for a total of 50, much less than the 100% full inductive charging scenario. The DC cable is also much reduced, to approximately 1500 km of 400 mm$^2$. 
Figure 28 Placement of primove segments in “islands” between Stockholm and Gothenburg. The Eastbound and Westbound islands aligned to optimize the power distribution.

Figure 29 Battery State of Charge Stockholm to Gothenburg.
5.10 Primove Highway System Vehicle Detection and Power Control

Energy will only be provided to a primary winding segment if a valid code is received from a VDSC transmitter. The valid code is assigned to the vehicle and the WPC via the transponder at the entrance to the primove Highway. The short-range inductive (near-field) communication of a transmitter to an antenna loop ensures that a transmitter must be immediately over an antenna loop for the signal to be received. The rear transmitter ensures that the segment under the pickup remains energized. The front transmitter starts energizing a segment in front of the truck to ensure that the segment is powered up when the pickup reaches it even if the truck is travelling at high speed. However the proximity sensor on the front of the truck disables the transmitter if another vehicle is nearer than 20 m to the front of the truck, and a similar proximity sensor on the rear disables the transmitter if another vehicle is nearer than 10 m to the rear of the truck (10 m of the segment will be covered by the trailer). Another sensor on the rear of the tractor will be enabled if there is no trailer fitted. The transmitter will also be disabled if the battery does not need charging. Hence the segment can only switch on if the truck needs charge, has a valid code, and no other vehicles can collect any of the power transmitted. The VDSC system in the WPC has at least 90 ms to decode the transmitted signal and switch on the segment.

5.11 Primove Highway Environmental Design

The primove system is designed to operate in -40 to +40 ambient temperatures, and 0 to 100% humidity. The primove system is inherently insensitive to weather conditions and has been demonstrated to operate in snow, sand, and mild floods. Salty slush does not affect primove power transfer.
The vehicle equipment meets or exceeds shock and vibration requirements and can be washed with water spray. The wayside equipment is also designed to withstand the weather conditions.

5.11.1 Electromagnetic Compatibility

The primove system has been shown to meet EN standards for electromagnetic compatibility except at the primary power transfer frequency, where it has been demonstrated and accepted that no harm arises from the exception. The TÜV SÜD has confirmed that the primove system complies with the regulations and requirements regarding electromagnetic field emissions (EMF) and compatibility (EMC)\(^4\).

**Induced Current Prevention**

The magnetic fields of the primove power transfer system will induce stray currents in conductive loops that intercept the flux. Such interception is rendered very difficult by constraining the flux with good magnetic circuit design. Wayside loops do not pick up excessive flux and only loops coincident with the pickup can obtain significant flux. Reinforcing rods in concrete underlayers could form such a loop and are not recommended in primove installations. Such effects can be mitigated with aluminum shielding if loops and metal understructures are unavoidable. The frame of the truck could itself form a loop with induced current, and current in the frame and body may not be acceptable. Shielding under the vehicle where necessary will essentially eliminate the currents.

5.11.2 Roadway Damage

The primove primary winding systems are tolerant to minor frost heaves and weather-induced highway erosion, wear, and damage. Major damage causing potential breach of the cable insulation must be repaired immediately.

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\(^4\) Personal correspondence, M. Roidt to S Seiffert, 2012
5.12 Safety

The primove highway system is safe by design and due to the technology employed. Standard good practice ensures the primove system is safe mechanically and electrically. The only unusual aspect of the primove system is the high values of magnetic flux employed across a short air gap. Extensive development of the primove transformer ensures the high magnetic fields are contained to the very close proximity of the pickup under the vehicle. Humans cannot be exposed to high fields under the vehicle nor in front or behind, as the segments are only on when the vehicle is moving. Any person immediately next to the highway would experience only very small fields much below standard exposure limits.

Persons and cargo in primove vehicles are protected from fields by receiver design and by shielding. Person travelling in non-primove vehicles in front and behind primove vehicles are protected from fields by the proximity sensors on the Primove vehicles that ensure the segments the non-primove vehicles are travelling over are not energized.

5.12.1 Magnetic Field Exposure

Under normal operation the magnetic field will be less than 6.25 µT in all public areas and in the drivers cab. This will be assured by design and operational controls and demonstrated by testing. This field level is lower than the recommended level for public exposure (ICNIRP, 2010) and is safe for all modern pacemakers (VDE, 2002).

In fault conditions the primove control system will ensure that the magnetic field is removed.

5.13 Reliability and Maintenance

The primove system uses redundancy in wayside equipment for enhanced reliability. The design target is 5000 hours between service affecting failures. The primove wayside system excluding traction substations is expected to have availability greater than 99%.

There are regular inspection and service intervals for wayside equipment, especially substation switchgear and WPC cabinet integrity and fan function. The functionality of the wayside equipment can be monitored from a central geographical position.

5.14 Cost Estimate

The cost is estimated for two scenarios. The first scenario is full inductive charging and includes continuous inductive charging between Stockholm and Gothenburg. The second scenario is called opportunity charging where a higher power transfer rate is chosen at only 35 % of the total distance.

5.14.1 Full Inductive Charging

The generic scenario in this report includes a hybrid truck with a 120 kW electric motor. A 100% primove solution in both directions requires thereby 120 kW continuously transferred power per direction/lane. The cost-estimate is based on a downscaled system of today’s test track components. The cost amounts to 28 MSEK per kilometer/direction. This cost includes all necessary wayside components which are

- Wayside box – pre-cast concrete housing with lid
- Wayside power converters (WPC) – 2 per wayside box
- Wayside cooling tower – one per wayside box
- Wayside winding material – all materials including shielding, excluding concrete
- Installation and commissioning is included

The resulting cost per kilometer in both directions is therefore 56 MSEK.
Based on the assumption of installing the complete foreseen distance between Stockholm and Gothenburg, and therefore taking the volume effect into account, the cost amounts to 15 MSEK per kilometer/direction.

