FABRIC

Feasibility analysis and development of on-road charging solutions for future electric vehicles

Feasibility assessment for applying Solution 5 to other use cases

Deliverable No.		D3.6.4	
Workpackage No.	WP3.6	Workpackage Title	Design
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Status		Final	
Dissemination level		Public	
Project start date and duration		01 January 2014, 48 Months	
Revision date		2015 - 05 - 16	
Submission date		2015 - 06 - 14	

This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 605405

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LIST OF SELECTED ABBREVIATIONS

ABBREVIATION	DESCRIPTION
AD	Automated Driving
ADAS	Advanced Driver Assistance Systems
BMS	Battery Management System
CO_2	Carbon Dioxide
DoW	Description of Work
DWPT	Dynamic Wireless Power Transfer
DXX.X	Deliverable XX.X
EM	Electro-Magnetic
EMC	Electro-Magnetic Compatibility
EMF	Electro-Magnetic field
ERS	Electric Road System
EV	Electric Vehicle
FABRIC	FeAsiBility analysis and development of on-Road chargIng solutions for future electric vehiCles
HDV	Heavy Duty Vehicle
HV	High Voltage
I2I	Infrastructure to Infrastructure
ICE	Internal Combustion Engine
ICT	Information and Communication Technology
LDV	Light Duty Vehicle
MF-WPT	Magnetic Field Wireless Power Transfer
OEM	Original Equipment Manufacturers
Prox Sensor	Proximity Sensor (for sensing the distance to another object)
TX.X.X	Task X.X.X
UC	Use Case
VDSC	Vehicle Detection and Segment Control (system)
WP	Work Package
WPC	Wayside Power Converter
WPT	Wireless Power Transfer

REVISION CHART AND HISTORY LOG

REV	DATE	REASON
0.1	16/02/2016	TRL: Deliverable structure, Table of Contents (first draft)
0.2	19/03/2016	SCANIA: Updated table of Contents
0.3	29/04/2016	SCANIA: First draft sent to TRL
0.4	4/5/2016	TRL: Review of draft
0.5	13/5/2016	SCANIA: Final version
1.0	16/5/2016	TRL: Submit for peer review
1.1	9/6/2016	SCANIA: updated after peer review

EXECUTIVE SUMMARY

The inductive on-road charging prototype developed by Bombardier/Scania within the Slide-in project has been assessed for its feasibility in application to all use cases defined for FABRIC. Potential adaptations of the system and possible limitations have been identified in this theoretical feasibility study and the overall results are summarised below in the following bullets:

- Preparation of identical in-vehicle hardware for use with cars is not feasible.
- Infrastructure compatibility for the urban use case is possible with modifications.
- With further development all the defined charging modes (Static, Stationary en-route and dynamic) at speed intervals (0-130km/h) could be possible for High Voltage (HV) use cases.
- Primove ITS functions are adaptable to enable some FABRIC use case.

1 INTRODUCTION

1.1 General

This deliverable will present a theoretical feasibility assessment of applying an inductive Electric Road Solution (ERS) solution (referred to as "*Solution 5"* in the FABRIC DoW) to the use cases defined for FABRIC. Scania and Bombardier have together tested an inductive on-road charging solution for trucks. This inductive solution will be assessed for its feasible application to other use cases' in addition to large trucks, in particular, cars and urban environments. Scania has undertaken this theoretical feasibility study, taking into account the requirements and specifications developed during FABRIC SP3, and utilising the results available from testing of the prototype system. Any potential adaptations of the system, limitations and comparison against the specifications and additional requirements have been identified.

1.2 Contribution to FABRIC objectives

This deliverable contributes to the objectives of FABRIC by addressing directly the technological feasibility and economic viability of dynamic on-road charging of electric vehicles.

Responding to a need to assess the potential feasibility of more extensive integration of electric vehicles in the mobility and transportation system, with a primary focus on dynamic wireless charging, as this enables the perceived drawbacks of on-board battery packs to be avoided. The present deliverable provides a close look to a wireless charging system for EVs which facilitates vehicles that are heavier than the ones examined in FABRIC, thus completing the picture regarding the feasibility of the wireless dynamic charging technology in the transport sector.

1.3 Deliverable structure

Chapter 1 – introduces and describes the background and goal of the deliverable.

Chapter 2 – explains the methodology used and the reason why this route was chosen. The link to the other key deliverables is also explained.

Chapter 3 – describes the technology of the Primove system, including both the wayside infrastructure and the on-board vehicle equipment. The testing setup is presented as well as test results from the Slide-in project.

Chapter 4 – contains the feasibility analysis and results. The set of use cases defined for FABRIC have been considered with the "*descriptive scenarios of use*" and "*charging modes*" taken into account.

Chapter 5 – summarises the document and draws the final conclusions.

Chapter 6 – references.

2 METHODOLOGY

2.1 Introduction

This will be a theoretical study of the Primove truck technology and an investigation into its capability to be applied to other use cases. During planning of the task the Work Package 36 team jointly decided that use cases such as cars and urban environments, as well as the ones defined in D4.3.1 should be assessed. This complies well with the description of the task set out in the DoW:

"*Existing inductive on-road charging prototype for trucks developed by Scania will be assessed for its feasibility to be applied to other use cases, such as cars and buses in urban environments.*

Scania will undertake this theoretical feasibility study, taking into account requirements and specifications developed during SP3 and any available results from testing of the prototype system available to date. Potential required adaptation of the system, limitations and comparison against the specifications and requirements will be identified."

2.2 Methodology for Feasibility Analysis

2.2.1 Use cases for the charging solution

The set of use cases defined for FABRIC in D4.3.1, both in Table 4: *FABRIC demonstrable use cases* and in Table 5: *FABRIC feasible use cases* summarised in Table 1 below, have been considered in this feasibility study. Since the Slide-in conductive ERS project focusses mainly on the technology for dynamic conductive charging and not the foreseen ITS the D4.3.1 "*descriptive scenarios of use"* as well as the "*charging modes"* have been taken into account. The relation to the "*descriptive scenarios of use"* has only been described when the assessment showed that adaptation of the system was required or other limitations were found.

2.2.2 FABRIC use cases to be analysed

As explained in 2.2.1, the Slide-in conductive ERS project focusses mainly on the technology for dynamic conductive charging (i.e. not the ITS services) hence the use cases from D4.3.1 "charging modes" and "descriptive scenarios of use" have been taken into account as well.

Charging modes:

- *Static charging*

- *Stationary en-route charging*
- *Dynamic charging*

Descriptive scenarios of use:

- *Driver scenarios of use*
- *Distribution system operator and energy retailer scenarios of use*
- *Road operator scenarios*

The properties of the Slide-in conductive ERS solution are assessed in relation to the *charging modes* and *descriptive scenarios of use* mentioned above.

Table 1 Assessed use cases for Slide-in conductive ERS technology.

