



Electric Infrastructure for Goods Transport

# Technology for dynamic on-road power transfer to electric vehicles

Overview and electro-technical evaluation of the state-of-the-art for conductive and inductive power transfer technologies

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## Summary

This document presents a review and evaluation of technologies for dynamic power transfer from road-side infrastructure to electric vehicles. Thus, technologies for stationary battery charging are not considered, and the attention is mainly directed towards on-road power transfer to moving vehicles. Two general types of technologies are considered, based on either conductive or inductive power transfer. The solutions for conductive power transfer are based on sliding contacts, while solutions for inductive power transfer are designed for contactless or wireless power transfer. The main attention when reviewing and evaluating the different concepts has been directed towards the potential application for freight transportation, although some of the reviewed concepts have not yet been demonstrated with the power levels required for such applications.

For dynamic conductive power transfer to moving vehicles, three general concepts have been proposed and demonstrated, based on overhead lines, conductive rails integrated in the road surface or conductive rails at the side of the road. The technology based on overhead lines can be considered as most mature, as it is based on experiences accumulated over many decades with operation of overhead lines for power supply to trains, trams or trolley-busses. This technology is currently promoted by Siemens, and several large-scale demonstration projects are already in operation or under planning. The main difference between infrastructure for road vehicles compared to trains or trams, is that railroad systems only require one conductor with one sliding contact, since the rails usually form the return path for the current, while dynamic conductive power transfer to road vehicles requires two separate conductors. For the concept developed by Siemens, a position-controlled double pantograph system is mounted on the vehicles intended for utilizing the infrastructure. As regular operation of such systems is currently being demonstrated in several projects, this technology can be considered ready for application to heavy freight transportation. The main functional limitation of this technology is that it cannot be directly applied to smaller vehicles. However, the practical implications and economic consequences of excluding or including small vehicles in the operation of electric road infrastructure have not been investigated, since the objectives of the ELinGO project are limited to studies of solutions for heavy freight transportation.



With the intention of avoiding the visual impact of overhead lines and at the same time enabling dynamic power transfer to vehicles with a wide range of sizes and power demands, several concepts for conductive power transfer technology integrated in the road surface have been proposed. The most developed concept is promoted by Elways in Sweden, based on rails with the sliding contacts below the surface of the road. Similarly, Alstom is promoting a concept based on sliding contacts at the road surface, which is adapted from an existing solution for power supply to city trams. These concepts have been demonstrated at relevant power levels, and a demonstration of the system developed by Elways on a public road has been started during 2018. Another concept for power transfer from short conductive rail sections mounted on the road surface has been proposed and demonstrated in smaller scale by the Swedish company Elonroad, and this concept is currently under further development. A concept for transferring power from a conductor at the side of the road has also been proposed and demonstrated for high speed operation of electric cars by Honda in Japan. Although there is no doubt regarding the technical feasibility of transferring sufficient power by any of the proposed concepts for dynamic conductive power transfer, there are several concerns regarding the durability and maintenance requirements of the solutions based on conductors integrated in the road surface. These concerns are mainly related to operation during winter conditions, with frost, snow, ice and exposure to salty environments. Although ongoing or planned demonstration activities with dynamic conductive power transfer are expected to provide further experience, it is not expected that currently confirmed plans will fully address all concerns related to long-term operation under Nordic conditions, and especially for coastal Norwegian winter climate.

Technology for inductive power transfer has the potential to provide power supply to moving vehicles from the ground level while avoiding the disadvantages of sliding contacts integrated in the road surface. Thus, a wide range of concepts and design approaches for dynamic inductive power transfer are currently under development. However, only the concepts from two different research groups have been demonstrated at the power levels required for long haul freight transportation. One concept has been presented by Bombardier, based on a three-phase distributed (meandering) winding along the road. This system has been mainly developed for trams or for opportunity charging of electric busses at each stop, but has also been demonstrated for dynamic power transfer to a truck on a dedicated test track. For the on-road applications in trucks and busses, this solution is based on direct control of the airgap by mechanically lowering the receiving coil from the vehicle. This allows for improved coupling during normal operation and for placing the receiving coil in a safer and more protected position when it is not in use, but also implies disadvantages due to moving mechanical parts and a relatively slow mechanical position control. Several different concepts that are not depending on mechanical position control of the receiving coil has been developed and demonstrated for busses, light trains and electric cars on basis of research activities at KAIST in South Korea. However, only one concept based on a relatively long planar coil section with distributed capacitance has been demonstrated for high power levels. This demonstration was presented for applications to a train, with a stationary infrastructure with power rating of 1 MW, and multiple receiving coils rated for 200 kW on-board the train. However, a lower air-gap was used for the train-based demonstration facility than what would usually be required for a road vehicle.

A wider range of system designs for dynamic inductive power transfer have been proposed and demonstrated at lower power levels, and publicly available information about the most relevant research activities and demonstration projects are reviewed in this document. From the available information, it can also be expected that most of the concepts proposed or demonstrated for operation at lower power levels can be scaled to the power ratings required for heavy duty trucks by appropriate

research and development activities. Indeed, the results from theoretical studies and practical demonstrations confirm that systems for dynamic inductive power transfer to moving electric vehicles are technically feasible, although it is generally expected to have higher cost of installation than solutions based on sliding contacts. However, the general technology and the components required for dynamic inductive power transfer are at an earlier stage of development than for dynamic conductive power transfer. Thus, further progress in performance and cost-efficiency of such solutions can be expected to result from the wide range of ongoing research activities on applications of dynamic inductive power transfer. Because of the actively ongoing development, it is still difficult to anticipate which concept will become the most preferable or dominant solution for potential future applications.

To indicate how the technology for dynamic inductive power transfer can be expected to develop, some critical research questions are briefly reviewed and discussed in this document. The need for standardization and interoperability between different concepts is also emphasized, and the potential for interoperability between vehicles and infrastructure with different physical dimensions and different power rating is briefly evaluated.