Further potential of improvement is to increase the segment length from 20m to 25m, which results in a 13% cost reduction.

### 5.14.2 Opportunity Charging

The alternative proposed system in this report, which is based on 200 kW power transfer rate and estimated 35% covering of primove in each directions, has an estimated cost of 35 MSEK per kilometer/direction. The scope of this cost is the same as for the full inductive charging, rated for a power transmission of 200 kW. The resulting cost per kilometer in both directions is therefore 70 MSEK, based on today’s test track components.

For the project scope, taking into account that 35% (156.5 km) is installed, the cost will reduce to 18 MSEK per kilometer/direction, or respectively 36 MSEK per kilometer in both directions.

Also here a further potential of improvement is to increase the segment length from 20m to 25m, which results in a 13% cost reduction.

### 5.15 Suitability for Other Vehicles

Primove power transfer systems have been demonstrated on cars, buses, trucks, and trams. All these vehicle types could be equipped with primove systems and receive energy on the primove Highway. Trams, buses, and trucks have been shown to draw primove energy from the same primove primary installation. Smaller primove pickups may need to be fitted to smaller automobiles, which will reduce the instantaneous power transfer.

Vehicles not equipped with primove can also travel on the primove Highway and will not notice any difference to a normal highway.

### 5.16 Future Expansion Potential

The primove Highway is easily expanded by adding more segments onto the end to extend the highway. The power supply and distribution system initially installed should be sized for the maximum expected future capacity to avoid installing extra cable and switchgear in the future.
6 DETAILS OF VEHICLE

In this chapter the test vehicle and the planned test activities will be presented.

Principle of truck for ERS system is generally to add new interface components to vehicle hybrid system, thus enabling electrical energy transmission between the inductive road and the vehicle high voltage propulsion system.

As an example the base for such a vehicle system should be a hybrid drivetrain, i.e., a truck equipped with both a diesel combustion engine, and an electrical motor, driven with electrical power from a voltage source, such as an onboard high voltage battery system.

Below is a principle illustration of a hybrid configuration, showing the main components of a split driveline in a hybrid with two torque sources.

![Hybrid vehicle illustration](image)

For a complete system test, it will be mandatory to equip the vehicle with an EM, and some kind of suitable energy layer to facilitate transition between EM mode and ICE mode, but during development phase of the interface components to ERS, this is not necessary.

Thus, the slide-in project has designed a specific diesel engine truck, which facilitates tests of the new components, without actually performing complete system tests on a hybrid truck, see Figure 33. The test vehicle used is a two-axle truck with a distribution box equipped with taillift (R480LB4x2MNB).

The test vehicle needs to be equipped with a power pick up that receives the transferred energy from the primove system. In this prototype the power received will be first measured and then converted to heat in three resistor banks. The vehicle cooling system will cool the resistor banks. The pick-up and rectifier will be cooled by an external cooling system. The system will be controlled and analyzed in the driver cab through CAN communication. These components are described in the Figure 34.

![Test vehicle prior to installation of shielding](image)
The pick-up, shown in the Figure 35, is below the frame slightly offset from the centre in order to clear the diesel tank.

![Figure 35 Installation of pick-up](image)

### 6.1 Shielding

The strong magnetic fields associated with the *primo*ve system could result in 1) Interference to vehicles systems and 2) injury to humans. To minimize the impact of 1 and 2 above, shielding needs to be installed underneath and on the sides of the truck.

For this first test the shielding is more extensive than what will be needed in the final system due to the requirements to retrofit the shielding to an existing vehicle, Figure 36, and the requirement to investigate different layouts of the *primo*ve equipment with regards to the vehicle chassis. One objective of the test activities will be to optimize the amount, placement and weight of the shielding required. Future work will have to investigate how the design of the vehicle could be changed to reduce it even more.
Figure 36 Principle drawing of shielding

Common fastening

Side panels

Fastening prepared
Shields not mounted

Pick up

The shield will be electrically isolated

Figure 37 Shielding and pickup installation
6.2 Test activities

The vehicle will be tested on the Bombardier test site in Mannheim. The main objective is to test the complete system and to measure the efficiency and EMF levels during operation.

6.3 Vehicle tests

1. To measure the efficiency of the primove system at standstill of the vehicle as function of distance between road unit and pickup.
2. To measure the efficiency of the primove system during driving as function of distance between road unit and pickup.
3. Measurement of the EMF at different states of operation outside and in the vehicle.
4. Measure the impact of ice, snow, gravel and water on the efficiency of the primove system.
5. Measurement of how the power efficiency varies when the center line is not followed.

6.4 Expected results vehicle tests

1. Efficiency of primove system with stationary vehicle > 90 %
2. Efficiency of primove system during driving along road centerline > 90%
3. EMF level according to ICNIRP (6,25uT)
4. No impact
5. No EMC problems with other systems in the vehicle

6.4.1 Added cost to vehicle system

Today the expectancy of added/reduced cost to vehicle compared to base system (hybrid 40ton) is:

- **Primove** equipment such as the pick-up (An estimation will be added in the second edition of the report)
- Battery cost (–)
  - When ERS is available, it will be likely that battery capacity should be significantly reduced, only to facilitate state transmission between ICE drive and EM drive, without torque interruptions. However, with no known data of ERS infrastructure, it is not possible to decide what battery type that would be selected.

These estimates are not definite as it is difficult to estimate costs dependant of future volumes, and dependencies of available ERS infrastructure.
6.5 Maintenance

Other added components, shall be designed so that these do not need service intervals.

6.6 Safety

Components that are added into the hybrid vehicle system will be electrically monitored for proper function. This will be included in the system design of the ERS vehicle system.

6.7 Efficiency

No measurements have been made yet of the inductive ERS. There are also components that have not yet been fitted to the vehicle. Expectance is that there will be measurable losses at:

- Power management in power electronics on-board with expected (not confirmed) efficiency of 95%.
- Other losses on board the vehicle of 98% including for example resistive losses within power electronics.
- Electric motor 95%.

