ELinGO

Electric Infrastructure for Goods Transport

Evaluation of constructability of dynamic charging systems for vehicles in Norway

Appendix I

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Contents

1 Introduction

The aim of this document is to assess the constructability of dynamic charging systems for goods transport by electric vehicles. This document is part of ELinGO's work package A2, which includes among other things technology evaluation and evaluation of system integration and costs.
Due to limited resources and relevant literature, a panel of various professionals related to road construction, railroad (contact line), energy transformation and civil engineering has made qualitative evaluations of dynamic charging systems based on available experience and literature. The panel has discussed the following aspects related to 1) contact-line-pantograph solution (Figure 1), 2) conductive rails integrated in the road surface (Figure 2), and 3) Inductive charging (Figure 3):

- Implementation of charging facility in new road
- Implementation of charging facility in existing/old road
- Operation and maintenance aspects
- Construction cost
- Aesthetics
- Personal safety/pedestrian safety
- Risk related to availability-downtime due to maintenance

The members of the panel were Professor Elias Kassa (railroad), Professor Anders Rønnquist (construction dynamics and contact-line for railroad applications), Professor Inge Hoff (road construction), Professor Amund Bruland (construction engineering and cost estimation) and Dr. Jon-Are Suul (electric energy conversion). The panel was facilitated by Pål Drevland Jakobsen.

In the discussions it was assumed that all charging-solutions were based on an on-board battery package, in order to avoid construction of charging lines along lay-bys, local roads etc while still achieving climate neutral zero (tail pipe) emissions.

The authors of this memo have also reviewed literature in search of experiences related to the constructability of dynamic charging of electric vehicles.

Figure 1 Contact-line-pantograph solution (eHighway)

Figure 2 Elway's solution.

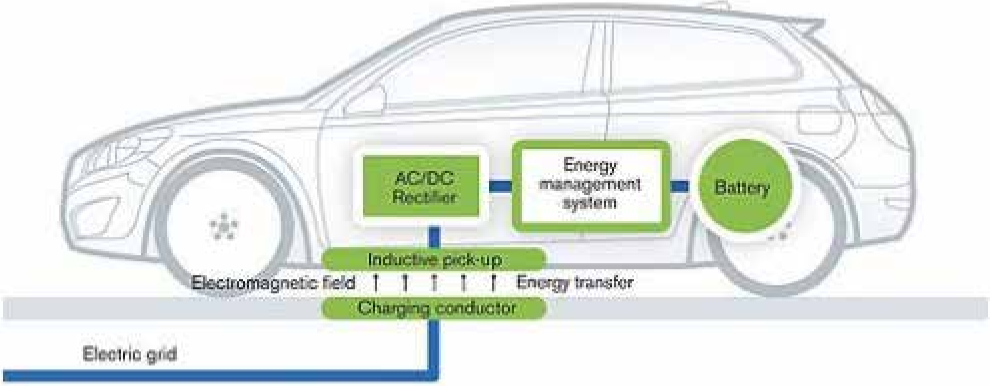


Figure 3 General illustration of the concept for inductive power transfer to an EV (Suul and Guidi 2017 after Volvo car newsroom).

1.1 Findings in literature related to cost and constructability of dynamic charging infrastructure for Electric vehicle (EV)

A general description and discussion of the different solutions is given in the following sections, describing separately the solutions for contact line-pantograph solution (chapter 2), conductive rails integrated in the road surface (chapter 3) and inductive charging (chapter 4). This section is however briefly describing some general findings in the literature related to costs and constructability of dynamic charging infrastructure for EV. Regarding costs, some general estimates can be found in various literature, and some relevant examples are briefly referred to in this report. However, most of the published estimates do not include a detailed description or breakdown of what is included in the calculations. Thus, mainly the costs assumed in WP 4 (Bohne, 2018) and the cost figures presented in a report from Fraunhofer (Fraunhofer, 2017) are explicitly referred to in the following chapters.

As an example of other studies, Song et al (2016) addresses that several evaluations have been conducted on power transfer performance for dynamic EV charging, but accuracy and reliability construction cost and maintenance cost studies still require improvements.

Highways England has executed a ball park figure for the potential installation of inductive charging infrastructure for EVs in motion. The cost estimate is based on numerous assumptions and concludes that "early-contractor-involvement" is needed to address and estimate construction cost (Highway England, 2015). In the same report, Highways England presents a breakdown of net present values per km of electrified road over 20 years, see Figure 4. In an estimated 20 years perspective the main cost is related to electric power and the second cost is related to the infrastructure in the road.

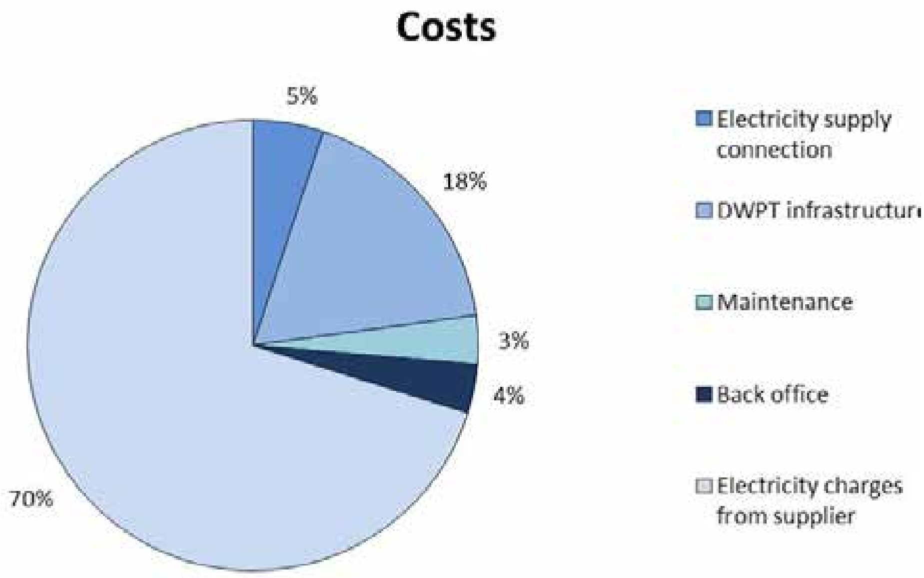
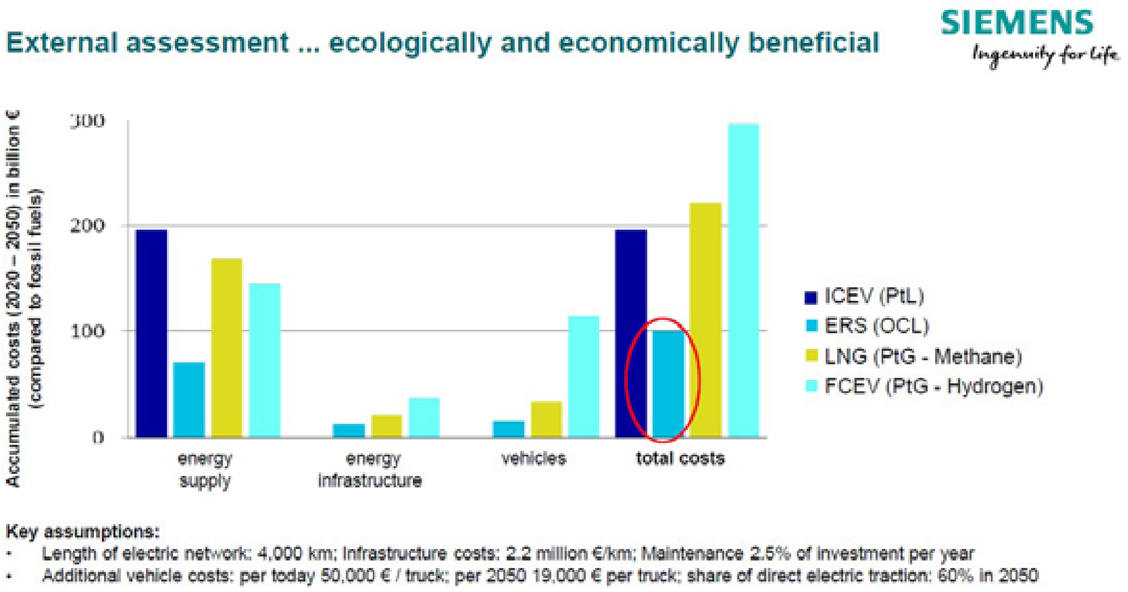