It should be noted that this document is mainly intended as a general introduction to the electro-technical aspects of the different concepts for dynamic power transfer to moving vehicles. Thus, issues related to cost or environmental impact of the different solutions are not discussed, although the selection between different concepts in many cases should be expected to rely on a combination of cost-benefit analysis and a range of trade-offs regarding technical performances. Issues related to mechanical construction, integration in road infrastructure and maintenance requirements for the different concepts are neither discussed in detail, as they are treated separately in another document.



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# 1 Introduction

This report presents a brief and general introduction to available and emerging technologies for dynamic power transfer to moving vehicles. The main attention of the review is directed to the technology for interfacing the moving vehicle to the stationary infrastructure. Some brief comments are also introduced regarding the structure of the required power distribution system along the road and the differences in requirements for the various concepts. A few general references to available studies of potential benefits from development of Electric Road Systems (ERS) are also included for the report to provide access to related information, although only the power transfer technology will be explicitly discussed. Issues related to cost and constructability will neither be explicitly discussed, since they will be treated separately in later stages of the ELinGO project. The technology overview is presented in two parts, where the first part discusses technologies based on conductive power transfer by sliding contacts while the second part discusses technologies based on inductive power transfer for avoiding mechanical and electrical contact.

For conductive power transfer, the basic concept of sliding contacts is well established and has been widely used in railway systems as well as for trams and subway lines over many decades. The main challenge for utilization in road traffic is the development of practical, safe and reliable mechanical interfaces, including the integration in the vehicles and in the road infrastructure. Thus, the development of conductive ERS solutions has been mainly driven by industry and there are few scientific publications related directly to the power transfer technology. This also implies that limited information is available regarding detailed design procedures or optimization methods for the electrical and mechanical elements involved in the dynamic power transfer. In this report, mainly a brief outline of the different emerging alternatives for conductive power transfer designed for commercial and heavy-duty transport is presented and available key information about the technologies is summarized.

Technology for contactless and dynamic inductive power transfer for transport applications is currently undergoing rapid development, as result of significant academic and industrial research activities during the last two decades. Consequently, several different approaches for design, optimization and implementation of ERS technology based on the concept of dynamic inductive power transfer have emerged. Although it is possible to categorize some of the various approaches pursued by various research groups and industries, it is still not clear which solutions will have the highest potential for future cost-effective large-scale implementations. Due to the progress in both design methods and components, including semiconductor devices for power electronic converters as well as passive components needed as part of inductive power transfer systems, the potential for practical implementation can be evaluated in at least two different ways. One approach can be to apply conservative design strategies based on components and optimization methods that are currently available. Such approaches can be assumed to provide the fastest progress towards practical implementations, but will also imply limitations in flexibility and performance and limited potential for cost reductions. Thus, the research community is still actively searching for concepts that can have the potential to avoid some of the limitations of available systems in terms of cost, efficiency, sensitivity to mechanical position and interoperability between various types of vehicles. Such considerations based on the potential for future developments and improvements of enabling technology will imply a longer timeframe for practical large-scale implementation. In this report, the presentation will be limited to a brief overview of the already developed concepts, and an indication of ongoing development trends that might influence the design of future systems for dynamic inductive charging.

## Part I - Technologies for Dynamic Conductive Power Transfer

### 2 Introduction to conductive power transfer concepts

Concepts for conductive power transfer to moving vehicles depend on sliding contacts. As mentioned, such technology has been utilized in transport applications for many decades. The most widespread application is the catenary systems for electrified railroads, where a pantograph is providing the power-take-off from an overhead line mounted above the track. The same general system configuration is also commonly used for trams, although lower voltage levels are usually applied for light rail passenger vehicles than for high power trains. Some rail-based transportation systems, especially subway systems are also using solutions with a "third rail." In such systems, the power supply is provided by a solid busbar, and not by a hanging line. The "third rail" is commonly located between the traction rails, with power-take-off by a sliding contact mounted below the vehicle, but can also be located above ground level on one side of the vehicle if the area around the power rail is inaccessible to passengers.

For rail-based transportation systems, the use of sliding contacts is relatively simple, as only a single line or busbar with voltage is needed while the rails are usually used as ground return of the power supply system. However, for road applications, two conductors with sliding contacts are needed, since the rubber wheels will isolate the vehicle from the ground. Still, trolley-busses fed from overhead lines have been commonly used for electric city busses and can be considered as conventional and well-established technology. There have also been a few previous trials with trolley-fed trucks, although widespread use of trolley-based power supply has never been reached outside city busses and certain applications for bulk transportation in mines [1].

The long and mechanically flexible connectors for power-take-off from the overhead lines in trolley systems have been mainly constructed for being always fixed to the conductors while driving at relatively low speed. Thus, trolley systems have not been used for high speed transportation, and have not had the possibility for quick connection/disconnection from the power supply system, which has limited the flexibility in operation of the vehicles. Although this is not a significant constraint for route-based transportation systems, more flexibility is needed for open interface systems where vehicles with different owners/operators and different missions should be able to utilize the same power supply infrastructure. Thus, emerging systems for power supply from overhead lines are based on different power take-off systems than traditional trolley busses, as will be discussed in the following section.

Until recently, sliding contacts from ground level have not been used for electrification of transport in open road environments, mainly due to safety concerns related to use of energized and openly exposed busbars within the reach of people in road or city environments. As will be shown in the following sections, solutions for ensuring safety of ground level power supply to city trams in open road environments are already in operation, and several attempts are currently directed towards development of systems for ground-level power supply by sliding contacts to regular road vehicles.