6.8 Weight

Estimate of added components and weights are:

- Pickup and lifting device (+330kg)
- Primove control and rectifier (+60kg)
- Shielding (+201kg)
- Battery (-kg), Not yet defined but is likely to be significantly lighter.

These weights are with today’s prototype available designs. In future, these are likely to be reduced significantly.
7 DETAILS OF POWER SUPPLY SYSTEM FROM ENERGY PROVIDER TO THE INDUCTIVE SYSTEM

In order to propel electric vehicles on the road the electrical infrastructure along the road has to be greatly expanded and this chapter will present and discuss one alternative solution on how this infrastructure can be designed.

7.1 System overview

The planned route of the ERS within this project stretches some 447 kilometres between Stockholm and Gothenburg, see Figure 14. The regional power grid, 130 kV, along the same route is owned and operated by Vattenfall. The 130 kV grid is stable and meshed which means that a single fault doesn’t cause an outage for the substations connected to it. This make the existing 130 kV grid well suited for additional loading which is favourable from an ERS perspective, all that is needed is some additional transformers in order to get the right voltage to the ERS. The regional grid is also well suited for a gradual expansion/reinforcement as the number of ERS-connected vehicles increases which of course means that the initial investment can be limited.
Figure 38 The first two road sections from Stockholm towards Jönköping. The red arrows illustrate available connection points within the 130 kV grid.
Figure 39 Third road section from Stockholm towards Jönköping. The red arrows illustrate available connection points within the 130 kV grid.

Figure 40 Road section from Jönköping (to the right) towards Gothenburg (to the left). The red arrows illustrate available connection points within the 130 kV grid.

Figure 38, Figure 39 and Figure 40 above show some available connection points on the 130 kV grid but within this project the ERS will be connected to a 30 kV grid that does not exist today. Therefore all infrastructure between the 130 kV substation and the road side has to be built from scratch in order to supply the ERS with 30 kV voltage, transformed and distributed as 750 V DC. Interesting is that this new 30 kV grid is also a suitable option for wind power connections. One alternative design of this 30 kV infrastructure, customized to fit the Bombardier ERS solution, is shown below in two single line diagrams; Figure 41 and Figure 42.
Figure 41 Principle single line diagram showing the power grid design from 130 kV down to the distribution substations along the road. The diagram is based upon the Bombardier ERS.

Figure 42 Principle single line diagram showing the power grid design from the 30 kV distribution substations down to the road integrated 750 VDC distribution system. The diagram is based upon the Bombardier ERS and the interface lines are a suggestion of how the delivery could be divided between different actors.
7.2 Infrastructure load

The cost of the needed infrastructure is mainly dependent on the distance between the road and the connection points in the 130 kV grid and the component cost of the ERS along the road. In order to pinpoint the exact connection points on the 130 kV grid and identify the needed grid reinforcements one needs to know the expected maximum load of the particular ERS. This project has approached this in two different ways. One scenario is called the “maximum load case” while the other is called the “average load case” and a short description of them both follow below.

7.2.1 Maximum load case

This scenario assumes that the road is heavily trafficked with trucks and that two very long truck convoys (~1000 m) travel with 1 second between each vehicle in both directions at the same time. This load case will most likely never occur in reality and should therefor only be interpreted as a reference case that indicates how infrastructure costs scale with the dimensioning power. Assuming this scenario will occur, the Bombardier ERS will need to deliver approximately 6 MW of power for each kilometer of road, including both directions. One should however also bear in mind that this maximum power case does not include any losses in the system which means that the “real” load on the regional grid will be even higher than 6 MW. In order to simplify calculations Vattenfall made an assumption, in an early stage of the project, that this scenario corresponds to a maximum load of 400 kW per 60 meters of road or 6.7 MW per kilometer. This means that all the calculations made, regarding the maximum load case design of the power grid, are based upon the an maximum load of 6.7 MW per kilometer and which probably corresponds well to the 6 MW load case if losses would be included.

7.2.2 Average load case

In the average load case the maximum load of the 130 kV grid have been estimated using the traffic flow intensities of 2012 with hourly resolution provided by the Swedish Transport Administration at two points, one east of Jönköping and one west of Jönköping. Roughly 21 500 vehicles travel on the road each day east of Jönköping and around 12 800 vehicles travel on the road west of Jönköping and 100 % of these vehicles are assumed to be connected to the ERS, see example of data in Table 10.

From these figures, together with the vehicle parameters specified in the generic scenario description in chapter 4, and losses from chapter 5.6 and 6.7, the maximum average load during one hour (at 16:30-17:30) was extracted and then multiplied by a so called safety factor5 set to 2. With this doubled maximum average power the average load case presents a dimensioning load for the ERS far below the maximum load case. With the average load case the dimensioning load for the ERS sums up to 0.96 MW per kilometer west of Jönköping and 1.4 MW per kilometer east of Jönköping. Note that these results also include all losses from the shaft of the electric motor on the vehicle up until the 30 kV connection point on the power grid according to Table 13 below. Since the efficiency of the transmission in the ERS has not yet been tested it was set to 90% in this calculation despite earlier estimations.

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5 The safety factor is used to take into account a needed over capacity of the system. It is chosen freely but within the project group the value 2 was considered reasonable.
Table 13  Total ERS efficiency up to the 30 kV-grid, all figures will be verified in a later stage within the project when it is possible to measure different system parameters.

| System efficiency of ERS up to the 30kV grid, relevant for the average load case |
|-------------------------------------|------|
| Electric motor                     | 95 % |
| Inverter supplying the electric motor | 95 % |
| Other losses on board the vehicle  | 98 %  |
| Transmission through the ERS       | 90 %  |
| Traction substation                | 99 %  |
| Total efficiency                   | 78.8 %|

The two above cases have been analyzed from a cost perspective in order to estimate the total investment needed in order to realize the infrastructure for the proposed ERS and the results are shown in chapter 7.5 Cost calculation. The analysis is divided between the cost of the 130 kV infrastructure and the cost of the 30 kV infrastructure and then presented as a fixed cost per kilometer of road.