Figure 4 Breakdown of NPV cost of 1 km road for 20 years. (Highway England 2015).

Figure 4 does not mention the total cost and gives only a qualitative indication of the relative share of the cost. Since operation over 20 years is considered, capital cost and costs of energy supply are also bundled into the same figure. As mentioned above, the number of relevant cost estimates is limited. Nevertheless, the general cost allocation gives a relevant overview of main elements of the cost for system operation, and indicates that even for an inductive charging system, which is expected to be the most expensive technology to install, the energy cost will be dominant for long term operation. The figure is therefore considered as useful information.

Siemens has worked for several years with the development of their concept for contact line-pantograph technology called eHighway. Siemens have prepared or initiated several restricted reports about the implementation and construction of their solution. Öko Institut (2017) has made a comparison of cost among other factors for various energy sources for vehicles, see Figure 5. This figure clearly indicates that an Electric Road System (ERS) with overhead contact lines (OCL) is expected to result in reduced accumulated costs over a 30-year period compared to today's solution with Internal Combustion Engine Vehicles (ICEV), transition to Liquified Natural Gas (LNG) or operation with hydrogen Fuel Cell Electric Vehicles (FCEV).



External assessment ... ecologically and economically beneficial

Key assumptions:

- Length of electric network: 4,000 km; Infrastructure costs: 2.2 million €/km; Maintenance 2.5% of investment per year
- Additional vehicle costs: per today 50,000 € / truck; per 2050 19,000 € per truck; share of direct electric traction: 60% in 2050

Figure 5 Comparison of energy supply, energy infrastructure, vehicles and total cost for combustion engines (ICEV), Siemens ERS, natural gas engines and hydrogen based fuel cells. (Siemens 2017).

Chen (2015) recently completed a PhD study on electrification of roads within the EU Project FABRIC. Some of the research papers published within the PhD study consider cost (e.g. Chen et al 2015) and mention various aspects related to constructability. However, the findings related to cost are mainly for small components needed for electrification (e.g. types of battery and energy storages and road construction) without any clear summary related to the full construction of electrified roads suitable for heavy freight transport. It should also be noticed that the FABRIC project is limited to solutions below 50kW. This has therefore limited relevance for the ELinGO project which are focused on goods transport and heavy vehicles.

Ceravolo et al (2016) informs about a study conducted at University California Berkeley about construction cost related to development of electric roads. The Berkeley study estimates cost of 1 000 000 USD/km road lane.

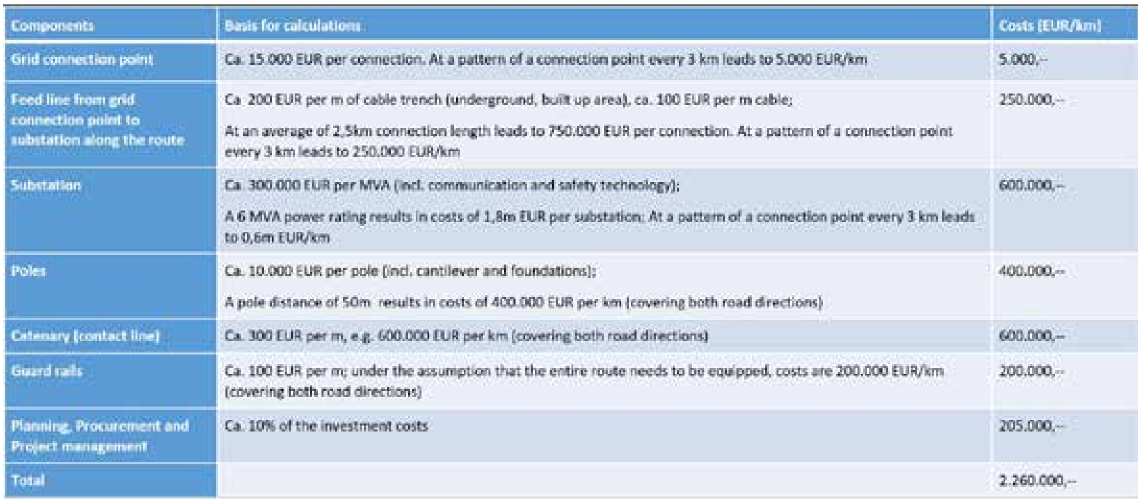
Analyses by BDI covering the whole German economy in the study ”Climate Paths for Germany”, shows economically cost-efficient strategies for successful reduction of 80 to 95 percent of Germanys Green-House Gas (GHG) emissions by 2050. Several main findings are described, among other that a 95 percent GHG reduction would push the boundaries of foreseeable technical feasibility, for instance that road traffic would have to be electrified to an even greater extent. The report gives some general cost estimates, but they are not presented in detail and can therefore not give any estimates directly related to electrification of roads within the context of the ELinGO project.