In the following section, the emerging systems for dynamic conductive power transfer will be briefly presented. The presentation will be limited to discussions of the power transfer technology. The drive systems on-board the vehicles will not be discussed beyond what is necessary for the description of the power supply system. However, it is assumed that all vehicles will have a hybrid propulsion system, with a battery storage and/or an internal combustion engine, allowing for operation without power supply from the road infrastructure. The capability for operation from an on-board energy storage, at least for limited distances, will be necessary for travelling on roads where infrastructure

for power supply is not available. Especially, this capability will be needed for the first/last-mile of transport between two points outside the main road network, in case of power system faults, and for any other necessary manoeuvring along the road which will force the vehicle to disconnect from the power supply system. For more general background information related to the potential advantages and consequences of electrifying road transport, several studies have been conducted in Sweden [2]-[6], and such issues will be treated separately for the Norwegian context within the ELinGO project. Questions regarding the necessary or suitable range of operation for a vehicle based on on-board energy storage will also be depending on the actual transport case, and should be considered independently of the infrastructure for dynamic power transfer to the vehicle.

### 3 Power Transfer from Overhead lines

A concept for electric power supply from overhead lines has been developed and promoted by Siemens since 2010 under the name "eHighway" [7]. The technology is partly developed on basis of equipment and standards for light rail systems and trolley-busses, with adaptations mainly related to the power take-off system and the mechanical interface to the vehicle.

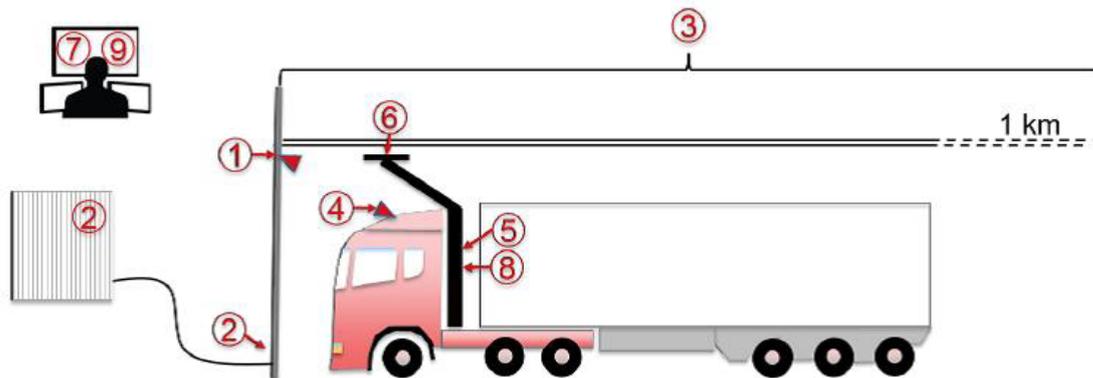


Figure 3-1 Schematic view of power supply for road transportation from overhead lines [9]

#### 3.1 General description of concept

An overview of a system for power supply to a moving vehicle from overhead lines is shown in Figure 3-1, with the main elements of the system listed in the following [7],[8], [9]:

1. The physical infrastructure for continuous power supply along the road, is similar to the power supply systems of overhead lines for trams or railway systems, although two conductors with independent contacts to the vehicle are necessary
2. Connection to a sub-station for power supply from the distribution network (typically 11 or 22 kV in Scandinavia). The substation includes equipment for fault detection and disconnection of line sections in case of emergencies or failure.
3. Sections of about 1 km of continuous overhead lines, supplied separately from the substation
4. The presence of overhead lines above the vehicle must be detected before the on-board power take-off equipment can be activated. The detection is in this case based on a laser scanner, which is also used to illustrate the position of the lines with respect to the pantograph of the power take-off system as a visual feedback to the driver of the vehicle.
5. The mechanical position control of the power take-off arms, which includes continuous position tracking of the overhead lines during driving
6. The pick-up system, based on a pantograph with two arms, where each arm provides two contact points for its corresponding conductor
7. Power measurements from the sub-station with online feedback to a control centre
8. On-board power conversion system for control of power flow and interfacing of the power supply with the on-board electrical drive system and energy storage unit. The onboard equipment can also include metering devices for monitoring and billing of the electricity consumption of each vehicle.
9. Operation and control centre for monitoring the operation of the system

The main functional difference compared to trolley-based systems is the actively position controlled pantograph, which allows for seamless connection or disconnection from the power supply infrastructure during normal operating speeds of the vehicle (i.e. up to 90 km/h). It can also be noted that the catenary systems of the overhead lines for the eHighway system have more similarities with the systems used for trains than to the systems used for trolley busses. This is assumed to be because the need for relatively higher operating speeds and seamless disconnection requires higher tension in the overhead lines than what is commonly used for trolley busses in city environments.

### 3.2 Overview of research and demonstration activities

The eHighway concept has resulted from development efforts at Siemens and several corresponding research projects on electrification of road transport supported by the German government since 2010 [7], [10], [11] [12]. The concept was chosen on basis of results from the initial research and development activities from [10], [11], and corresponding technology has been developed and demonstrated by Siemens in a test-track north of Berlin since 2012 [7]. As part of the research activities in Germany, the technical solutions of the eHighway systems have been reviewed by the German Federal Highway Research Institute (BASt) for evaluating the impact on regular road infrastructure, traffic safety and traffic flow [13]. On this basis, the solution has been approved for field trials on German roads. Similar assessments of this technology have been conducted in Sweden as a basis for demonstration activities, but the regulatory aspects related to safety and compliance with regulations for public roads are not further discussed in this document.

The first demonstration project of the eHighway system on a public road started operation in Sandviken, Sweden, from June 2016 [7], [8]. The installation includes 2 km of overhead lines along one lane of the E16 road. From the opening of the demonstration project, one diesel-hybrid vehicle from Scania has been operating for testing and verification of the system in normal road traffic. A second vehicle has also been adapted for operation in the system, and started operation during 2017. These two vehicles will be operating in the system for a two-year test period. A picture of the vehicles in operation is shown in Figure 3-2.