Use case	
1.	Driver and EV registration to a central FABRIC database
2.	Driver login to FABRIC
3.	User account management
4.	EV identification
5.	Charging assistance
6.	Charging management high-level and low-level (load balancing)
7.	Energy supply tariff modulation
8.	Charging and road infrastructure availability status updating
9.	Billing
10.	Planning of a trip
11.	Guidance to a charging facility or to a destination
12.	Dynamic route and booking management
13.	Emergency charging
14.	Integration of FABRIC with UTMC

3 DESCRIPTION OF THE CHARGING SOLUTION

3.1 Description

Primove is the e-mobility unit within Bombardier Transportation, whose focus is on creating market-ready wireless charging solutions for all types of rail and road electric vehicles. The system has been tested as a charging option for trams, buses and cars in both stationary and dynamic modes.

The Primove system is brought to the FABRIC project by Scania in collaboration with Bombardier, and will be assessed for its feasible application to other use cases as FABRIC solution 5. Note that the system will only be considered in a theoretical study and will not be subject to test track trials as is the case with FABRIC solutions 1 to 3 that are being developed within the project.

3.2 System overview

The Primove Highway system is based on inductive charging from a stationary energy source to a moving vehicle, with primary windings (stationary energy source) installed in 20m segments along the highway. The segments are powered-up when an authorised and Primove equipped vehicle passes over the segment, which is able to accept energy, and is moving at 50km/h or more. If another vehicle covers part of the segment, then the segment will not be energised (as indicated by proximity sensors located on the Primove vehicle). A secondary winding within the pick-up on the vehicle will accept the energy, providing power to run the electric motor and charge the on-board battery.

A series of segments can be placed along the length of the roadway or in segment clusters (islands), with gaps between these energy islands, where the on-board battery is used to move the vehicle. The islands are strategically located along the highway, maintaining the vehicles battery charge. The diesel engine of the truck will be off during normal cruising, but will start and assist the electric motor when additional power is needed during acceleration, passing, and climbing hills. The diesel will also provide power when the battery becomes depleted, for instance when the truck is not on a section of the Primove Highway or far from a charging point. Permission to use the Primove Highway and collecting payment 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 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.

3.3 System Technology

The fundamental Primove Highway technology is a transfer of energy from the roadway to the vehicle using the well-known AC transformer principle. As shown in **Figure 1**, 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 to 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. The primary core adopts an elongated configuration, so that the flux can be transferred to the secondary core as the vehicle moves. For more effective power transfer efficiency, the AC frequency is set at 20kHz 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 highway segments of 20m each, as shown in **Figure 2**. The segments are energised only when the Primove vehicle transmits the authorised 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 20kHz AC needed to energise the segments. In the event of losing a single station on the line, that rectifier station can be isolated and the remaining stations can power WPC's on the line.

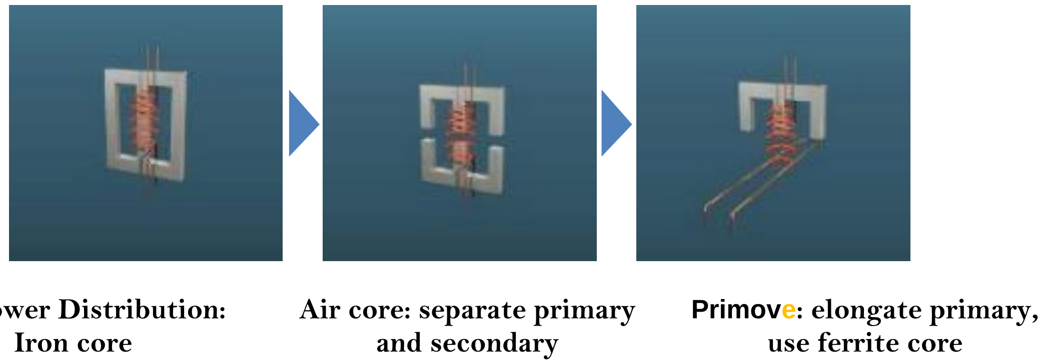

Figure 1 Primove transformer principe

3.4 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 developed for applying this technology to buses and trams, being part of a project funded by the German federal ministry of transport, building and urban development. The test facility for Primove Highway was developed with testing of trucks in mind.

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

The power supply for the system is a substation with a lower standard voltage of 400VAC, see Figure 2. To feed the inductive system an active front end is used.

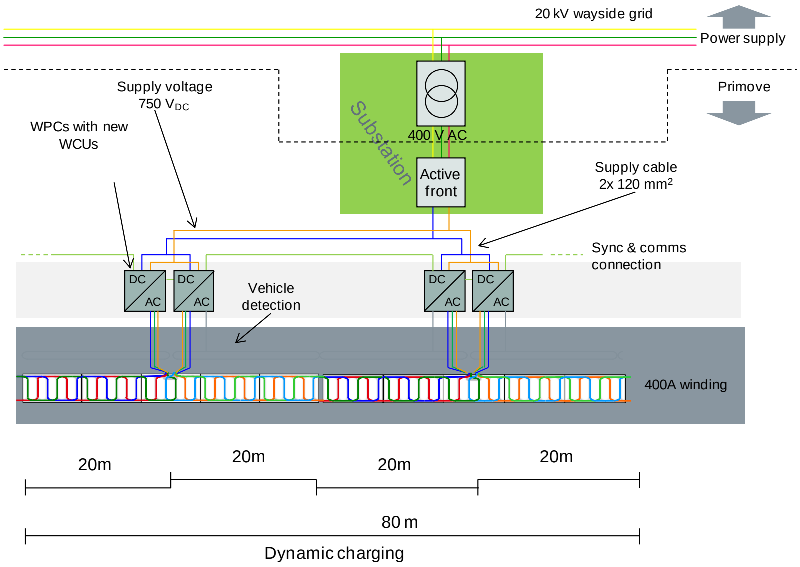

Figure 2 Primove test track setup

The test setup of only 4 segments has been chosen to determine the functionality of driving into the segments and out of the segments and observe the behaviour of the system.

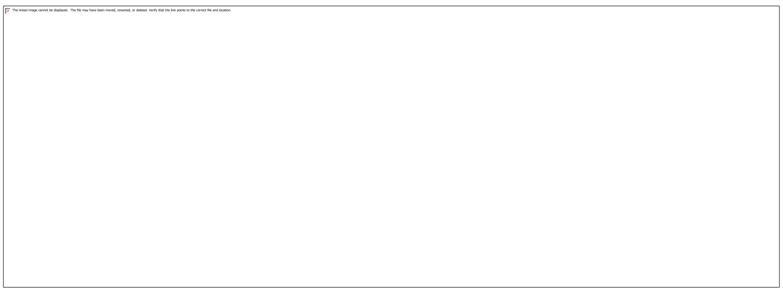

Figure 3 Primove test track overview

Running parallel to the inductive pathway, the facility includes a stretch of uneven road surface consisting of gravel, to test the shock and vibration behaviour of the system in a real life environment.