According to the World’s Road Transport Organization (IRU), representing the worlds trucking companies, the only possible way to reach the European climate coals is electrification of long haul trucking (IRU, 2017).

The German Transport Ministry (BMVI) has made a public report that evaluates the cost of implementing contact-line-pantograph solutions as well as solutions based on conductive rails in the road surface and inductive charging for trucks. The main contributions to the construction cost are given in Table 1 and presented as €/km road. The Fraunhofer study assessed the costs for Electric Road Systems

(ERS) infrastructure under various scenarios, e.g. amount of energy needed to transfer. Table 1 relates to a busy part of the German Autobahn system and takes passive protection and local grid connection costs into consideration.

Table 1 Cost in €/km road for implementation of pantograph-contact line for trucks (Fraunhofer 2017). (Translation by Patrik Akerman (Siemens))



Components	Basis for calculations	Costs (EUR/km)
Grid connection point	Ca. 15.000 EUR per connection. At a pattern of a connection point every 3 km leads to 5.000 EUR/km	5.000,--
Feed line from grid connection point to substation along the route	Ca 200 EUR per m of cable trench (underground, built up area), ca. 100 EUR per m cable; At an average of 2,5km connection length leads to 750.000 EUR per connection. At a pattern of a connection point every 3 km leads to 250.000 EUR/km	250.000,--
Substation	Ca. 300.000 EUR per MVA (incl. communication and safety technology); A 6 MVA power rating results in costs of 1,8m EUR per substation; At a pattern of a connection point every 3 km leads to 0,6m EUR/km	600.000,--
Poles	Ca. 10.000 EUR per pole (incl. cantilever and foundations); A pole distance of 50m results in costs of 400.000 EUR per km (covering both road directions)	400.000,--
Catenary (contact line)	Ca. 300 EUR per m, e.g. 600.000 EUR per km (covering both road directions)	600.000,--
Guard rails	Ca. 100 EUR per m; under the assumption that the entire route needs to be equipped, costs are 200.000 EUR/km (covering both road directions)	200.000,--
Planning, Procurement and Project management	Ca. 10% of the investment costs	205.000,--
Total		2.260.000,--

One reason why the cost estimates vary widely and between different sources can be expected to the lack of transparency regarding what was included in the estimates. In this respect report from Fraunhofer(in German) is a useful reference since it clearly separates the different contributions to the estimated total cost (for instance grid connection, power distribution, different elements of the construction). Thus, these cost estimates can be easily updated if more accurate estimates for the different elements of the total costs can be found. It should be noted that it can be expected that the estimates for overhead contact line (OCL) technology would be most accurate in this report, due to the general maturity level of the technology and a relatively wide basis of experience with similar systems.

In ELinGOs work package A4, a report is prepared regarding Estimates of costs and emissions reduction from heavy transport by road. This study also looks at ground level supply systems (GLS) (Bohne, 2018).

In addition to the reports that have considered for OCL-ERS technology there are also a few reports looking into GLS. As an example, the Slide-In project published in 2014 are listing the cost for Alstom APS to 16,3 MSEK (Olsson, 2014). Note that this cost is excluding installation of APS. A study from Highways England estimated that installation an inductive system into the roadway, using the cheapest method, would cost 1M GBP per lane and km (highways England, 2015).

The International Energy Agency (IEA) has in the Report ”The Future of Trucks” (2017) described, among other factors, the investment needs. This report describes that the incremental costs of advanced vehicle technologies, in particular electric and hydrogen trucks, as well as their supporting infrastructure, are substantial. When talking about savings, the report mentions reduced fuel costs and modernization of the road as subjects with the largest potential.

Figure 6 is from the IEA report, and shows the heavy-duty freight vehicle and fuel costs over five years of usage in 2050 in the Modern Truck Scenario, including infrastructure costs. The IEA report concludes that the costs of building infrastructure are dwarfed by the savings of having electric roads.

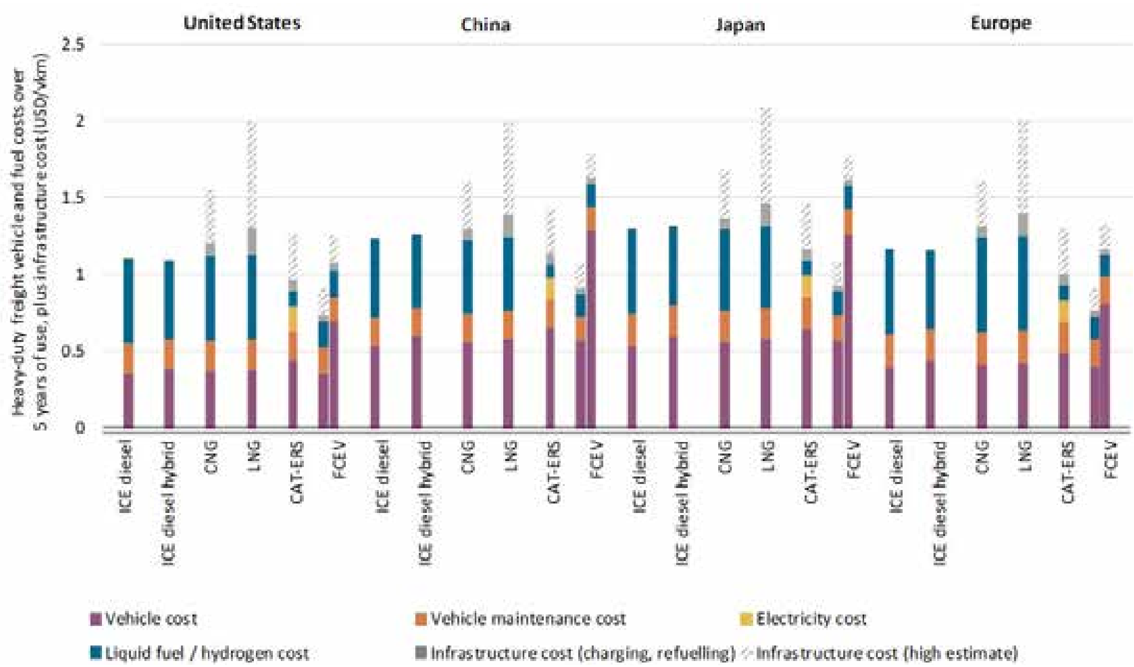


Figure 6 Heavy-duty freight vehicle and fuel costs over five years of usage in 2050 in the Modern Truck Scenario, including infrastructure costs (with high and low infrastructure utilization assumptions) (IEA, 2017)

Further relative descriptions of expected construction costs and qualitative comments regarding maintenance requirements are presented for the different technologies in chapters 2-4.