Another demonstration project for the eHighway technology, close to Los Angeles, California, also started operation during July 2017 [7]. Overhead lines were installed for both directions in a one-mile section of a highway, and the location is selected due to the vicinity to the ports of Los Angeles and Long Beach, which generate very high levels of on-road goods transportation to the nearby railroad terminals. The demonstration has included three freight trucks with different propulsion systems, one diesel-hybrid truck from Volvo, a natural-gas-hybrid truck and a battery-electric truck, which have been tested from July to December 2017.



**Figure 3-2 Pictures of Scania trucks in operation at the E16 demonstration site in Sandviken, Sweden [7], [14]**

Considering the demonstration project in Sandviken and the plans for the demonstration in California, the eHighway system was in 2016 considered by the authors of [9] to have a Technology Readiness Level (TRL) of 6, which corresponds to "System/subsystem model or prototype demonstration in an operational environment." With these demonstrations in full operation, a TRL of 7, corresponding to "System prototype demonstration in a relevant environment," has been achieved by 2018. Furthermore, during 2017 plans were announced for construction of an eHighway system a 10 km section of the A5 Autobahn close to Frankfurt in the German state of Hesse, with expected commissioning towards the end of 2018 [7], [15]. It has also been confirmed that two other field trials will be organized

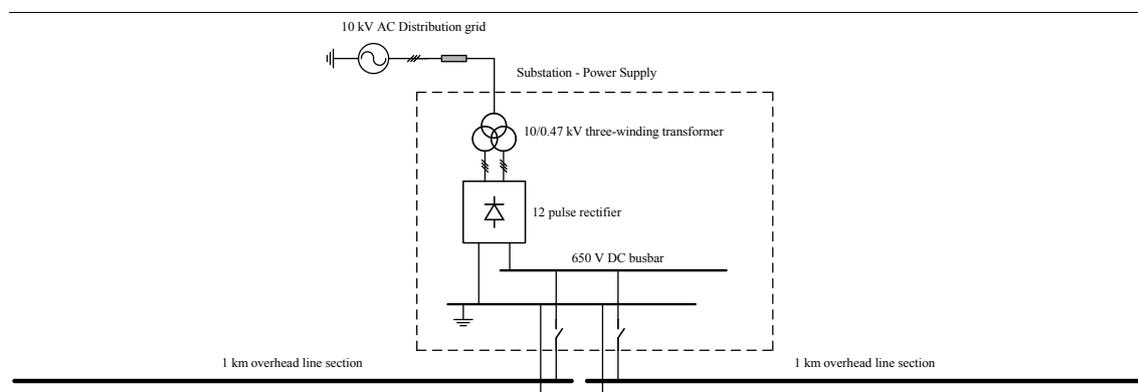
in Germany, one on the A1 Autobahn close to Lübeck [16], and one on a federal road in Baden-Württemberg [17]. These demonstration projects are expected to start operation during 2019. With these plans being conducted, the system can be expected reach TRL 8 (Actual systems completed and qualified through test and demonstration) and TRL 9 (Actual system proven through successful mission operations) around 2020.

It can also be mentioned that one of the main lines of research activities related to operation of vehicles at the demonstration track operated by Siemens has been directed towards development of the power-take-off solution. As mentioned, the power take-off is based on a pantograph solution, with one arm for each overhead line, which is actively position-controlled and depends on detection of the position of the lines. Siemens has developed the position-controlled two-armed pantograph as a complete unit that can be mounted on the vehicle. The main integration with the vehicle is the connection to the power system, and the adaptations in the cabin and control panels of the vehicle, where the detection-system for the position control as well as the functions for connecting to and disconnecting from the overhead line must be interfaced with the regular instrumentation. It might be expected that the vehicle manufacturers will continue the development of standardized integration of the power-take-off unit from Siemens in their vehicle models if the eHighway system will be widely utilized. Further development for reducing the cost and improving the performance of the pantograph unit could also be expected.

### 3.3 Power conversion and distribution system for overhead lines

According to information from Siemens regarding the demonstration site in Sandviken, the power distribution system for the overhead lines appears to be adapted from light rail solutions. Thus, the overhead lines are mounted at a height of about 5.15 m above the road surface, and provide dc voltage to the vehicles. Usually, such systems provide 750 V DC, but the installation in Sandviken is operating with 650 V [18].

An overview of the system topology from the installation in Sandviken is shown in Figure 3-3. The substation providing the power supply to the overhead lines is directly adapted from similar installations for railroad or tram systems [18]. The power conversion system is in this case based on a three-winding transformer and a diode rectifier supplying a dc voltage of about 650 V to a local dc busbar and switchboard. Thus, the system in Sandviken is not designed to feed power from the vehicles back to the grid, but this could be easily achieved by using an actively controlled Voltage Source Converter as an active rectifier. However, the road at the demonstration site in Sandviken is relatively flat, and it can be assumed that there is no relevant potential for regenerating power to the grid.



**Figure 3-3 Power system for supplying the overhead lines in the eHighway demonstration site at E16 in Sandviken, Sweden [18]**

As already mentioned, each section of the overhead lines is 1 km for the demonstration site in Sandviken, and the installation includes two sections, with separate circuit breakers and protection systems. In case of faults or emergencies, the involved line section will be automatically grounded to ensure safety for regular vehicles and for firefighting crew and medical personnel in case of traffic accidents involving the overhead lines. The system also includes a possibility for de-icing operation by running a large current in the overhead lines for melting ice by heating.

The use of 1 km line sections will also limit the need for installations beyond the equipment in the sub-station compared to the other emerging solutions that will be discussed in the following sections. For a practical road installation, one sub-station can supply at least one section of 1 km in each direction of both lanes of the road. With such a configuration, one sub-station can supply 4 separate 1 km sections and cover at least 2 km of road distance. This implies the need for one sub-station at every second km along the road. In general, the line sections could also be designed to be longer than 1 km, and could possibly be interconnected as they often are in railway systems. Furthermore, Siemens has indicated that one sub-station can supply additional line sections, and that the distance between sub-stations can be increased up to about 10 km [7]. However, any difference in length of the sections, or interconnection of multiple sections, will not change the main principles of the system design, although adaptations of the safety precautions and protection strategies might be required.