3.5 System Operating Modes

In all modes of operation vehicles will enter the Primove Highway through a gateway across the road, similar to that shown in Figure 4. Transponders in Primove equipped transport trucks will notify the driver and obtain clearance to supply power. If the Primove mode (for energy transfer) is desired then a code is given to the truck that will be used to energise Primove segments. The power pick-up on the truck then deploys to the required power transfer height and the desired power is transferred 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 the “parked” position when not in Primove mode.

3.5.1 System Normal Operation

In normal operation trucks are travelling at 90km/h and are separated by at least 20m. Upon reaching a Primove segment, the code sent by the VDSC (Vehicle Detection and Segment Control) transmitter on the truck will be detected by the VDSC antenna on the roadway and the WPC will energise the segment. If a vehicle in front is closer than 20m the VDSC transmission will be halted and the segment will switch off, preventing a non- Primove vehicle from driving on an energised segment. A second proximity sensor on the back of the truck will switch off the Primove segment if a vehicle is following too close behind (so there is no risk of driving on an energised segment). Even at higher speeds the segment has the capability to rapidly switch on, ready for when the vehicle pick-up 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 into the non-Primove lane, then the VDSC transmitter will no longer be detected and the segment

will be de-energised. Figure 4 demonstrates the Primove Highway architecture and Figure 5 shows the Primove test track.

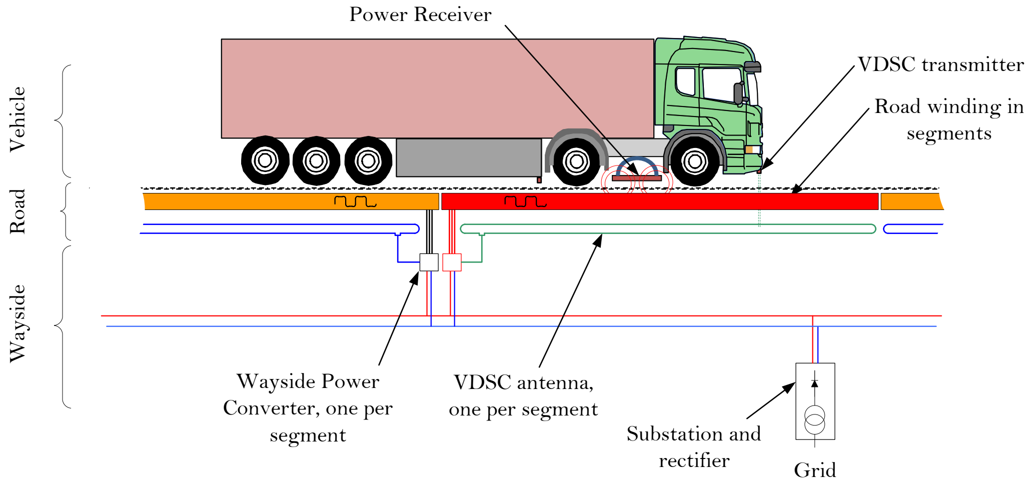

Figure 4 Primove Highway architecture

Figure 5 Primove test track

3.5.2 *Degraded Operation*

In times of high congestion, vehicles may bunch together and in these circumstances Primove power transfer is largely suspended due to the lack of a 20m safety spacing between the vehicles. In these cases, the diesel engine alone will move the truck once the battery becomes discharged. In bad weather conditions, vehicles should leave more space, and the 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 truck's diesel engine will be employed as the primary power source.

The system will operate if any number of WPC's fail. However, in this case sufficient energy transfer to keep the battery charged may not be available.

3.5.3 Emergency Operation

In case of an emergency due to a collision, the system operation may reduce to a 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 signals to energise segments are disabled when the vehicle speed drops below 50 km/h.

If a traffic accident damages Primove wayside equipment or involves destruction of the highway surface (for example. 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.

3.6 System Efficiency

3.6.1 Measurement conditions:

- The test track facility has a total length of 300m, containing four 20m segments, each equipped with Primove technology. The track uses the same technology as used for the static inductive charging, but adapted to the needs for transferring power while driving;
- The system is capable of delivering 200kW on-board to the vehicle, under optimal conditions;
- The vehicle was driving at constant speeds of 20km/h, 35km/h and 70km/h;
- Energy was transferred over an 85mm or 100mm air gap, measured between the bottom of the pick-up and the track;
- Installation in the road was carried out under the same requirements as for other (static) installations. The principle difference is that the electrical components are installed above ground for measurement purposes and the segments were not encased in solid concrete, but with removable covers to allow access for changes; and
- As the segments in this set-up were longer than the truck, the active time per segment was limited, to ensure that the field would not remain on when the truck was standing still.

Figure 6 Test track where measurements were conducted.

3.6.2 Efficiency measurements

After an initial static check to ensure that all components were correctly installed and that static power transfer was working, several test runs were done with varying speeds, different lateral positions and different air gaps. Due to limitations in the test track length, speeds for the different tests were limited to 70km/h for safety reasons. For higher speeds, a longer section of track would be required, enabling the vehicle to get up to speed, carrying out the testing and then afterwards for braking.

The results show that power transfer above 150kW was not a problem at different speeds, and a pick-up misalignment of 100 to 150mm has minimal impact on the power transferred from the wayside to the on-board system.

With a non-optimised system, efficiencies were obtained above 80% and approaching 90% demonstrated.

In the current set-up, power transfer of maximum 183kW was achieved with 85mm distance between road and pick-up and an efficiency of 89%. The measurements clearly show that one of the main parameters in the power transfer was the air gap.

Figure 7 Scania truck at the Primove test track

The results in Figure 8 and **Figure 9** demonstrate that power transfer by inductive technology was feasible in a dynamic case, allowing one to transfer over 120kW efficiently and with an achievable lateral operational tolerance possible. The results reported were from one sample and a series of further measurements are required to confirm the findings. System optimisation will further increase efficiency bringing it close to the levels achieved in static charging. **Figure 8** describes the measurement setup and measurement points.