2 Contact line-pantograph solution

The contact-line-pantograph solution is based on a well-known technology that has been used for decades in transportation of both goods and persons. Although several practical adaptations of the infrastructure and the pantograph on-board the vehicle has been made for flexible operation of road vehicles at a wide range of speeds, the general functionality is similar as for single overhead-line systems for railroads and trolley-busses.

2.1 Implementation of charging facility in new road

For the implementation of charging-line-facilities above the roads, there are no special pre-works that is needed for roads outside urban areas. In both urban and rural areas there are no special pre-works that needs to be addressed on the road construction. The main limitation is that there must be space for the infrastructure along the road. For implementation of charging lines in new road tunnels and bridges, it is expected to increase the required cross-section/height above each driving lane in order to fit the lines.

The charging line would demand columns every 60 – 100 m along the road demanding to the roads geometry. The installation of columns and charging lines is an industrialised process, meaning that there are available design codes, contractor-knowledge etc on the implementation of charging-lines.

2.2 Implementation of charging facility in existing/old road

For the implementation of charging-line-facilities along existing roads, the pre-cautions are the same as for implementation in new roads, except for bridges and tunnels. For some old tunnels designed according to old versions of Statens vegvesen Handbook 21 (now Handbook N500), there would be a need to increase the height of the tunnel to fit a regular catenary system for overhead lines. Alternatively, it could be possible to adapt a solid bus-bar system in the roof of tunnels with limited space, although this solution has not yet been fully developed for road applications in the same way as the regular catenary system.

For bridges, dependent on their design, implementation of charging-lines can be conflicting with the main mechanical structure. However, it can be assumed that the vehicles travelling on an electric road will have an onboard battery or a hybrid drivetrain, and will be able TO drivedrive without continuous charging. Thus, implementation of charging lines along road stretches can be done without implementation in the most complicated existing bridges and tunnels.

2.3 Operation and maintenance aspects

As mentioned, this solution is based on established technology. Relative precise data on operation and maintenance for railroads can be obtained from the Norwegian National Railroad Authorities, and can be assumed to constitute a reasonable estimate for road application. The difference of having two overhead conductors for electric roads is not expected to cause significant differences for regular operation and maintenance.

2.4 Construction cost

The National Railroad Authorities has been contacted in order to share the span of construction cost for this solution. For railroad lines and columns, the cost in Norway is approximately 5000 NOK/m railroad. These lines are dimensioned for train speeds up to 250 km/h, thus it could be expected that the construction cost along roads can be reduced, as driving speeds are lower with lower demands to mechanical strength of the lines. On the other hand, the application for road traffic requires two contact lines, with corresponding catenary systems which could increase the cost. The dimensioning of lines might also be affected to more vehicles per line compared to trains. In total, the panel expects the variation of cost to be relative low.

Within the ELinGO project a lower cost estimate of 13 MNOK/km and an upper estimate of 18 MNOK/km is assumed. This cost estimates includes electrification in both directions, i.e. two traffic lanes (i.e. per km road with two electrified lanes). (Bohne, 2018). The lower cost estimate is in line with the best-case costs calculated by Fraunhofer (Fraunhofer, 2017), while the upper cost estimate is lower than the worst-case cost calculated by Fraunhofer (Fraunhofer, 2017).

2.5 Aesthetics

The implementation of lines above the road and additional columns on the side of the road can by many be perceived as a visual interruption. This is usually expected to be a main concern of public acceptance for such infrastructure. However, for residents near busy highways (where installation of ERS is most likely) the aesthetic value of the current highway conditions could be less than the value of eliminating emissions from heavy freight transport.

2.6 Personal safety/pedestrian safety

Just as with other structures along a highway (e.g. traffic signs or bridges) a contact line system will need to be separated from traffic in some way to avoid collision with the columns. A collision in the columns may cause breaks in the columns so they fall, and further cut the transfer of electric current. Guard rails along the road might be needed for protection of the infrastructure.

One potential difference compared to railroad systems is that road vehicles can be isolated from ground by the tires, while rail vehicles will be grounded by the rails. Thus, a fallen overhead line touching a vehicle might cause dangerous potentials to ground unless the fault is immediately detected and the line is disconnected. However, in contrast to railway systems, the contact lines for electric roads are held in place by tightly spaced dropper wires. These ensure that even if a break in the contact line occurs, the contact line should not fall into the space where vehicles are moving.

For road users, assessments by BASt in Germany, Trafikverket and VTI in Sweden have concluded that there are no significant concerns regarding safety arising from the overhead lines or the catenary system obstructing any views from the road.

2.7 Risk related to availability-downtime due to maintenance

It is well known that railways have suffered from frequent line breakages and that this has significant impacts on availability and traffic flow. However, railway tracks are usually narrower than roads, and historically the railroads have not kept a wide enough open area besides the tracks to prevent damage from falling trees (e.g. due to snow or storms) onto the wires. A break in the contact line is automatically detected by the tensioning devices, leading to a shutdown of the power supply to that section, which is usually much longer for railroads than what is preferred for roads (i.e. ca 10 km long compared to 1-2 km for roads). However, for highways, a sufficiently wide area along the road should usually be maintained open, and this should prevent that falling trees directly damaging the overhead lines. Furthermore, if trees would fall on a highway, this would usually prevent normal traffic independently from the presence of overhead lines.

Another reason for contact line breakages in railways have been poor pantographs. For, it has therefore been considered to include a pantograph monitoring system from the very beginning, and to prohibit trucks with non-conforming pantographs from connecting to the infrastructure. This would also further reduce the risk of line breakage.

If a line breakage would occur, it would not necessarily prevent traffic from flowing, as long as the line is kept safely above road. Since it is assumed that also vehicles utilizing the infrastructure will have a battery or a hybrid drivetrain, they would also be able to maintain undisrupted operation on the road. Thus, the consequences of line breakage are expected to be less severe than for railways where the whole line might be blocked for traffic. For highways with more than one lane in each direction, it might also be possible to maintain reduced capacity in the worst case of a severe damage to the infrastructure, as long as safety for all vehicles can be ensured by blocking traffic in only the lane with the overhead lines.