As mentioned, the vehicles utilizing the installation in Sandviken will be diesel-hybrid trucks, but for further expansion of such infrastructure, it will become relevant with zero emission vehicles (i.e. battery or hydrogen) having a larger on-board storage that will provide a reasonable range without access to power supply from the road infrastructure. The trucks, and possibly busses, utilizing the overhead lines are expected to have quite similar interfaces between the power take-off system and the on-board propulsion system, although with certain manufacturer-dependent adaptations. It is expected that the vehicles will have on-board battery storage with rated voltage in the range between 400 and 900 V. Most likely a DC-DC converter will be the interface to the propulsion system, providing voltage adaptation and control of the current from the overhead lines.

It should be noted that the main practical limitation of applicability for overhead lines is that such infrastructure is only suitable for large vehicles. However, the overhead lines are expected to be quite flexible in terms of supplying vehicles with different power demands, and no practical constraints on power availability is expected for vehicles able to utilize the infrastructure. Thus, the selection of maximum charging power for vehicles will be mainly a matter of practical and economical trade-offs as well as standardization, both for the vehicles and the developers of the infrastructure. Although it seems like 650-750 V is becoming the preferred voltage range, the studies in [19], [20] indicate that 1500 V, which is also a standard voltage level for rail-based systems, might become a preferable option in case of large-scale implementation. However, the selected voltage level will also influence the requirements for the conversion systems on-board the vehicles. In case wide adoption of dc distribution at 750 V leads to emerging standardization of vehicle technology, it might be less likely that the voltage level will be changed in the future.

### 3.4 Summary of status for power supply from overhead lines

The status of this technology can be summarized as:

- The technology is based on conventional and well-proven concepts, where the actively position-controlled power take-off unit is the main new addition compared to systems for railways and trolley-busses.
- A demonstration site in practical road traffic is operation in Sweden since 2016, and 6 months of demonstration on a public road in California has been completed during 2017. Three demonstration projects on public roads in Germany are planned for operation in 2018–2019
- Currently considered to be at TRL level 7, but no technical constraints are expected for reaching TRL level 8 or 9.
- It is expected that such systems can be quickly implemented if there is will for investment.
- The sub-stations of such systems could easily be designed for bidirectional power flow, as has been implemented in the test track in Germany [14]. However, the demonstration facility in Sweden is not designed for power flow from the overhead lines back to the utility grid. In general, it is not expected that there will be any need for bidirectional power flow in flat areas or roads with relatively high and regular traffic.
- The main technical disadvantage in terms of operation and scalability is that the concept can only be used for large vehicles like trucks and busses. However, only the technical functionality is considered in this document, and no attempts are made to quantify the potential economic advantages and disadvantages of providing infrastructure for all types of vehicles in a regular traffic pattern.
- Since installed overhead lines will not influence regular traffic or the road surface, they can potentially coexist with other solutions for dynamic power transfer to moving vehicles based on conductive or inductive technology integrated in the road cross-section at or below the surface. Thus, technology for conductive or inductive power transfer to smaller vehicles could for instance be installed on selected parts of a road with overhead lines for powering long distance heavy freight transportation.
- The main disadvantage for public acceptance is expected to be the visual impact of overhead lines, although this will likely be of less concern for large scale highways with high traffic density. However, this concept is not considered suitable for city environment due to concerns regarding public acceptance of the visual impact.

## 4 Power transfer from conducting rails integrated in road surface

Several concepts for power transfer to moving vehicles from conducting rails integrated in the ground surface have been proposed during the last years. Such systems have already been implemented for city trams, to avoid the visual impact of poles and overhead lines needed for catenary systems. One of the concepts under development is based on adaptation of technology for trams, while other systems are developed specifically for road vehicles, as will be reviewed in the following.

### 4.1 General description of concepts and overview of proposed implementations

The motivations for developing concepts allowing for dynamic power transfer from conductive infrastructure integrated in the road surface has been mainly to overcome the limitations in terms of applicability for electric road systems based on overhead lines. Thus, the two main advantages that should be obtained with such systems are:

- Possibility for vehicles in a wide range of sizes to utilize the infrastructure
- Avoiding the installation and corresponding visual impact of overhead lines

The second point has also been a driving motivation for developing city tram systems supplied from the road surface. Especially Alstom has been developing and promoting a system with on-road sliding contact for trams, as will be further discussed in the following section. However, in the same way as for overhead lines, rail vehicles need only one sliding contact since the contact between the wheels and the steel rails provide a path for the return current. Thus, the main difference between systems for trams with ground surface power supply and power supply infrastructure for regular road vehicles, will be that the conducting rails in the road surfaces must contain at least two separate conductors to ensure a return path for the current.

Currently, there are three concepts for conductive roadway power supply under development, as will be briefly discussed in the following.

### 4.2 Solution from Alstom

As already mentioned, the solution promoted by Alstom is based on already developed technology for roadway power supply to city trams for avoiding use of overhead lines. The resulting solution has been used as one of the cases in the Swedish project on "Slide-in Electric Road Systems," where the system has been demonstrated on a test-track in cooperation with Volvo [21]. A relatively detailed description of the system as well as an analysis of potential implementation on the highway between Stockholm and Gothenburg is also available in [21]. As demonstrations on a test-track have been conducted, the solution is considered in [9] to have reached a TRL level of at least 4. The main technical issues related to the power transfer technology are summarized and illustrated in the following.