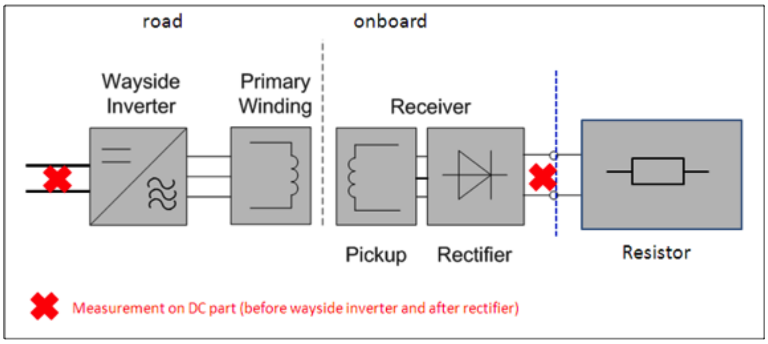

Figure 8 Point of power measurement

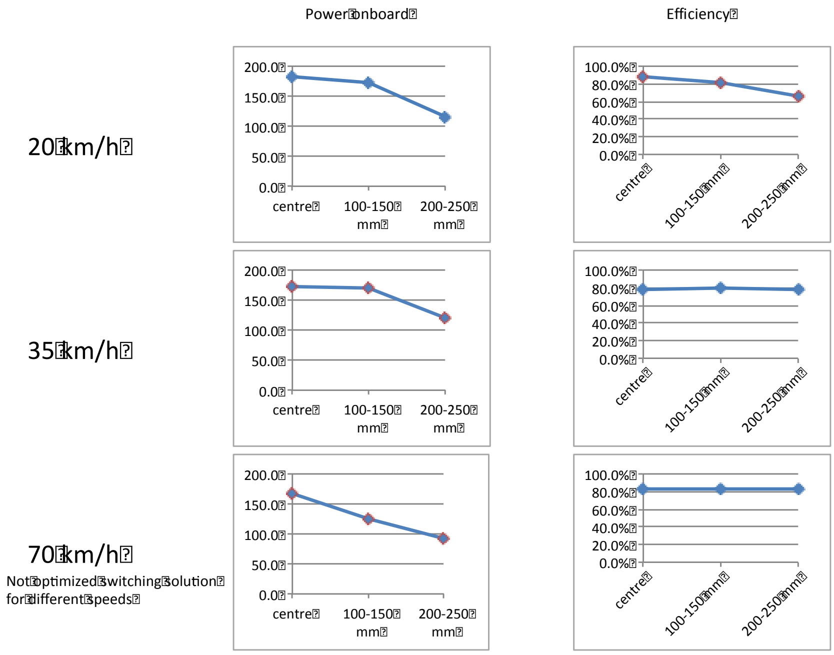

Figure 9 Pick-up (bottom) at 85mm from track (air gap <100mm) at different driving speeds.

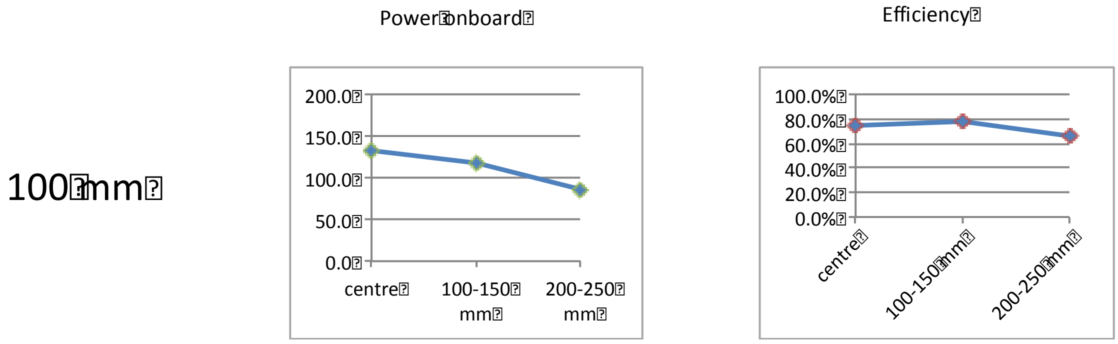

Figure 10 Test with 100mm air gap, from the pick-up (bottom) to the road, traveling at 35 km/h.

3.6.3 Roadside energy transfer efficiency

The global efficiency measurement depends on several different independent dynamic factors that make it difficult to give a definitive and correct value in this report. One example is the type of cable material used and the volume of ERS vehicles utilising the highway, which can result in a non-linear voltage drop in the cables with respect to the power transferred. In this report copper cables are used and the cable losses are estimated to be 1.8 %.

The global efficiency at the roadside level is estimated in **Table 2** below. Therefore, if approximately 2 out of 13 vehicles per kilometre in both directions on the highway are trucks, there would be a total power requirement per km of 470 kW.

Table 2 Global efficiency calculation for Primove

Designation	% Loss	Loss	Power	Comment
Total "User" power for 1 section (at trackside level)	NA		532 449 to 599 006W	Power at the on board traction equipment upstream the converter
Sub-station rectifier (transformer + rectifier)				Sub-station rectifier (transformer + rectifier) excluded
Cable losses	1.8%	9 584 to 10 783W		Refer to previous section
Total required power at trackside level			522 866 to 588 224W	Sub-station power
Transfer losses between road and pick-up	10 to 20%	52 287 to 117 645W		Vehicle travelling within 150mm from the track centre.
Power available for on board traction			470 579W	13 vehicles travelling at 100km/h
Total	11.6 to 21.4%	61 872 to 128 428W	532 449 to 599 00W	
Global Efficiency	78,6% to 88,4%			

Primove systems will typically perform at 80-90 percent power transfer efficiency measured between and including the wayside inverter and vehicle onboard converter.

3.7 Road and vehicle requirements

The Primove Highway solution can be applied to any highway alignment. The Primove Highway vehicle is any road vehicle equipped with the Primove vehicle equipment. A specific example is the heavy transport truck.

3.7.1 Primove Vehicle Equipment

The Primove equipment added to the truck includes pickup, pickup lifter, rectifier, VDSC antennae, Primove controls, HMI, distance (proximity) sensors, payment transponder, and shielding as needed. The truck with Primove equipment is shown graphically in

Figure 11. Primove equipment will add up to 500 kg to the vehicle in the scenario.

3.7.2 Primove Vehicle Controls

The vehicle control architecture is shown in **Figure 12Figure 12**. The Primove power receiver is capable of delivering 200kW continuous power to the DC bus on the vehicle. The receiver includes the Primove power pick-up, a rectifier to convert the 20kHz, 3-phase AC power from the pick-up to DC voltage, and a lifting device to raise the pick-up into a locked position when the vehicle is not using the Primove highway. The pick-up has a linear 3-phase winding with taps to allow for wide gap and alignment variations.

The lifting device lowers the pick-up 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 pick-up position to obtain the nominal voltage. The lifting device continues to adjust the pick-up position to maintain nominal voltage, while Primove power is transferring. However, the pick-up returns to the large gap value when Primove power transfer stops. The pick-up lifting device also has a forward barrier built in to it, which sweeps debris aside and protects the pickup from impacts.

The acceptable DC voltage variation is 550 to 950 Volts. Should the pick-up voltage become 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 pick-up, as this employs more turns and produces a higher voltage. When the Primove power transfer stops, the rectifier returns to the lowest available 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 50km/h the Primove controller will hold the VDSC transmitters off.