In general, the line and column system is expected to be easily accessible for repair works when the electrical transfer is shut off and traffic is stopped. In terms of winter maintenance, it is advantageous that the charging infrastructure is above the road and not influencing the road surface. Thus, the infrastructure would not interfere with any normal procedures for winter maintenance. For re-asphalting or other intrusive maintenance along the road, the presence of the overhead lines might have to be considered (i.e. height of machinery must be limited to avoid damage to the lines), but this is not expected to pose any significant constraint.

3 Conductive rails integrated in the road surface

Such solutions for dynamic charging of vehicles are based on a sliding contact for transferring power from rails integrated in the road surface to a receiver in the vehicles. There are several systems that are currently under development and testing. Figure 7 shows the cross-section of a system proposed by Alstom, with rails funded in a concrete slab to support two flat contact surfaces with minimal elevation above the road surface. Figure 8 shows the solution proposed by Elways (for a two-lane road), which is based on a metallic rail with the conductors integrated in two slots below the road surface. This solution avoids that energized conductors are exposed at the surface of the road, and the rail is designed as an integrated unit to be directly installed in the road without any concrete foundation and with only bitumen adhesives used as interface with the asphalt surface. Figure 9 shows the solution from Elonroad, which is based on rails mounted onto the road surface. The tails contain short sections of a single conductor of alternating polarity, which will be elevated about 5 cm above the regular surface of the road.

Figure 7 Alstom charging solution implemented in concrete slabs inside a road (Duprat 2016).

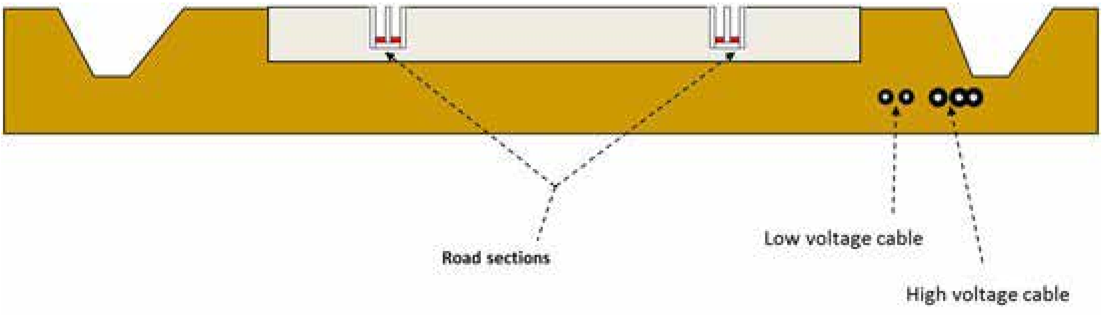


Figure 8 ELWAY's solution shown for two lanes (Elways 2017).

Figure 9 ELonROAD's solution.

3.1 Implementation of charging facility in new road

For implementation of the solutions from Elways and Elonroads in new roads, the panel expects the road to be constructed and completed with asphalt prior to installation of the charging infrastructure. The panel does not see any benefits of doing the installation of charging infrastructure in parallel with the asphalt works, since cutting of the asphalt to enable a track can be done efficiently and relatively cheap. Thus, it is expected to be simpler to install the rail by a separate process after a flat road surface is completed than to create the track during the asphalt work. For the concept from Elonroad, based on installation of the charging infrastructure on top of the asphalt, a combination of bolts and bitumen-adhesives can be used. However, the installation of the power supply to the rails might be more challenging and might require more extensive interventions in the road surface of an existing road, than if the power supply can be installed during the construction of a new road.

For the concept from Alstom, the installation will depend on the assumed fundament for the rails. If a large concrete slab is assumed, it should most likely be installed before the surface layer of the road is completed. However, if a slimmer structure of the concrete fundament than indicated in Figure 7 is used and if it is modularized in short sections according to the conductors on the surface, it might be possible to install the system after the regular asphalt work is completed. In this case, a process similar to what is assumed for the solution from Elways could be applicable.

Common for all the solutions is that the bottoming work of the road must be done rigorously, with thorough focus on material quality in order to avoid frost-heaving that may damage or cause accelerated degradation of the charging infrastructure and/or its integration with the road surface.

3.2 Implementation of charging facility in existing/old road

The implementation of these solutions in existing roads is expected to be similar as for implementation in new roads. There might be a possible exception for the solution from Alstom if it will be depending on a large concrete fundament. If this is the case, it will require a more invasive installation in the road, and will be less suitable for installation in existing roads than the solutions from Elways and Elonroads.

The panel would like to emphasize that the potential impact of frost heaves will be a main risk of implementation in existing roads for all the three solutions. For the actual installation work, the main advantage of installation in a new road might be if pipes for power cables to each section of the rail can be pre-installed before the upper asphalt layers of the road are completed.

3.3 Operation and maintenance aspects

The panel expects difficult and costly winter-maintenance for contact charging on the road surface. The main reason is that it should be expected that these solutions could reduce the durability of the asphalt surface, and also that the environmental conditions during winter operation could lead to significant wear and tear of the infrastructure installed in the road surface.

In addition to the impact on the road of installing the electric road system (ERS) into the roadway, the impact on the ERS itself of being located in the road must also be considered. Especially the conditions during winter conditions and the consequences that could have on the expected life time and maintenance costs must be carefully assessed.

The system from Elways is assumed to be drained, to avoid that water with salt and dust are will fill the slots. A solution has also been developed for cleaning the rails from snow, ice and dust that might accumulate in the slots. However, if is not confirmed how robust the system will be for long term operation during winter conditions and if use of salt for de-icing might cause corrosion of the rails and/or the conductors in this system. Since the rails are installed at or below the road surface, no specific challenges are expected with respect to regular snow ploughing.

For the solution from Alstom, the conductors are slightly elevated above the road surface, and presence of the sliding contacts at or above the road surface might cause potential conflict with regular procedures for snow ploughing. Since the sliding contacts are assumed to be relatively wide and will be directly exposed to all sand, dust, salt and any other pollution in the road surface, it is also expected that winter conditions can cause significantly increased wear of the conductors.

Furthermore, the Alstom solution is assumed to be fixed in a concrete fundament, which can be drained or undrained. The combination of asphalt and concrete is challenging due to various thermic and elastic properties over the operational temperature range assumed to be from -25 degrees C to +40 degrees C. If the systems are kept snow and ice-free due to heating, many potential problems might be avoided. However, the expected operational cost to keep roads snow and ice free with heating is expected to reject this as a possibility.