#### 4.2.1 Background and general configuration of Alstom APS ERS concept

Alstom has already developed a concept for roadway power supply to city trams, which is marketed under the term "Aesthetic Power Supply" (APS), and commonly referred to as "Ground-level power supply system" or as a "Catenary-free" power supply solution. As the names indicate, the main motivation for developing this system has been to avoid the visual impact and practical installation of overhead lines in city environments. The concept has already been implemented, or is currently under construction in 10 cities on several continents. According to Alstom, they have supplied more than 300 tram vehicles for about 140 km of track, and since the first installation in 2003 they have accumulated about 23 million km of operating experience with the system [22], [23].

a) Tram with APS in operation [23]



b) Testing of truck with adapted APS system [21]



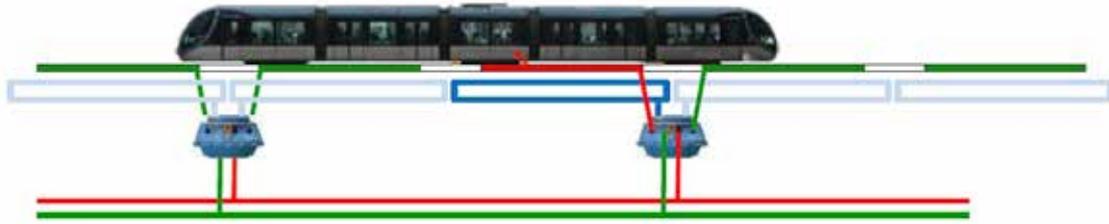
**Figure 4-1 APS power supply systems from Alstom for tram and truck applications**

It can be noticed that a similar system for ground power supply for trams has been developed by Ansaldo [24]. However, there is no indication available that this system is under further development for application to road vehicles.

A picture of a tram with the APS power supply from Alstom is shown in Figure 4-1 a), while a system adapted for use on a truck is shown in Figure 4-1 b). From the pictures, it can be seen how the tram system has only a single conducting bar in the middle between the two rails, while the system adapted for the truck requires two conducting bars in the road surface. The figure of the truck also indicates how a positioning system of the power-take-off unit is needed for road vehicles, while this is not necessary for rail vehicles where the position of the power supply is always fixed with respect to the position of the regular rails.

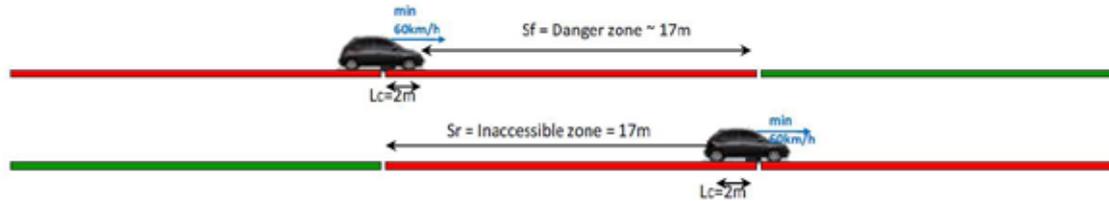
An indication of the general functionality of the system as initially developed for tram applications is given in Figure 4-2. As indicated by the figure, the conducting elements of the road-level power supply system is constructed by short sections, and each section is only energized when it is completely covered by the tram. The sections that are not fully covered by the tram, or are not supposed to supply any power are grounded. Thus, it is always safe to walk on the track. The conductors of the sections are elevated about 15 mm above the road surface, and according to Alstom this is sufficient to avoid problems with leakage currents during rainy weather conditions. However, in case the track is flooded so that a part of the section will be submerged in water, this will be detected by the monitoring and protection system and the section will not be turned on when a vehicle passes. The same will be the case if there are other faults or malfunctions in a section. Thus, the vehicle will have to run on power from its on-board batteries until it reaches a healthy section that will be automatically energized when it will be covered by the vehicle.

Each conductive section of the system is 8 m long, and there is 3 m between the conductive elements of two consecutive sections [21], [23]. Thus, each section unit is about 11 m long, with insulating elements of about 1.5 m at each end for interfacing to the next sections. In this case, each tram has two sliding shoes for power take-off, with more than 3 m distance, so that there is always one power-take-off device that can receive power from an energized section. The installation has integrated antennas for detecting location, speed and direction of the vehicle for activating and deactivating the section of the power supply infrastructure. Further descriptions of the system are available in [21].



**Figure 4-2 Schematic view of how Alstom APS power supply system is operated for a tram [21]**

In applications for road vehicles, it cannot be always assumed that each section of the power supply system will be covered by a vehicle, and it would be unpractical to construct sections that are shorter than small cars. However, in city traffic it is assumed that small electric cars will always have a reasonable range by battery storage. Thus, mainly highway applications are considered, and it is assumed that energization of the conducting bar can be allowed in a danger zone in front or behind the vehicle as shown in Figure 4-3. Considering a speed of 60 km/h (17 m/s) and a practically constrained time-zone of 1 s around the vehicle where it will not be possible to enter the road without causing a traffic accident, the danger zone in front of the vehicle will be about 17 m, which covers more than 1 section. Similarly, there will be an inaccessible zone behind the vehicle of maximum 17 m, which will be most critical for short vehicles, while a shorter zone can be assumed for long vehicles like busses or trucks. Under these conditions, the detection of the vehicle position and speed will be used as conditions for energizing the sections, and power supply from the road will not be enabled for speeds lower than 60 km/h. According to the considerations in [21], this approach for operation of the system should prevent hazards for pedestrians, but it is noted that motor bikers driving very close to a car using the infrastructure might be within the area of energized conductors. There might also be concerns regarding the friction and road grip of vehicles when driving on the exposed conductors at the road surface.



**Figure 4-3 Schematic view of Alstom APS power supply system operated for a car [21]**

Considering the assumed threshold for activation of power transfer, the solution from Alstom is mainly intended for highways and outside city environments. However, it can be noted that according to [25], an internal study by Volvo and Alstom has concluded that sections of about 5 m length can be suitable for installation in relevant city environments.