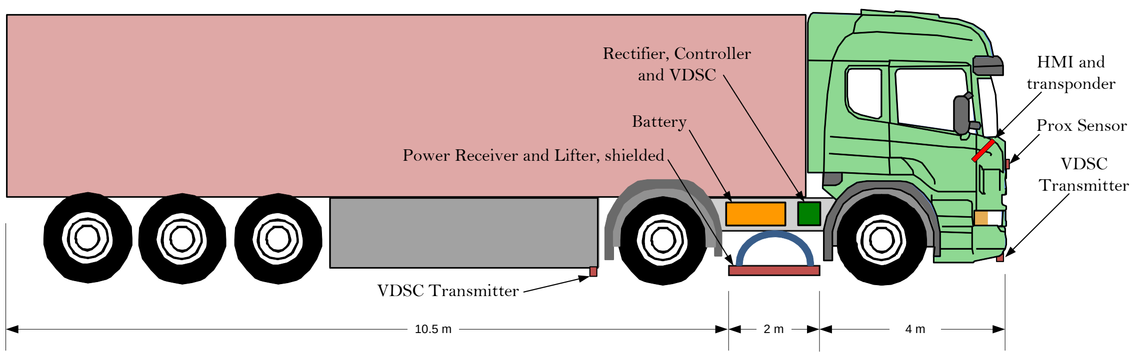

Figure 11 Generic heavy-duty truck with Primove equipment.

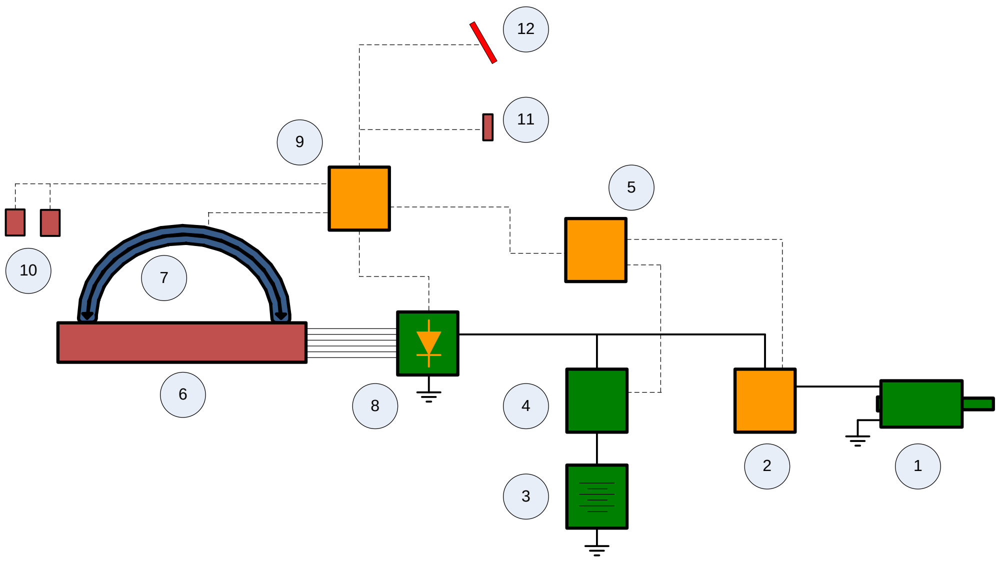

Figure 12 Primove vehicle control architecture. 1: Electric traction motor. 2: Traction motor control inverter. 3: Traction battery. 4: Battery Management System. 5: Vehicle control system. 6: pickup. 7: Pickup lifting device. 8: Rectifier with tap change switch. 9: Primove vehicle controls. 10: VDSC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

3.8 Primove Highway System Roadway Equipment

The 20m primary winding segments are embedded 40mm 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 format to enable paving over top. All Primove windings, antennae, start point junctions, and connector leads are installed prior to the final paving step. In areas where utilities run under the road a layer of aluminium is required between the Primove winding and the utilities.

To install Primove windings only the top 200mm of asphalt road surface must be ground away in a strip 800mm 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 13.

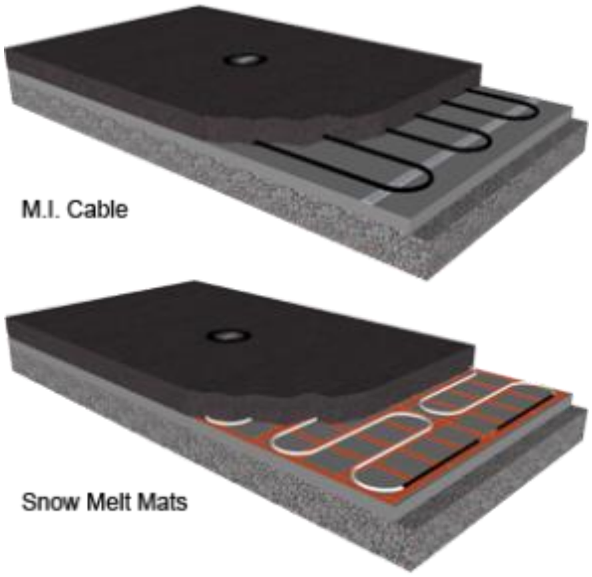

Figure 13 Cables for melting snow from roadways

3.9 Primove Highway System Wayside Equipment

The primary winding segments are driven by WPC's located along the wayside beside the highway. 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 vehicle's energy consumption, and duly 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 30kV 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.

3.10 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 energised. The front transmitter starts energising 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 20m to the front of the truck, and a similar proximity sensor on the rear disables the transmitter if another vehicle is nearer than 10m to the rear of the truck (10m 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, the vehicle speed is over 50km/h and no other vehicles can collect any of the power transmitted. The VDSC system in the WPC has at least 90ms to decode the transmitted signal and switch on the segment.

3.11 Primove Highway Environmental Design

The Primove system is designed to operate in -40 to +40°C 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.

Figure 14 Primove Highway test track facility

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.

3.11.1 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)[1].

3.11.2 Induced Current Prevention

The magnetic fields of the Primove power transfer system will induce stray currents in conductive loops that intercept the flux. Such inducement is rendered very difficult by constraining the flux with a good magnetic circuit design. Wayside loops do not pick up excessive flux and only loops coincident with the pickup can obtain significant flux. Reinforcing

[1] Personal correspondence, M. Roidt to S Seiffert, 2012

rods used in concrete under layers could form such a loop and are not recommended in Primove installations. Such effects can be mitigated with aluminium shielding if loops and metal under structures are unavoidable. The frame of the truck could itself form a loop with the induced current, and the presence of a current in the frame and body may not be acceptable. Shielding, placed under the vehicle where necessary will essentially eliminate the currents.

3.11.3 Roadway Damage

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

3.12 Safety

The Primove Highway system is safe by design of the technology employed in its construction. 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 that are employed across a short air gap. Extensive development of the Primove transformer ensures the high magnetic fields are contained in very close proximity to the pick-up 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.