7.3  Maintenance and safety

When building new power transmission infrastructure the maintenance and safety issues are tricky to predict and this project is no different. A rule of thumb surrounding maintenance is that the total cost of the maintenance per year during the calculated lifespan of the equipment is around 1-2 % of the total investment. This rough estimate of the maintenance cost is relevant for the high voltage infrastructure with 130 kV. However it is probably not such a good measure of the maintenance cost within the medium/low voltage level as most of the installed components will be designed to be maintenance free and only require periodic checkups, maybe once every 6 years followed by the needed reinvestments. Therefore it is very hard to predict any average yearly maintenance cost of the complete system.

The safety issues related to this project can be divided into two parts. The first issue is regarding the infrastructure that will be installed in the vicinity of the road and the second issue concerns all the other electrical installations needed. To solve these issues the infrastructure needed near the road have to be installed with a necessary safety distance from the roadside and also be protected from the unlikely event of a vehicle impact. What the necessary distance is for an ERS will need to be analyzed and decided by the appropriate authorities in a later stage of the project but existing information is described in chapter 4.4. The second safety issue concerning all other electrical installations is no different in this project compared to any other high/medium/low voltage installations which means that all installations are regulated by existing rules and guidelines provided by the electrical safety authority.

7.4  Efficiency of distribution grid

The distribution of electric power is not possible without losses and the goal is always to minimize the losses as much as possible. When the Bombardier ERS is operating at nominal power in accordance to what has been described in this report the efficiency of the suggested 30 kV distribution network has been calculated to lie in between 99,09 % and 99,42 %. A detailed presentation of how the losses on the 30 kV grid is distributed is shown in Table 14 below. The losses have only been calculated for the use of PEX-cables as it is unlikely that OHTL-would be used in the real installations and also because the OHTL losses would lie in the same magnitude.
Table 14 Presentation of the losses on the 30 kV grid and how they are distributed.  

<table>
<thead>
<tr>
<th>Losses on the 30kV grid, per 130kV switchgear, relevant for the average load case</th>
<th>Power loss, kW</th>
<th>Distributed power, %</th>
<th>Efficiency, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gothenburg- Jönköping Avg. load case</td>
<td>PEX-cable along the road</td>
<td>47</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>PEX-cable 130kV – 30kV</td>
<td>106</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>Sum</td>
<td>153</td>
<td>0.86</td>
</tr>
<tr>
<td>Stockholm – Jönköping Avg. load case</td>
<td>PEX-cable along the road</td>
<td>76</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>PEX-cable 130kV – 30kV</td>
<td>109</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>Sum</td>
<td>185</td>
<td>0.91</td>
</tr>
</tbody>
</table>

The losses in the table above have been calculated with respect to the nominal operation of the system, i.e. 100 % of the ERS is operating at rated load and without problems.

The losses on the high voltage (130 kV) grid does not affect the dimensioning of the underlying ERS and therefore they are not studied within this report. Those losses can however be assumed to be included in the overall national transmission grid losses that in general is said to be around 3-4 % in Sweden.

7.5 Cost calculation

The needed infrastructure for the ERS is based on two grid voltages, 130 kV and 30 kV, and the investment costs have been estimated independently for each voltage level. The cost for the infrastructure needed to transform the 30 kV to the 750 V DC, which is supplied to the ERS, is included in the 30 kV infrastructure. The total infrastructure cost per kilometer is calculated from the total investment cost which is then divided with the total distance of the road (447 km).

7.5.1 Cost of 130 kV infrastructure

These calculations have been made by Vattenfall Eldistribution AB and the goal is to utilize the existing 130 kV grid as much as possible. The available connection points to the regional network can be seen in Figure 38, Figure 39 and Figure 40. The two different load cases presented in chapter 7.2 require different adaptations of the 130 kV grid but the substation setup will be similar and consist of two redundant transformers 130/30 kV in order to provide grid stability, see Figure 42. In the average load case only minor adjustments are needed in the existing 130 kV substations but this is not true for the maximum load case. A total of five completely new 130 kV substations with corresponding power lines and three new 400/130 kV power transformers in existing substations are needed in order to meet the power requirements for the maximum load case. The costs of the 130 kV infrastructure is presented below in Table 15, divided between the two load cases.

Table 15 Compilation of total investment cost of the 130kV infrastructure.

| Cost of the 130 kV infrastructure between Stockholm and Gothenburg, 447 km (MSEK) |
|---|---|---|---|
| Route Jönköping – Stockholm | Route Gothenburg – Jönköping | Reinforcements in additional grid | Total |
| Maximum load case | 471 | 280 | 339 | 1090 |
| Average load case | 254 | 83 | - | 337 |

7.5.2 Cost of 30 kV infrastructure

In order to calculate the cost of the 30 kV infrastructure the so called EBR-catalog⁷ has been used wherever possible but some components have been estimated from experience or by input from industrial producers such as ABB.

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⁶ “PEX-cable 130 kV-30 kV” means the power cable between the 130 kV switchgear and the nearest road substation. The distance have been assumed to be 5 km.
Some basic assumptions have also been made in order to simplify the calculations such as:

- The distance from the 130 kV substations up to the nearest 30 kV substation is assumed to be 5 km.
- The stretch of road that is supplied by each 130 kV substation is calculated as the average distance between all 130 kV substations on the specified route and with respect to the different load cases.
- Each 30 kV roadside substation is assumed to occupy an area of 20x10 meter and the cost for civil works is set to be 500 kSEK per substation, regardless of its power.

The total investment cost of the 30 kV infrastructure is summed up in Table 16 below.