## 4.2.2 Power distribution systems

Due to the many short sections, the power distribution system with its associated switchboards and control systems will be more complex for the APS solution than what has been described for overhead lines. An overview of the assumed power distribution system is shown in Figure 4-4. As indicated in the figure, a similar configuration of the primary distribution system as for the eHighway solution in section 3.3 is assumed, with sub-stations including rectifiers for supplying 750 V DC located at about every 2nd km along the road. However, in this case, the feeders from the substations are interconnected on the dc-side. It is indicated in the figure that each sub-station is designed for 900 kW, but as for the overhead lines it is not expected that there will be any practical design constraints on power availability beyond the increased cost of dimensioning systems for higher power. No information is provided about the converter topologies applied in the substations, but it is assumed that passive diode rectifiers are used. If so, the system is not inherently designed for bidirectional power flow, but this could be achieved by applying a Voltage Source Converter as an active rectifier.

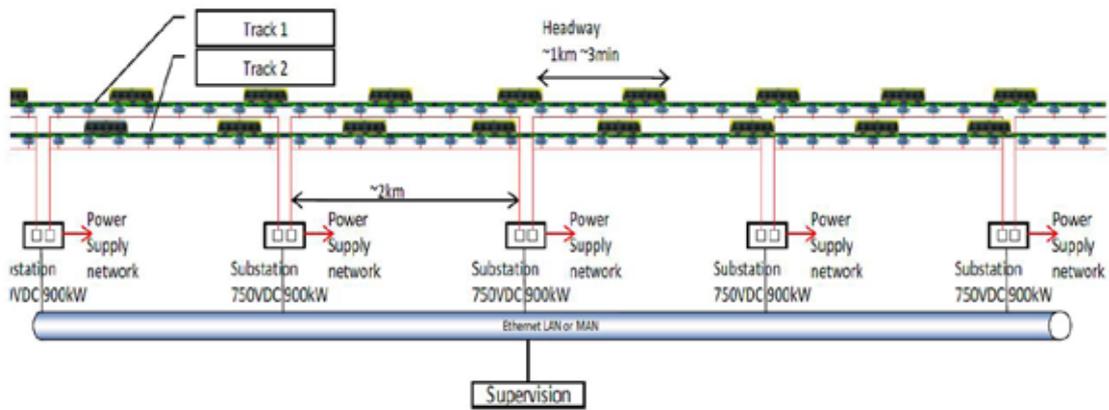


Figure 4-4 Power Supply system for Alstom APS concept [21]

Further details regarding the power supply system to each individual segment of the road between the sub-stations is shown in Figure 4-5, where it is indicated that each segment is controlled by a "Power Box" (PB). For the tram systems, each PB contains a switch, as well as corresponding logic and safety mechanisms including fuses. Thus, the PBs are ensuring the energization and disconnection of each conducting segment on the road surface, according to the presence of any vehicle requiring power supply. The main elements of a PB is shown in Figure 4-6, and further descriptions of the safety mechanisms and real-time supervision strategy for controlling the operation of the PBs are available in [21]. It can be noted that the demonstrations of the system have been based on an average DC voltage of about 690 V [23], and a calculated voltage range of about 670–740 V DC at the PBs is found in [21], depending on the distance from the sub-station.

For the tram applications, the switches in the PBs of the APS concept has been dc circuit breakers. However, it is expected that practical road applications will have a potentially much higher number of switching actions over the required lifetime than a dedicated tramline, and that the limited number of switching actions within the lifetime of a mechanical dc circuit breaker can become disadvantageous with respect to cost and need for maintenance. Thus, Alstom will upgrade the PB design for road applications by using solid-state semiconductor breakers instead of electro-mechanical breakers [23]. Such solid-state breakers are expected to be more compact and flexible than mechanical circuit breakers and can endure a much higher number of switching actions, but are also expected to increase the cost of the system.

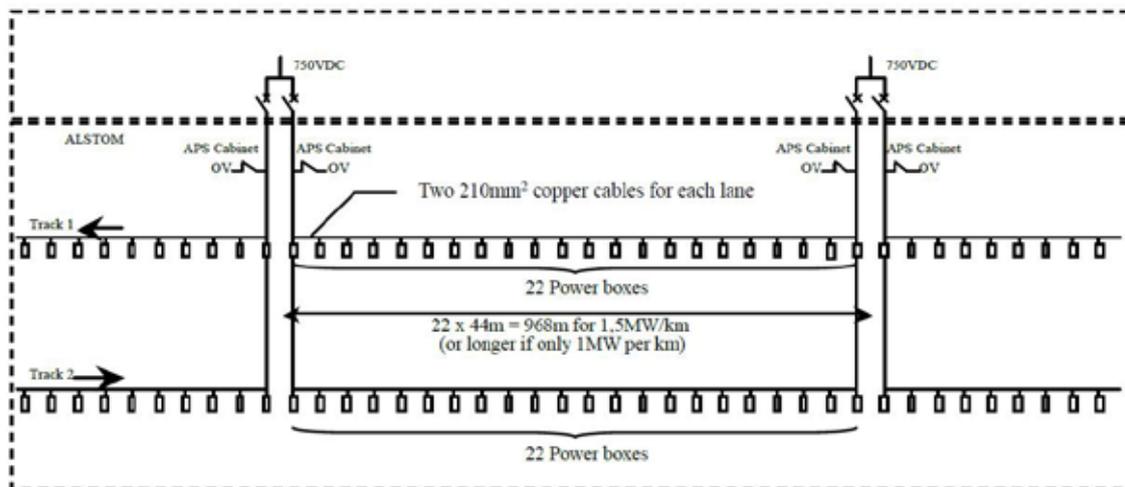


Figure 4-5 Details of power supply for the sections in Alstom APS concept [21]