People travelling in non-Primove vehicles, both in front of and behind, are protected from these fields by the proximity sensors on the Primove vehicles that ensure that the non-Primove vehicles are travelling over segments that are not energised.

3.12.1 Magnetic Field Exposure

Under normal operation the magnetic field will be less than 6.25uT in all public areas and in the drivers cab. This will be assured by design and operational controls. During all tests, safety with respect to magnetic fields has been measured, both inside the truck (driver cabin and load area) as well as next to the truck. In all test cases, the EMF was below the ICNIRP 1998 limit of 6,25µT. This field level is lower than the recommended level for public exposure (ICNIRP, 2010) and is safe for all modern pacemakers (VDE, 2002).

In the case of a vehicle not equipped with the right activation system enters the Primove charging area, the system will not switch on. This has been checked and demonstrates that no magnetic field will be active when a non-equipped vehicle drives over the Primove wayside road segments. In fault conditions the Primove control system will ensure that the magnetic field is switched-off.

3.13 Reliability and Maintenance

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

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

3.14 Cost Estimate

The cost of this system is estimated under the following two scenarios. The first scenario is full and continuous inductive charging on the highway between Stockholm and Gothenburg. The second scenario is called opportunity charging, whereby a higher power transfer rate is utilised, but on only 35% of the total road distance covered.

3.14.1 Full Inductive Charging

The scenario in this report utilises a hybrid truck with a 120kW electric motor. A 100% Primove solution in both directions thereby requires 120kW of 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 28MSEK per kilometre/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; and
- Installation and commissioning is included.

The resulting cost per kilometre in both directions is therefore 56MSEK.

Based on installing a system along the complete distance between Stockholm and Gothenburg, the cost amounts to 15MSEK per kilometre /direction.

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

3.14.2 Opportunity Charging

The alternative system proposed in this report is based on a 200kW power transfer rate and an estimated 35% of the highway replaced with Primove segments in each direction. This has an estimated cost of 35MSEK per kilometre/direction. The cost is the same as for the full inductive charging, with a rated power transmission of 200kW. The resulting cost per kilometre in both directions is therefore 70MSEK, based on the present test track components design.

For the proposed scheme, taking into account that only 35% (156.5km) is installed, the cost will be 18MSEK per kilometre/direction, or 36MSEK per kilometre in both directions.

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

3.15 Future Expansion Potential

The Primove Highway is easily expanded by adding more segments onto the ends 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.

3.16 Details of Vehicle

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

For example the platform 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 on-board 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.

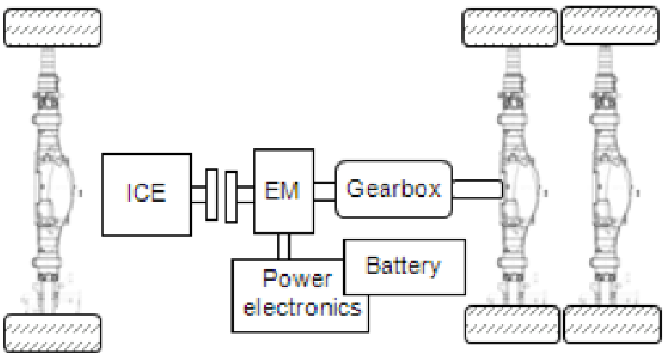

Figure 15 Hybrid vehicle illustration

The Slide-in project has designed a specific diesel engine truck, which facilitates tests of new components, without actually performing complete system tests on a hybrid truck, see Figure 17. The test vehicle used is a two-axle truck with a distribution box equipped with tail lift.

Figure 16 Test vehicle prior to installation of shielding

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 energy 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 analysed in the driver cab through CAN communication. These components are described in Figure 17.

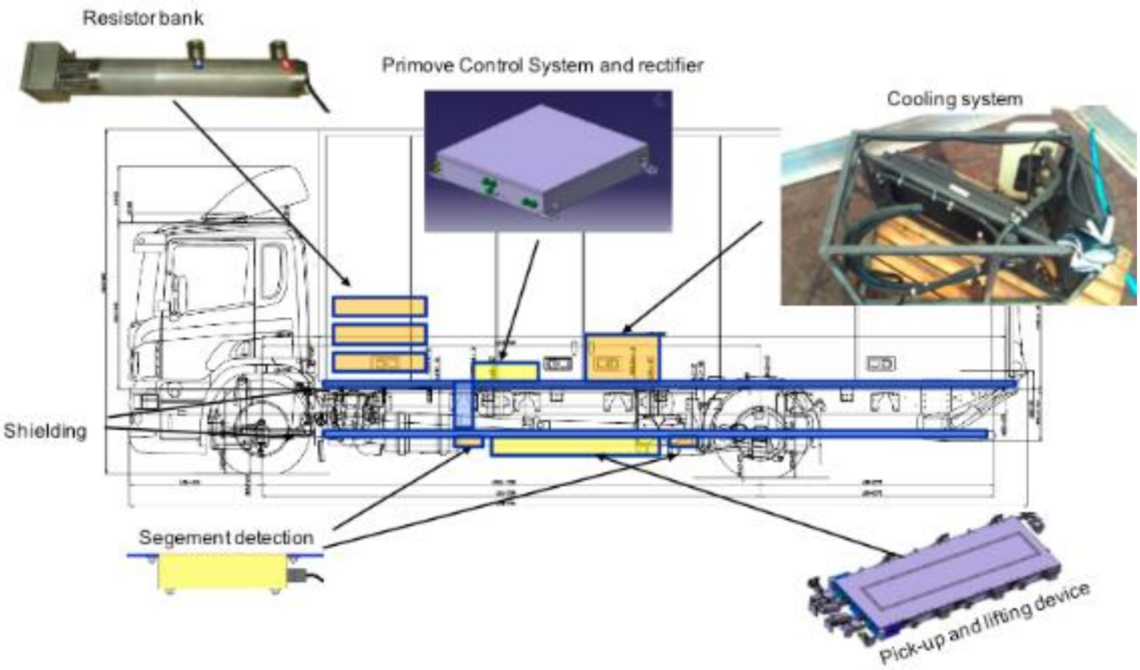

Figure 17 Test vehicle setup

The pick-up, shown in **Figure 18**, is below the frame slightly offset from the centre in order to clear the diesel tank.

Figure 18 Installation of pick-up

3.16.1 Shielding

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

For this first test the shielding is more extensive than needed in the final system due to the requirements to retrofit the shielding to an existing vehicle,

Figure **19** , 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 optimise 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.