<table>
<thead>
<tr>
<th>Table 16: Compilation of total investment costs of the 30kV infrastructure.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cost of the 30 kV infrastructure between Stockholm and Gothenburg, 447 km (MSEK)</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>With PEX-cables, total</td>
</tr>
<tr>
<td>per km</td>
</tr>
<tr>
<td><strong>Of which traction substations cost</strong></td>
</tr>
<tr>
<td>Maximum load case</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Average load case</td>
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<tr>
<td></td>
</tr>
</tbody>
</table>

The total investment for the 30 kV infrastructures presented in Table 16 above should only be considered as a rough estimation of the infrastructure costs as all the figures are uncertain until a real quotation have been made. As can be seen in the table, all traction substations represent a very large portion of the total costs of the 30 kV infrastructure and therefore it is important to mention that the prices of the traction substations are especially hard to estimate at this early stage of the project. One 1,5 MW* traction substation is estimated to cost around 500 kEUR (~ 4,4 MSEK), and a 6,7 MW around 12,4 MSEK. These prices are a result of estimations from, and discussions with, experts within both ABB and Bombardier but the margin for error is still rather large. However, if one should perform this project in reality, the large volume of equipment might help to lower the investment costs substantially. There are also other factors as raw material costs and exchange rates that could fluctuate over time.

7.5.3 Total infrastructure cost per km

The needed infrastructure for the ERS is based on two grid voltages, 130 kV and 30 kV, and the investment costs have been estimated independently for each voltage level. The later infrastructure also includes the transformation to 750 V DC supplied to the ERS. Therefore the total infrastructure cost per kilometer is calculated from the total investment cost which is then divided with the total distance of the road (447 km), se compilation below:

<table>
<thead>
<tr>
<th>Table 17 Total cost of the infrastructure supplying the ERS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total cost of the infrastructure between Stockholm and Gothenburg, 447 km (MSEK)</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Maximum load case</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Average load case</strong></td>
</tr>
</tbody>
</table>

7.6 Copper price

The cost of many components in the suggested ERS and the associated infrastructure is strongly dependent on the raw material price of copper. In order to ensure a fair comparison between the different ERS solutions the price of copper was locked on the 17th of September 2012 to 54,2 SEK/kg.

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* The EBR-catalog is catalog that uses statistics from real industrial projects to provide a rational tool for planning/budgeting of electrical infrastructure projects.

* A 1 MW traction substation is assumed to cost the same.
8 IMPLEMENTATION CONCEPT

The commercially available technologies used for continuous electrification of road transport have not yet qualified for implementation in any significant extent. It still remains both a technical and juridical verification in Swedish climate conditions as well as a credible business model for implementation. There are also a number of techniques for the electrification of the road network that are still in a development stage. These should be given time to develop and mature before deciding if, when and to what extent the road network is electrified.

The different technologies must be qualified independently both regarding technical feasibility and market validation as well as in demonstration. The Swedish Transport Administration is until then not ready to decide on or recommend decisions on the wider implementation of ERS.

A construction of an ERS, including both installations in the road and power supply, for example along the distance Stockholm-Gothenburg, is expected to take a long time to implement. The Swedish Transport Administration believes that in order to get most benefits from the investment as early as possible, any initial implementation should be made on a stretch where traffic of local point-to-point character is larger than in general. When local vehicle owners see an economic benefit of investing in the technology, the ERS construction and usage can more quickly get implemented.

8.1 Implementation in point to point traffic

There are various ideas about how a technology can penetrate a market. The Swedish Transport Administration believes that it must prove commercially mature for success; and technical functionality in itself is not enough. There must also be a profitable business in mind to attract the capital needed to invest in infrastructure and to attract vehicle manufacturers to build the adapted vehicles. A few demonstrations of "showcase type", that shows the technology's abilities may be financed by public funds, but for wider implementation there must be profitability both for the society and the industry.

Successful implementation of new technology has often proved to require commitment and shared knowledge between community and industry for a long time. During this time the technologic functionality is verified, so the market and the future users, can rely on it. Once the technology is mature, it can be tested in smaller scale real life conditions. Before deciding about further large-scale tests any teething problems can be corrected both in the vehicles, road, surrounding infrastructure and the required communication in between these. In order not to delay the implementation process work with standardization and legal issues should also start at an early stage.

A study should be conducted to find a relatively short distance with high traffic flow that is appropriate for a first implementation. Such sections are often to be found in a fixed traffic relationship, a route, eg between a dry port and a shipping port, or between production and distribution facilities. Another option could be a highway for public transport in a major city. Meanwhile, potential customers, willing to switch to electrically powered vehicles and begin utilizing the new technology, should also be contacted. Implementation during the development stage should be prioritized based on where both the customer interest and road traffic are highest. A test or demonstration should preferably be commercially attractive. That is, there should be a revenue side that can help fund the demonstration. Market players venturing in a demonstration is one of the signs that technology is considered mature enough to implement.

8.2 Stage two and standardization

Once the trial period is over and evaluated the experiences that have emerged forms the new target for further expansion. If the trial has been successful and positive feedback from those who used the road has been spread, the interest from new operators will increase and the
expansion rate can accelerate. Based on the earlier inventory of local transport needs, new sections are built and deployed, and finally, tied together along the entire distance. Probably, it is relatively much more expensive per unit length to electrify various sections of the road than it is to electrify a longer continuous stretch. The benefits of doing it gradually are however still greater since such an implementation allows constant evaluation by the vehicles in service and corrections will not be as costly as they if the entire route needs to be adjusted. It is also natural to begin converting sections with high traffic loads where economic and environmental benefits can be achieved more easily.