Maintenance of road wear and degradation by re-asphalt spreading is expected to be complicated for the solutions from Alstom and Elways. A special asphalt rig that only add asphalt on each side of the charging infrastructure may be developed. However, asphalt relies on being a continuous plate without cuts in order to secure its mechanical properties and to avoid rapid degradation. This will be a challenge for the systems from Elways and Alstom since they depend on breaking the asphalt surface in the middle of a lane, which might cause significantly faster degradation of the upper asphalt layer than for a regular road.

The solution from Elonroad has the advantage that it is intended to be mounted on top of the asphalt surface. Thus, increased degradation of the road surface due to the cuts in the asphalt is expected to be limited. However, thermal gradients and frost might be a significant challenge for maintaining the rails fixated at the road surface. Furthermore, it is expected that the system from Elonroad would have to be removed before re-asphalting a road. A solution for cleaning the rails from snow has been demonstrated by Elonaroad, but this solution will not be directly compatible with normal procedures for removing snow and the elevated rails might fully prevent the use of regular equipment for snow ploughing.

3.4 Construction cost

The construction costs will depend on whether the implementation is for an existing road or a new road under construction. The cost of installation for the electrical infrastructure in the road is expected to have the potential of becoming relatively low compared to the other possible solutions (overhead line or inductive charging). However, there might be significant differences between the three considered solutions for conductive charging in the road surface, depending on the practical implementation and integration in the road. This also include costs related to disruption to the traffic flow if the infrastructure is to be installed on an existing road.

The solution from Alstom is assumed to be the most expensive to install if it will require a concrete slab integrated in the cross-section of the road. This can also be assumed to require longer installation time, unless a solution for direct installation of complete premade sections is utilized. The solution from Elways is assumed to be suitable for relatively quick installation, since it is based on relatively long rail sections that can be installed directly in the road with only asphalt and/or additional bitumen adhesives needed for integration with the existing road surface. If the solution from Elonroad can be installed on top of a finished road infrastructure, is it assumed that the construction can have relatively low cost, although the time required for the installation would depend on the method for fixing the rails to the road. However, if the solution from Elonroad will be changed to a rail being installed in the road surface, the installation procedure could be expected to become more similar to what is required for the solution from Elways.

For all the difference concepts of conductive power transfer integrated in the road surface, the construction (and maintenance) of the road around the charging infrastructure is expected to be higher than for the other charging solutions. In addition to the procedure for installing the rails, the installation of the power supply to each rail section should also be considered. This cost would become highest for the solutions having the shortest rail sections. Furthermore, for installation on existing roads, the access to each rail with power supply might depend on cutting the asphalt or drilling operations for installing power cables to the side of the road. This might also cause longer installation time and longer disruption of traffic. For installation in new roads, the pathways for the power cables to the side of the road should be prepared during an earlier stage of the construction phase, and would then be expected to cause less additional cost.

The ELinGO project has calculated a lower estimate of 13 MNOK/km and an upper estimate of 26 MNOK/km. This cost estimates includes electrification in both directions, i.e. two traffic lanes (Bohne, 2018). It should be noted that these estimates are significantly lower than the costs calculated by Fraunhofer in Germany (Fraunhofer 2017) as the upper estimate used within ELinGO corresponds to the lower, best-case estimate from Fraunhofer. This assumption is mainly based on calculations and estimates related to the demonstration projects in Sweden, as further explained by Bohne (Bohne, 2018). However, significant variations in cost estimates should be expected for the different solutions depending on the assumptions, since there is not yet any accumulated long-term experience or established large-scale installation procedures established for such systems.

3.5 Aesthetics

The systems are barely visible. This has been one of the main motivations for developing solutions for conductive power transfer integrated in the road surface. The only visible part of the infrastructure will be the rail in the road surface, which will not make any significant difference compared to a traditional road.

3.6 Personal safety/pedestrian safety

Systems for conductive dynamic power transfer share several safety challenges due to the sliding contacts integrated in the road surface. As a first safety precaution for preventing exposure to energized conductors, all the solutions under development depend on sectioning of the conductive rails so that the voltage will be switched on to each section only when needed for supplying power to a moving vehicle. Beyond the general approach of sectioning the rail to avoid the danger of people being exposed to energized conductors in the road surface when there is no vehicle utilizing the infrastructure, the solution from Alstom, Elways and Elonroad present significant differences in the practical implementation.

The solution from Elways is based on conductors integrated in slots below the road surface. Thus, the surface of the rail is always at ground potential, and the design is intended to ensure that it is safe to walk on the rail even if the conductors below the surface are energized. Therefore, the solution from Elways is based on relatively long rail sections and it is not assumed to be critical with very accurately timed strategies for energizing each section depending on the position of the vehicle. Although the system from Elways is currently under demonstration on a public road in Sweden, further details have not been available regarding how this system has been considered to fulfil safety requirements for public roads or how the solution applied in Sweden would comply with any national regulation in other countries.

The solution from Alstom is based on two parallel flat and relatively wide conductors at the road surface. Thus, this system would give immediate potential for exposure to dangerous voltage if the rails are energized without being covered by a vehicle. Therefore, the system is based on relatively short rail sections. To avoid that the rails sections will have to be very short, the proposed strategy for ensuring practical safety is based on the consideration that there will be no persons in a limited zone directly in front or behind a moving vehicle. The distance in front of the vehicle where no person should be expected will depend on the speed. Typically, a speed threshold of about 60 km/h is assumed and energization of each rail section will only be allowed when an approaching vehicle is detected with a speed above this limit (Olsson, 2014).

The solution from Elonroad is based on a single conductive rail with very short sections having alternating polarity. Thus, only every second section will be energized when it will be required to supply power to a moving vehicle. Since the length of each contact surface of the rails is only 1 m and only one section should be energized at the time for supplying a single vehicle, the energized section will always be covered by the vehicle.

In addition to the electrical safety issued mentioned above, which are mainly related to pedestrians and persons moving outside of any vehicle, the consequences for regular traffic safety of integrating a rail system in the road surface must be considered. In this respect, the main concerns would be related to differences in friction and any danger to smaller vehicles on the road. Although no thorough evaluations of these issues have been conducted for this memo, it is assumed that the openly exposed and relatively wide sliding contacts of the system from Alstom might cause significantly lower friction for vehicles passing the rails. It is also considered that motorcycles passing close to a vehicle utilizing the infrastructure might pass into the zone where the rail might be energized (Olsson, 2014). Similarly, the system from Elonroad where the conductor is elevated about 5 cm above the road surface is expected to cause some concerns related to safety when overtaking other vehicles and when changing lanes along the road, especially for small vehicles and/or at high speeds.