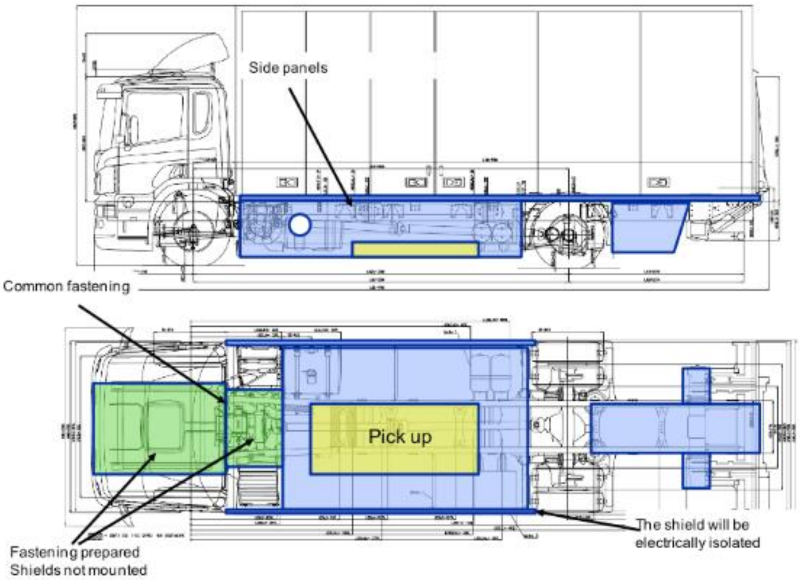

Figure 19 Principle drawing of shielding

Figure 20 Shielding and pickup installation

3.16.2 Added cost to vehicle system

Today the expected additional/reduced cost to the vehicle with respect to the base system (hybrid 40 ton) is:

- Primove equipment such as the pick-up; and
- Battery cost (-).
    - When the ERS is available, battery capacity should be significantly reduced, as it is only required to facilitate state transmission between ICE drive and EM drive, without torque interruptions. However, with no known data on ERS infrastructure, it is not possible to presently select the battery type.

These estimates are not definitive, as it is difficult to estimate costs dependant on future volumes, and available ERS infrastructure.

3.16.3 Maintenance

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

3.16.4 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.

3.16.5 Efficiency

In addition to the Primove equipment, there are components that have not yet been fitted to the vehicle. Expectance is that there will be measurable losses in the following;

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

3.16.6 Weight

Estimate of added components and weights are:

- Pick-up and lifting device (+330kg);
- Primove control and rectifier (+60kg);
- Shielding (+201kg); and

- Battery (-kg), Not yet defined. Likely to be significantly lighter.

These weights are with today's prototype available designs. In future design iterations, these are likely to be reduced significantly.

4 FEASIBILITY ANALYSIS AND RESULTS

4.1 Introduction

The Primove conductive ERS system will be assessed for its feasibility to be applied to other use cases defined in FABRIC, see [2]. Note that the system will only be considered in a theoretical study and will not be subject to test track trials as is the case with FABRIC solutions 1 to 3.

The use cases chosen in 2.2.1 and 2.2.2 have been analysed in sub chapters below.

4.2 Slide-in vs. FABRIC demonstrable use cases

The Slide-in solution has been assessed for the FABRIC demonstrable use cases below.

Table 3 Slide-in vs. FABRIC demonstrable use cases.

	Use case	Slide-in relevance	Same as FABRIC?
1.	Driver and EV registration to a central FABRIC database	No support for this use case has been implemented in the Slide-in solution but the Primove system has similar functionality.	Close
2.	Driver login to FABRIC	Similar functionality exists in the Primove system that could be adapted for FABRIC.	Close
3.	User account management	No support for this use case has been implemented in the Primove solution but there is no technical reason why this could not be done	No
4..	EV identification	Primove has implemented EV identification	Yes
5.	Charging assistance	In the Slide-in inductive project no such functionality was developed. But there exist interface structures to show the power transferred in the ICL Furthermore, the usage of Advanced Driver Assistance Systems (ADAS) which are currently under development.	No

6.	Charging management high-level and low-level (load balancing)	No high level management exists in the Slide-in inductive project that could be applicable to the user case. Low level management as described in FABRIC [2] is also not available but there could implemented.	no
7.	Energy supply tariff modulation	No support for this use case has been implemented in the Primove solution but there is no technical reason why this could not be done.	No
8.	Charging and road infrastructure availability status updating	No support for this use case has been implemented in the Slide-in solution but there is no technical reason why this could not be done.	No
9.	Billing	This feature is available in the Primove system and could be adapted for FABRIC use	Close

4.3 Slide-in vs. FABRIC feasible use cases

The Slide-in solution has been assessed for the “FABRIC feasible use cases”. Note that these “feasible use cases” are to complement the technology demonstration-focused use cases with functionalities that are either currently available as off-the-shelf products, or are under research and development in current EU funded research projects. Since these products and services are already being developed, it would not be efficient to repeat and re-develop them within the Slide-in conductive ERS project. One could expect though that with the appropriate interfaces in place, these products and services could be integrated seamlessly in a future, feasible conductive ERS system. The foreseen use cases that apply to a system such as Slide-in conductive ERS and extend its user friendliness are the same as the ones identified as “FABRIC feasible use cases”, see Table 4 below

Table 4 Slide-in vs. FABRIC feasible use cases.

	Use case	Rationale	Feasible use in Slide-in solution
1.	Planning of a trip	This is a mainstream functionality present in almost all modern vehicles. Current navigators allow for detailed route planning, including passage from specific POIs. Traffic information and ETA estimation are not uncommon. ITS research projects have focused heavily on the subject and each exploits dynamic navigation and mapping for its own purposes such as ecological driving.	This functionality may allow the pre-booking of charging facilities along a route, taking into account the range of the EV.
2.	Guidance to a charging facility or to a destination	This is a very common functionality. Research projects focus on exploiting open standards and maps for ITS routing.	Leading the EV towards a charging facility based on dynamically updated charging facilities database.
3.	Dynamic route and booking management	Dynamic routing is a functionality of all GPS navigators and it is activated when the vehicle deviates from the route. Smart re-routing is the objective of several ITS projects based on different criteria.	In real traffic conditions, major delays compared to the planned time of arrival at a pre-booked charging infrastructure are to be expected. This is why a system that automatically makes the necessary booking and rerouting adjustments without the interference of the end-user is very desirable. The same system can be used in cases the infrastructure goes offline unexpectedly.

4.	Emergency charging	This functionality does not contribute to the technology assessment of Slide-in prototypes but focuses on user convenience in the future when EVs are adopted by the public in a large-scale.	This is a functionality that is foreseen to exist when electro-mobility is widespread and systems such as FABRIC are common place. This functionality reduces range anxiety by providing a means to charge the EV without prior planning. However this will be done in a structured and organized manner so as to guarantee the good operation of the overall system but also discourage this practice.
5.	Integration of Slide-in with UTMC	This is a foreseen functionality/system service for the road operators. However this is a feasibility use case because of different UTMC systems and standards that cannot be address within Slide-in and because it does not contribute to the technical assessment of dynamic conductive charging.	Slide–in charging infrastructure should be integrated with Urban Traffic Management and Control systems to ensure good traffic flow and enforcement.