Cooperation in the EU should also be initiated to standardize the various input parameters in the system to allow traffic across borders when the system reaches the higher level of deployment. The standardization work should begin early to follow, review and determine the most applicable interface between the pick-up and the vehicle to allow the pick-up to be easily mounted on different types of vehicles. It should also include the electrical interface between the pick-up, vehicle and the roadside infrastructure so the vehicle owner as well as both the vehicle and pick-up manufacturer only have one voltage level or voltage interval to relate to. Furthermore, the interface for transferring information between the vehicle and the roadside infrastructure, such as for communication and billing systems, must also be standardized.

8.3 Maintenance aspects

Maintenance costs for the infrastructure is currently unclear since the final concepts are not yet defined. This technique has not been verified by snow removal, de-icing and frost heave or maintenance coating of asphalt.

**Maintenance pavement of asphalt**

It is likely that new routines and new construction equipment are needed to perform the maintenance of the road with regards to the new electrical installations in the road segment. In order to verify the methods for maintenance, both a section of road and the machines must be developed and built. Electrification from below requires major interventions in the existing roadway, which will require a closure of the lanes. It is likely that the shutdown time will be more extensive compared to if the route is not electrified.

**Rutting effect**

Rutting effect, as a result from several vehicles driving in the same track, is considered to be greater if the route is electrified. Rutting implies that the road structure breaks down faster and maintenance is required more frequent to ensure that water cannot penetrate the structure and cause a rapid degradation of the same.

**Winter road maintenance**

A system for energy transfer placed in the road surface will require new routines and vehicles for winter road maintenance. This may involve, for example graders and plow trucks that do not damage any elevated road installation. Similar to the maintenance equipment, also these tools for deicing and snow removal requires testing before they can be deployed. There is also a risk that water can accumulate within the joints between the installation and the road surface and thereby cause frost damage. Normally, the water is drained but there is a risk that an elevated installation can be a barrier that hinders water to be drained from the road surface. Therefore tests to ensure problems with snow and ice does not prove to be particularly troublesome will be included in future evaluation of the solutions.
Effects from climatic conditions

An additional uncertainty is how frost heaving affects the installations in the road. More specifically, how is the roadway raised compared to the electric road system and is insulation required to reduce the impact? During the spring thaw, a raised roadway could cause a so-called bathtub effect when the ground defrosts from the top and melt water cannot be drained. Furthermore, cracks may also occur in the top movable asphalt layer if other electric road components are built into the road structure and simultaneously attached deeply into frosted ground. Electric road systems built into the road structure must therefore be designed to move the same way as road structure in general and cope with movements both transversely and longitudinally. The magnitude of the frost heave is expected to vary more laterally than longitudinally and either can be prevented with proper design of the road construction. It might however be associated with a considerable cost if fixed during conversion of an existing road.

8.4 Associated infrastructure

The infrastructure required along the road in order to enable control, monitor and measure energy, need to be built before the first cars starts operating the road. How these systems interact with each other must also to be investigated. Similar systems exist along the railroad and experience from the sector could be the basis for how the infrastructure could be built. Maintenance required for the feeding stations differ between high and low voltage components. The high voltage system’s main components typically have high availability with relatively low maintenance. The maintenance required for the low voltage system is more difficult to assess, partly since it to some extent is new technology that will be used where experience from any longer tests not yet exits.

8.5 Legal aspects

The legal aspects and obstacles for an ERS on highways have not yet been defined. Such barriers may include electrical safety laws, environmental laws as well as land accesses. Some of these questions may be easy to solve, but other issues requires a real case to be tested and evaluated against the legislation. Therefore, it is important to early analyse where legal barriers may exist and start the legal testing based on a real scenario.
9 DISCUSSION OF RESULTS

A discussion of the preliminary results from the Slide-in project with an inductive system solution.

9.1 What is the difference between a plug-in hybrid truck and an ERS truck with primove technology?

An ERS truck with primove technology requires a pick-up to receive the transferred energy from the road. It must also be fitted with components for communication and identification in order to facilitate electrical safety and a billing system. It is likely that the added weight from these components is similar to the reduced weight of energy storage system. Furthermore, added components shall be designed so that these do not need extra service intervals.

To minimize the impact of magnetic fields, shielding needs to be installed underneath and on the sides of the truck. For this first test the shielding is more extensive than what will be needed in the final system due to the requirements to retrofit the shielding to an existing vehicle and the requirement to investigate different layouts of the primove equipment with regards to the vehicle chassis. One objective of the test activities will be to optimize the amount, placement and weight of the shielding required.

9.2 Discussions regarding the Bombardier primove ERS.

One concept for primove components is proposed in this report. Several tradeoffs have been made and other decisions are reasonable. The described concept shall be seen as a feasible solution, which has been verified as much as possible within the content of this project.

It can be read in the report that 20 meter long inductive charging segments are chosen. Each segment requires a number of components along the road, and it is possible to reduce the total number of components for the 447 km if the segments can be made longer than the 20 meter. It seems technical feasible to make longer segments and thereby a cheaper system. Longer segments will on the other hand reduce the practical availability of primove power, if assumed that non-primove vehicles can not drive over an energized charging segment. Shorter segments could also have been chosen with the advantage that they enable transfer of power to slow moving or stopped vehicles.

The only unusual aspect of the primove system with respect to safety is the high values of magnetic flux employed across a short air gap. The remaining technologies utilized are well known off the shelf technologies. For static charging the TÜV SÜD has confirmed that the primove system for buses complies with all regulations and requirements regarding electromagnetic field emissions (EMF) and compatibility (EMC). One of the next steps in the Slide-in project is the feasibility study with the Scania truck on a test track. The studies will include EMF and EMC testing.

This report is generally based on the generic scenario, but alternatives have also been investigated and discussed. One result hereof is that it seems reasonable that a lighter battery pack will be suitable for the long-haul trucks. It can be anticipated that many vehicles will have destination and/or home base in the major cities next to the highway in mention. If the main purpose of the long-haul trucks are transport at the Gothenburg-Stockholm route, and the trucks anyway always are nearby the highway, it does make sense to apply only a light battery pack. It has been verified in this project that a lighter 100 kWh battery pack, even with only 35% of the 447 km covered with primove, is suitable for the purpose.