3.7 Risk related to availability-downtime due to maintenance

As mentioned, the main practical concerns of the panel regarding solutions with conductive rails in the road surface is related to winter maintenance and durability of these systems. If the presence of the conductive rails will cause faster degradation of the asphalt during winter conditions, the result will be more frequent need for maintenance and correspondingly reduced availability of the road. It should also be considered if leakage currents may occur if the systems are not kept snow/ice/water free, and if this would lead to any specific increase in requirements for maintenance and/or cleaning of the system.

In the event of damages to the mechanical or electrical infrastructure in the road, the lane with charging infrastructure needs TO be closed during the repair. Charging infrastructures inside concrete is expected to be most difficult and time consuming to repair, unless the system is installed as larger pre-cast elements that can easily be replaced.

4 Inductive charging

The panel consider the constructability and practical implications of inductive charging systems integrated in Nordic roads to be highly dependent on its tolerance against deformations in the road. The deformation tolerance for inductive charging systems are not known and could be expected to vary significantly for different implementations. As discussed within the state-of-the-art review regarding the electrotechnical solutions within the ELinGO-project (Suul & Guidi, 2018), many different concepts and design strategies for inductive charging are possible, but it is currently not clear what solutions have the largest potential to become dominant or preferable for practical implementation on roads. Thus, the assessment in this chapter is kept relatively brief and on a general level without differentiating between specific concepts or implementations.

4.1 Implementation of charging facility in new road

For implementation of inductive charging facility in new road construction, it is expected that the main coils of the inductive charging infrastructure will be integrated between the base and binding course. In some cases, it can be assumed that the fundament for the charging infrastructure will have to be integrated in the base layer. The wearing course and binding course would provide sufficient cover for protecting the inductive charging coils, both in daily operation and during road maintenance. For the sub-base, extra attention should be made in order to avoid frost-heaves and ground settlements.

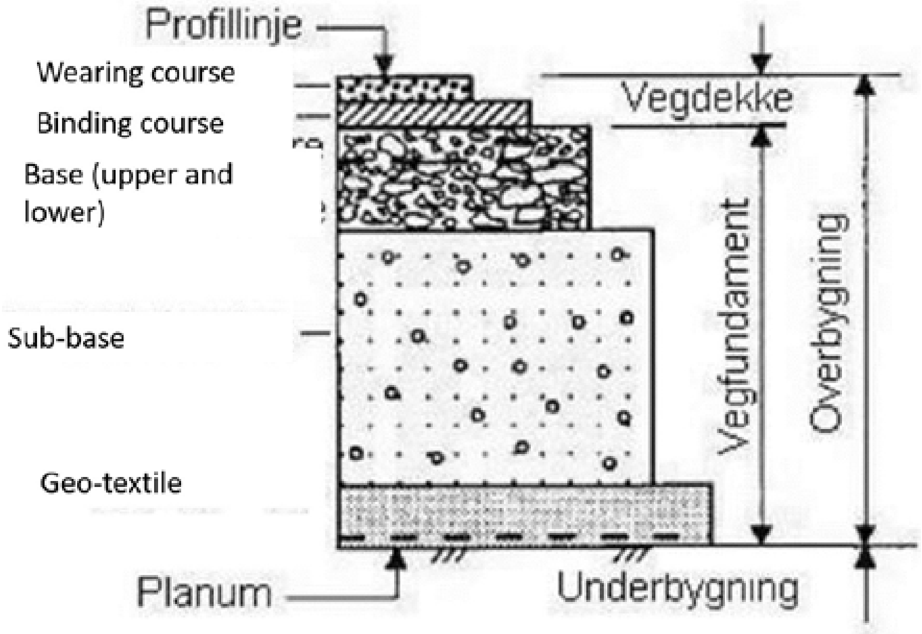


Figure 10 Layers in roads according to Statens vegvesen håndbok N200.

The tolerances for deformation on the inductive charging coils are not known, but it is expected to be sensitive against movements and variations. However, the sensitivity is expected to be highly dependent on the actual construction. Thus, it might be possible to design inductive power transfer systems with increased sensitivity with respect to seasonal mechanical movements in the road structure. However, this does not seem to have been widely considered in literature or for the existing demonstration projects, which are mainly located in areas with relatively mild climate.

It should be noted that several demonstrated concepts for inductive charging have been based on casting the electrical infrastructure in concrete, either by on-site casting or by installation of premade concrete elements which contain all the electrical parts of the infrastructure. This might be an effective approach for ensuring sufficient mechanical strength to avoid deformation of the inductive charging coils. However, a significant concern for application in Nordic roads is related to the different material properties of concrete and asphalt, which might cause thermic stress and accelerate the degradation of the mechanical integrity within the road structure. Thus, system designs and installation methods that would ensure similar mechanical tolerances for the inductive charging coils as for the rest of the road cross-section would be preferable.

4.2 Implementation of charging facility in existing/old road

For implementation of inductive charging in existing roads it is expected that the wearing and binding course needs to be removed prior to the installation. It is also a necessity to have control of the sub-base for reducing the risk of frost-heave and road settlements that may interfere with the charging system.

For the high-power demonstration projects and test tracks already in operation, available pictures and general information seem to indicate that the installation has been based on cutting away the wearing and binding courses in the middle of an existing road or test-track. The charging infrastructure has subsequently been integrated with the base layer, either by on-site casting in concrete or by installation of pre-made concrete modules containing the charging infrastructure. Subsequently, the middle part of the road has been re-asphalted. Although this might be a practical approach for small-scale installations and demonstration projects intended as a proof of concept, such approaches are not assumed to be suitable for large-scale implementation in roads, since the cuts in the asphalt is expected to cause accelerated degradation of the road surfaced.

4.3 Operation and maintenance aspects

Inductive charging is by the panel found qualitatively most favourable for maintenance in winter-climate. The system is fully enclosed below the road surface and can be protected from salt and water (snow and ice). Removal of snow from the road can be done conventionally with ploughing in combination with salting.

As mentioned regarding the practical installation, there will always be some movement in the road due to temperature variations and the mechanical stress due to the vehicles using the road. This result in a need for road construction that prevent movements that will cause problems for the electric elements in the road. The maintenance requirements will depend on where in the road construction the installations are located; if it is only integrated within the asphalt layer or deeper in the road construction. For Nordic conditions it would be reasonable to assume as a goal that the charging infrastructure should be integrated in the road in such a way that there will be no need for affecting more than the asphalt layer and possibly the base layer. Although it will be a disadvantage with respect to power transfer efficiency to have too thick layers of asphalt above the inductive charging coil, very thin upper layers may cause increased need for maintenance. Furthermore, a very thin layer above the coils might cause very high requirements for accuracy during maintenance procedures and repairs in the upper asphalt layers to avoid influencing or damaging the installation. Thus, installation of the coils close to the surface might increase the cost of maintenance.