4.4 Slide-in vs. FABRIC "charging modes"

The properties of the Slide-in conductive ERS solution are assessed in relation to the charging modes mentioned below:

- *Static charging*
- *Stationary en-route charging*
- *Dynamic charging*

The current system design is based on a scaling of the static 200kW high power charging system with extended segment length. This has shown the technical feasibility of the system, as well as interoperability between dynamic and static system states, verified by using the same components at the vehicle side and using the same vehicles for both use cases.

In order for Primove to develop into a series product for dynamic charging, the following development steps are identified:

Design changes on the magnetic design to fulfill requirements for:

- Utilization of standard installation processes during civil road works, considering the requirements and procedures for road installation work; and
- The road side of the charging system (primary winding) must be designed to be scalable in length. There must be a flexibility to connect a different number of power electronics (depending on traffic density) and different classes of power electronics (depending on demanded power/vehicle types). This can be realised by using a standard primary winding with defined segment lengths. Each power electronics control can feed one or more segments (depending on vehicle density).

4.5 Slide-in assessment for the Car user case

Primove power transfer systems have been demonstrated on cars, buses, trucks, and trams [3]. Below the properties of the Primove ERS solution are assessed in relation to user cases involving cars. Any potential adaptations of the system, limitations and comparison against the specifications and additional requirements will be identified.

4.5.1 Pick-up size

Pick-up size needs to be reduced for a car application. The current weight is 330kg and is not mountable on a car chassis.

4.5.2 Power transfer and voltage

Further development is needed of the Primove system to assure interoperability between different vehicle sizes and power classes.

4.5.3 Power transfer efficiency

Current power transfer is optimised for heavy duty vehicles and further development is needed for lower power applications. The power independent losses must be minimized.

4.5.4 Component weight

The weights of added components are believed to be lower for EVs that need less power e.g. cars and light duty vehicles compared to heavy duty vehicles. This is due to the:

- Power transfer:
    - smaller cables
    - smaller pick-up
    - smaller actuators

    - less height adjustment (when ground clearance is lower)
- Power control
    - smaller rectifier
    - smaller control and segment detection equipment

Furthermore added weight from EMF shielding could be reduced by partially integrating the shielding in the car body.

4.5.5 Vehicle Speed

Vehicle speeds defined for power transfer within FABRIC [2] is 0 - 130km/h. Due to limitations in the Primove test track length, vehicles were only tested at 20 to 70km/h. For safety reasons no higher speeds where tested. The results show that power transfer above 150kW is not a problem at differing speeds. Also a misalignment of 100 to 150mm has minimal impact on the power transferred from the wayside to the on-board system.

Power transfer at higher speeds than 70km/h should be possible with regards to the fast assessment possible by the VDSC.

4.5.6 Infrastructure

The Primove system has a safety zone monitored by sensors on the vehicle to enable a safe energising of each segment. This needs to be adapted for smaller road segments to accommodate the size of a car. Supporting opportunity charging in urban areas, where the traffic could be congested and not allow for a full 20m segment to become energised. Incorporation of smaller segments would increase the per km cost due to the increased number of transponders needed for segment control.

Maintenance aspects are similar to the tested design and mentioned in 3.8

4.5.7 Safety

The system has been tested for hazard concerns as mentioned in 3.12., but adaptations of the EMF shielding for cars is needed. Furthermore, a review of the system operation modes should be carried out. Cars can travel at distances closer than 20m and a safety distance of 20m in congested urban traffic will render the system unusable. If smaller segments are used then a speed lower then 50km/h and a safety distance below 20m could be applied. However, further development is needed, regarding partially covered segments in urban areas and EMF exposure to humans.

4.6 System interoperability

In this section the interoperability with potential FABRIC systems assessed.

4.6.1 Communication

The Primove system are different from FABRIC solutions, by not using Wi-Fi as a means of communication between the wayside and vehicle equipment, but a radio communication standard developed for the Primove system. Details have not yet been disclosed, but could eventually be available for external solutions.

4.6.2 Energy transfer

The Primove system for power transfer operates at 20kHz. Interoperability with systems that operate at 85kHz is an unresolved issue that needs further testing.

5 CONCLUSIONS

The main conclusions are summarized as:

- Further development of Primove systems is necessary for complete application to car user case, defined for FABRIC in [2];
- Primove system is usable for HDV user case, defined for FABRIC in [2]; and
- With adaptations, all defined charging modes (Static, Stationary en-route and Dynamic charging) and speed intervals (0 - 130km/h) could be fulfilled with the Primove system.

See more detailed conclusions below.

5.1 Slide-in vs. FABRIC ITS use cases

None of the services of *FABRIC demonstrable use cases* [2], are identical to the ones in the Primove system but some are similar:

- Driver login to FABRIC;
- EV identification; and
- Billing.

With EV identification several of the functions described in FABRIC [2] could be realised. No new hardware is needed for Primove. For the user cases functionality to be realised, centralised management software and new HMI is in need of development.

5.2 Slide-in vs. FABRIC charging modes

The properties of a Primove solution are assessed in relation to the charging modes, *Static charging, Stationary en-route charging* and *Dynamic charging.*
The Slide-in inductive ERS project only demonstrates dynamic charging but the other two charging modes have been tested and used on public roads for bus applications.

5.3 Slide-in vs. Car use case

The following properties of the Primove solution have been found to be affected in a use case with cars or light duty vehicles:

- Pick-up size will have to be smaller,
- Possible smaller segments where the width of the road segment must be minimized to adapt to a smaller area of shielding due to the cars size.

- Power transfer will likely be lower and new hardware on the vehicle side is needed i.e. pick-up, rectifier, shielding, segment detection and control units; and
- Vehicle speed is higher but could be supported.

Further development and trials are needed to provide a usable system for car or light vehicles, but the foundation of the Primove system is a good starting point and there is currently on-going testing for car applications

5.4 Slide-in vs. urban environments use case

The following properties of the Primove system should be resolved for a suitable performance in the urban environments use case:

- Infrastructure
    - Need of shorter track segments (< 2m) to support power transfer for smaller vehicles;
    - Segments that fit under EV's and shielding
    - Sensors to detect what segment to activate as to inhibit EMF exposure to people or non-shielded vehicles.
    - Road maintenance e.g. snow removal need special processes and tools.

6 REFERENCES

[1] Viktoria Swedish ICT, “Slide-in Electric Road System, Inductive project report, Phase 1”,Scania CV, Gothenburg, 2014

[2] FABRIC D4.3.1 “Final use cases definition”

[3] Primove. 2016. Primove projects. [ONLINE] Available at: http://primove.bombardier.com/projects.html. [Accessed 8 June 2016].