Covering 100% of the distance Stockholm-Gothenburg with primove is a very flexible system where vehicles can enter and depart at a random location and always request charging. It is however also feasible to make e.g. 10 stretches, each 16 km long, optimized positioned to minimize the depletion of the batteries, where primove power can be drawn. The initial
investment will be significantly lower and the system can be expanded gradually when there is an observed need.

9.3 Discussions regarding the electricity distribution solution for an ERS between Stockholm and Gothenburg.

The dimensioning load for the analyzed ERS has been set to 1.4 MW/km between Stockholm and Jönköping and 0.96 MW/km between Jönköping and Gothenburg, based on the Slide-In projects generic scenario description and on real traffic flow figures monitored by Swedish Transport Administration.

An electricity distribution solution with a 30 kV grid along the ERS road with 1 - 1.5 MVA substations ("Traction substations") at every km has been proposed for the inductive ERS. The grid substation setup on the 130 kV regional grid level will consist of two redundant transformers 130/30 kV in order to meet the electric road system power requirements. Based on the dimensioning "average load" case there is no need for reinforcements of the 130 kV grid. The regional grid is well suited for a gradual expansion/reinforcement as the number of ERS-connected vehicles increases which means that the initial investment can be limited. There is also an additional option for wind power station connections to this new 30 kV grid. The expected up-time for the electricity distribution parts of the inductive ERS is > 99 %

The total investment cost for an ERS between Stockholm and Gothenburg is estimated below to 28239 MSEK, or 63 MSEK/km, and includes both the adoption of the regional grid and the road installation. The investments for a complete control system and payment solutions are not included in this figure.

Based on the assumption of installing the complete foreseen distance between Stockholm and Gothenburg, and therefore taking the volume effect into account, the cost amounts to 30 MSEK per kilometer.

Further potential of improvement is to increase the segment length from 20m to 25m, which results in a 13% cost reduction.

| Table 18 Total investment cost for inductive ERS between Stockholm and Gothenburg |
|----------------------------------------|--------|--------|
| Relevant for the average load case     | MSEK   | MSEK/km|
| Estimated cost for adoption of the regional grid substations and transformers (130/30 kV). | 337    | 0.8    |
| Road 40: Gothenburg – Jönköping (Dimensioning load = 1.0 MW / km) | 83     | 0.2    |
| Road E4: Jönköping – Stockholm (Älvsjö) (Dimensioning load = 1.5 MW / km) | 254    | 0.6    |
| The cost for the 30 kV distribution (PEX-cables) from the 130/30 kV substations to the roadside "Traction substations" and along the road. | 580    | 1.3    |
| The cost for the "Traction substations" including installation. | 2290   | 5.1    |
| Bombardier ERS including road installation | 25032  | 56     |
| Total investment cost for a complete inductive ERS between Stockholm and Gothenburg | 28239  | 63     |
9.4 How does the traffic situation and intensity effect the requirements of the grid?

According to simulations on the ERS in chapter 3 the variations due to traffic dynamics significantly (>10 %) increases the average losses at scales less than about 1 km, on larger scales the daily traffic variations are the dominating load variation.

At roads with lower traffic intensity or lower penetration of ERS-vehicles the distance between the transformer stations can be increased. In these cases, the main concern is shifted from the thermal limits of the components to the voltage drop. The ERS described in chapter 3 has been simulated with 5 % of the vehicles using the ERS and with the same cables but 25 % of the transformer stations installed. This system could handle the load with good margin but more simulations are needed to determine the maximum loading of such systems. Thus the system can be built in steps with transformer stations added over time as the proportion of ERS-vehicles on the road increases.

Traffic jams could be a critical high load case due to the high density of vehicles. However since the primove ERS for safety reasons probably will not allow power transfer when vehicles travel at the low speed or with short intermediate distance, which is typical for traffic jam situations, this will probably not be an issue.

According to simulations on the ERS in chapter 3 slopes on the road up to 3 % have a small impact on the total average power consumption of the ERS.

9.5 A summary of the estimated total system efficiency

The total ERS efficiency from 30 kV grid to the electric motor in the vehicle is estimated to 78.8%. All figures will be verified in a later stage within the project when it is possible to measure different system parameters.

Table 19 Total efficiency of the energy distribution between the 30kV grid to the vehicle engine.

<table>
<thead>
<tr>
<th>System efficiency of ERS up to the 30kV grid</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric motor</td>
<td>95 %</td>
</tr>
<tr>
<td>Inverter supplying the electric motor</td>
<td>95 %</td>
</tr>
<tr>
<td>Other losses on board the vehicle</td>
<td>98 %</td>
</tr>
<tr>
<td>Transmission through the ERS</td>
<td>90 %</td>
</tr>
<tr>
<td>Traction substation</td>
<td>99 %</td>
</tr>
<tr>
<td><strong>Total efficiency</strong></td>
<td><strong>78.8 %</strong></td>
</tr>
</tbody>
</table>

For example resistive losses within power electronics. Rough estimate of the Bombardier primove solution. Including transformer and rectifier.
10 FUTURE WORK

The future work includes a thorough validation of the roadside ERS cost and efficiency figures estimated in this report. The planned demonstration site for the ERS system in place and properly working will provide a lot of information to the project that will require time to analyze and develop. Apart from being able to accurately measure the system efficiency, of interest is for example also to understand what is required to future expand the ERS and allow for increased vehicle power.

Additional questions to be answered are the affects on conventional traffic using the ERS and also the feasibility for passenger cars to use the technology.

A more in-depth analysis of the total lifecycle cost for the ERS system is furthermore also planned in the future work. These calculations will include a sensitivity analysis both regarding the cost and the technical components installed.
11 ERS REFERENCE CASE BASED ON OVERHEAD LINES

The chapter describes an ERS based on overhead lines as a reference case to the inductive ERS.