The ELinGO project has focused on Norwegian conditions, where asphalt is the main road surface. However, in other regions, for instance in the US, the road surface often consists of concrete. The aggregate used for asphalt and concrete may also vary in different part of the world. For example, in Utah (US) the aggregate often consists of tailings from the mining industry which may have a high metal content (Fransson and Börjesson, 2018). This could be a significant challenge for inductive charging systems, since it will cause additional losses and reduced efficiency. Requirements for aggregates also vary significantly, and there are often separate national descriptions for every country. This might imply that significant changes in material requirements and construction methods would be necessary to facilitate implementation of inductive charging infrastructure. However, in Norway and the Nordic countries, the metal content in aggregates are generally low.

Considering the issues mentioned above, the wide variety of road conditions and local requirements and the limited experience with large-scale installation and maintenance of systems for dynamic inductive power transfer, it is expected that further efforts in research and accumulation of practical experience will be needed for identifying the most suitable procedures for installation and maintenance in roads under various environmental conditions.

4.4 Construction cost

The electrical parts of the infrastructure for inductive charging is expected to be significantly more expensive than for conductive solutions. This is mainly because such systems depend on higher amount of expensive materials, including special copper wires and ferrite elements for the coils, capacitors for ensuring resonant operation and power electronic converters for controlling the operation of the coils. However, the construction cost of the road (aggregates, asphalt) is expected to be in line with the conductive solutions based on a rail in the road surface.

Also for inductive charging, the construction costs will depend on whether the installation is intended for an existing road or a new road under construction. If a system is to be installed on an existing road, the costs related to disruption to the traffic flow must also be included in the calculations. Due to the wide range of possible solutions for dynamic inductive power transfer, and the limited available information on practical implementation of high-power systems suitable for heavy freight transport, any detailed analysis or estimation of construction cost have not been conducted within the ELinGO project. However, Fraunhofer 2017 has estimated a cost between 3.1 and 4.9 M€/km (BMVI 2017).

4.5 Aesthetics

The charging system is fully integrated in the road and all elements of the system are either covered by asphalt or can be located in small cabinets along the road. Thus, the presence of such systems is not expected to have any significant influence on the aesthetics compared to a regular existing road.

4.6 Personal safety/pedestrian safety

With inductive charging systems, there will be no energized conductors directly exposed in the road surface. Thus, the solution will avoid exposure of people to dangerous potentials in the road lanes. The main health and safety concerns with such solutions are therefore related to the potential long-term effects of exposure to electromagnetic fields. There are international regulations for exposure of persons without special training to electromagnetic fields, and these regulations must be complied with at locations where people can be present in the lanes of the road. However, it can be assumed that similar procedures as proposed for the systems with conductive rails in the road surface can be applied. Thus, the coils in the road surface can be activated for a certain distance in front of and behind moving vehicles. Such strategies should be considered to imply lower safety concerns for inductive solutions than for conductive solutions, since the exposure to magnetic fields do not constitute any immediate danger. For charging infrastructure designed for slow traffic and opportunity charging associated with traffic lights, the length of the coil sections should be shorter than for highways to ensure that the regulations for electromagnetic exposure is not violated at the road surface where people can walk around a vehicle. It should be noted that compliance with the standards for exposure to electromagnetic fields must be ensured by a combination of design measures of the infrastructure as well as for the receiving unit on-board the vehicles. Thus, also the shielding of the coils on-board the vehicle will be important to ensure that that people are not exposed to fields exceeding limits set by international standards. Although this can be anticipated possible to achieved by appropriate design strategies, it is expected to be a specific challenge for ensuring potential interoperability between different systems.

4.7 Risk related to availability-downtime due to maintenance

Technology for inductive charging of cars and trucks is the least mature technology considered in this document, and therefore limited practical experience is available. However, since the charging system is fully enclosed and is not exposed to environmental loads or moving mechanical parts and it is less influenced by thermic loads than systems installed directly in the road surface. The panel identifies this as positive features for reducing the risk and maintenance requirements, and for increasing the availability of the infrastructure.

Since the infrastructure is embedded below the road surface any repair of the physical infrastructure in the lane will imply the need for stopping or redirecting traffic. The advantage of the system being installed below the road surface is that any electrical failure will not require immediate intervention. Since it can be assumed that vehicles utilizing the infrastructure has on-board energy storage or a hybrid drivetrain, an electrical failure within a single road-side section will only require that this section is disabled while the vehicles can travel as normal. Any repairs can then be scheduled for times when impact on traffic flow is expected to be a minimum.

5 Conclusive remarks and suggestions for further work

This memo presents a brief and mainly qualitative evaluation of constructability, operation and maintenance of different technologies for dynamic on-road charging of electric vehicles. The presented assessments are based on relevant available literature and general information about the different technologies as well as experience with construction and operation of roads and railroads in Norway.

Among the three general solutions considered in the document, the contact-line-pantograph solution is considered as the technically most developed and mature solution. One significant practical advantage of this solution is that the infrastructure is based on long-time experience from trains and trams. Thus, there is a relevant base of experience from the technology provider as well as subcontractors for installation, operation and maintenance of such systems.

Technology for dynamic conductive power transfer by conductive rails integrated in the road surface have also been developed during the last years, and the first trials on a public road for one such solution developed by Elways started operation in 2018. Thus, further experience from this demonstration project can be expected to accumulate during the next few years. Until now the evaluation of previous demonstration projects is not sufficient to make any conclusions regarding the various technical solutions. Therefore, it is considered necessary to continue the evaluation of construction methods, costs, operation and maintenance requirements for solutions with conductive dynamic power transfer in the road. Such further work must also include difficulties with respect to winter conditions, including maintenance and the degradation of the road surface.

The situation is similar also for dynamic inductive power transfer, since limited evaluations of such solutions have been conducted for Nordic climate. Although the feasibility of dynamic inductive power transfer has been confirmed and several demonstration projects are in operation, this technology is still at an earlier stage of development in the sense that further improvements of performance and functionality as well as reduction of costs can be expected. There are also many different possible implementations of such technology under development, which makes it difficult to predict which design approach that have the highest potential for becoming a preferable solution or if multiple solutions can be expected to coexist. In this respect, further research and developments towards ensuring interoperability of different solutions will be important for future application of such technology.

Based on the qualitative work presented in this memo, the panel concluded that there should be a need for continued development of different options for practical implementation of the different concepts for dynamic power transfer to moving vehicles.

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