11.1 Overview

An overhead line, or overhead wire, is used to transmit electrical energy to trams, trolleybuses or trains at a distance from the energy supply point (Wikipedia, 2013 [1]). It is known variously as:

- Overhead contact system (OCS)
- Overhead line equipment (OLE or OHLE)
- Overhead equipment (OHE)
- Overhead wiring (OHW) or overhead lines (OHL)
- Catenary
- Trolley Wire

In this paper the generic term overhead line is used. This is also the term used by the International Union of Railways. (Uic, 2013)

11.2 Overhead line systems for rubber tire vehicles like for buses and trucks

An electrical circuit requires at least two conductors. Trams and railways use the overhead line as one side of the circuit and the steel rails as the other side of the circuit. For a trolleybus there are no rails to send the return current along—the vehicles use rubber tyres and the normal road surface. Trolleybuses use a second parallel overhead line for the return, and two trolley-poles, one contacting each overhead wire. The circuit is completed by using both wires. Parallel overhead wires are also used on railways equipped with three-phase AC railway electrification, which is a rare system nowadays.

Figure 43 Trolleybus in Switzerland, (Hess, 2012). Please note the unsupported “lose” trolleybus type overhead line. This type restricts the vehicle speed and demands the typical trolley poles (fish-rods) for connecting electrically.
11.3 Trolley truck systems
Closed trolley truck systems have been around for a long time but have disappeared from the market, such as in Stockholm, see Figure 44. Cheap oil as well as being bound to closed systems made them unattractive. One application that survived is mines where these systems are used for powering haul trucks, see Figure 45.

![Figure 44 Trolley truck in Stockholm](image1)
![Figure 45 Trolley assisted haul truck](image2)

11.4 Challenges for trolley vehicles system
The challenges for making trolley truck systems attractive again are:

- The ability to connect and disconnect vehicles at speed (dynamic plug in to wayside power)
- The ability to keep track and bill trolley vehicles using the system individually (similar to mobile phone systems)
- The ability for system speeds up to approximately 100 km/h (for handling long distance coach buses).

Such “modern trolley systems”, with vehicles enhanced with an intelligent/active current collector for dynamic plug in to wayside power, as well as a module for billing of energy was envisioned and described by Svenska Elvägar AB in 2010 (Elvag 2010).

11.5 Siemens eHighway system
In 2012, Siemens AG, presented a complete solution including trucks and electric infrastructure, under the trademark eHighway, see Figure 46, (Siemens, 2013). The eHighway technology includes a catenary wire supporting the overhead contact wire, thus enabling higher speeds than traditional trolley technology, as well as supporting an intelligent current connector. eHighway uses a current of approximately 750 V DC, a widely used voltage for trams, trolleybuses and subways. The overhead line is placed 5.15 meters above ground and the distance between the lines are 1.35 meters. There are a European standard for overhead lines and a supplement for trolleybuses. This standard places the contact line at a height of 5.5 meters and a distance of 0.6 meters between the lines.
11.6 Advantages of overhead line systems

- Open, not proprietary technology, ensures competitive market with several suppliers
- Safe and well proven system technology implemented in more than 350 systems and 40,000 vehicles worldwide
- Existing European standard can be adapted for modern trolley systems.

11.7 Disadvantages of overhead line systems

- Can not be used for passenger cars
- Perceived as ugly and old-fashioned
- Supporting vertical pole structure as well as downed wiring is a possible safety hazard that needs to be addressed.

11.8 Cost estimate of overhead line systems

Since overhead line systems exist as a commercial product on an open market there are a variety of suppliers. Overhead line systems targeting railway applications are by far the biggest compared to trolleybus applications. Trolleybus applications are city solutions with a cost-driving factor thus making them more expensive. Two contact lines together with the DC rectifier technology makes the infrastructure cost higher but the vehicle solution more cost efficient. Examples of cost estimates for overhead wire systems are presented in Table 20.
Table 20 Cost comparisons between overhead wire systems

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>MSEK/km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Railway system, 2 directions</td>
<td>15 kV 1-phase frequency 16 2/3 Hz</td>
<td>6 (Elvag, 2010)</td>
</tr>
<tr>
<td>Trolley bus system, 2 directions</td>
<td>2 directions, 750 V DC</td>
<td>9 (1 MEUR/km)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Wikipedia 2013 [2])</td>
</tr>
<tr>
<td>Svenska Elvägar, estimate 2010</td>
<td>2 directions, 750 V DC</td>
<td>10 (Elvag, 2010)</td>
</tr>
<tr>
<td>Siemens eHighway, estimate 2012</td>
<td>2 directions, 750 V DC</td>
<td>7-35 (Gladstein, 2012),</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Los Angeles Times, 2012)</td>
</tr>
</tbody>
</table>

11.9 Standards for overhead lines

Since overhead line systems have been used worldwide for a long time, the standards have already been created and can be applied also for modern trolley systems. Below in Table 21 is a list of the European standards.

Table 21 European standards for overhead wire systems

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN 50119</td>
<td>European Standard EN 50119:2001</td>
</tr>
<tr>
<td>EN 50367</td>
<td>European Standard EN 50367:2012</td>
</tr>
<tr>
<td>BVH 543.3501</td>
<td>Design of high voltage power lines, The Swedish Transport Administration</td>
</tr>
<tr>
<td>Contact Lines for Electric Railways</td>
<td>Siemens AG</td>
</tr>
</tbody>
</table>
12 WORKS CITED


ICNIRP. (2010). Guidelines for Limiting Exposure to Time-Varying Electric and Magnetic Fields (1 Hz - 100 kHz). Health Physics vol. 99, no. 6, pp.818-836


VDE. (2002). *Safety in electrical, magnetic and electromagnetic fields - Part 3-1: Protection of persons with active implants in the frequency range 0 Hz to 300 GHz,* Std. VDE 0848-3-1:2002-05