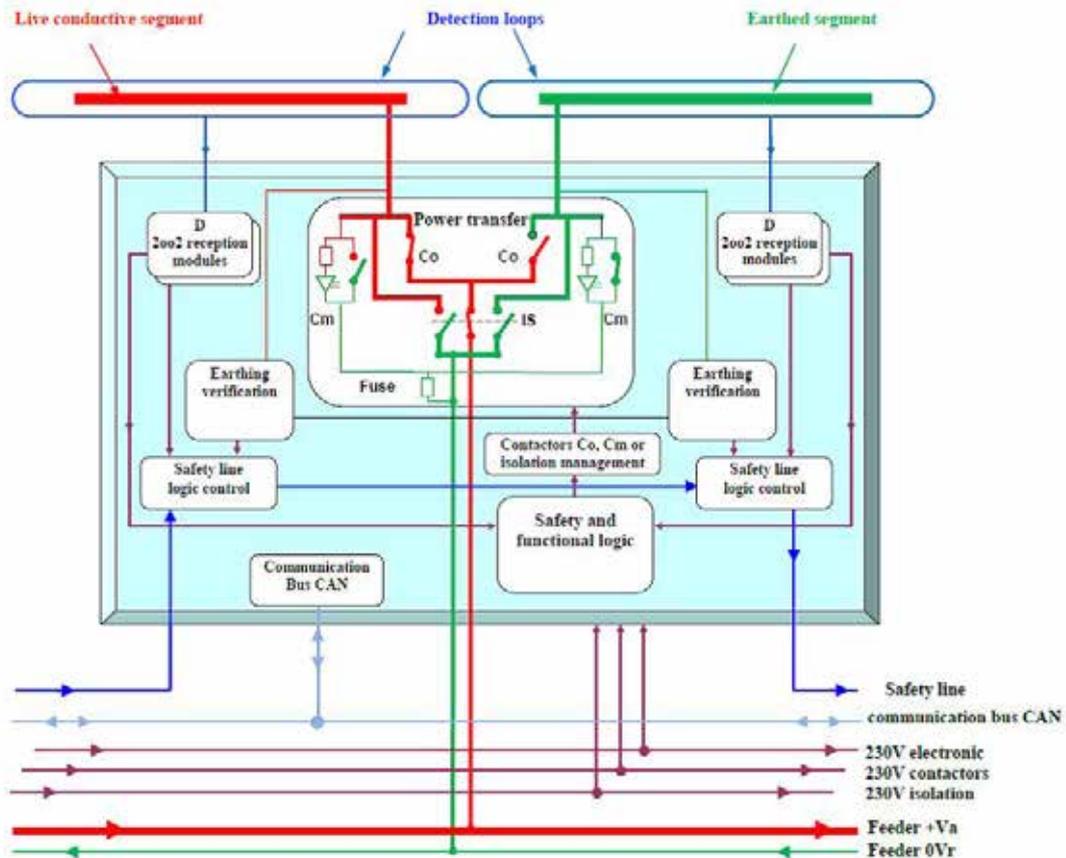


Figure 4-6 Details of a "Power Box" in Alstom APS concept [21]

### 4.2.3 Power take-off and integration in road surface

The Alstom APS solution was demonstrated on a test-track in cooperation with Volvo during the "Slide-in Electric Road System" project in Sweden [21]. However, these demonstrations were based on APS elements for trams, without any specific re-design beyond practical adaptations and the design of the position-controlled pick-up system for making the collector shoes follow the conducting tracks in the road. Two varieties of the pick-up system were designed in cooperation with Volvo, as shown in Figure 4-7.

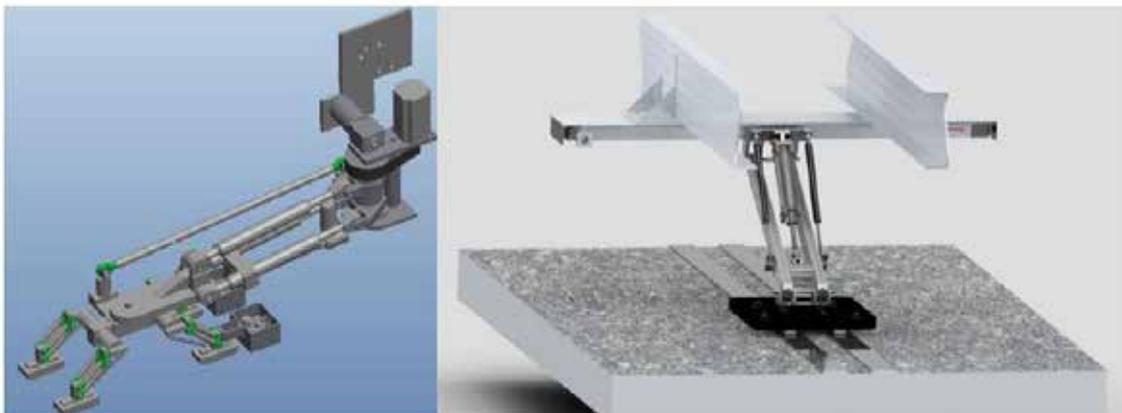


Figure 4-7 Two different types of position-controlled pick-up systems for the Alstom ERS designed in cooperation with Volvo for the test-track demonstrations in Sweden [21]

As mentioned, the main difference compared to the tram applications is that two collector shoes are needed due to the lack of an inherent return path for the current, and the need for the active position control due to the free movement of the vehicle with respect to the conductor sections in the road surface. If continuous power transfer to the vehicle should be achieved, the power-take-off device should also have double collector shoes, making it able to cross the neutral zone between two segments. This can be seen in the left picture of Figure 4-7. However, it is assumed that such a design is only relevant if the distance between the sections is kept shorter than what is defined for the tram applications.

The conductive rail elements of the ERS installation must be integrated in the road surface, for instance as indicated in Figure 4-8. Although the initial demonstrations in Sweden have been performed with power supply sections directly adapted from the tram system, Alstom has indicated that they are preparing a narrower rail design for ERS applications. Thus, the profile of the conductors indicated in Figure 4-8 is less wide than what can be seen in Figure 4-1 b). The elevation above the main road surface is assumed to be 15 mm, i.e. the same as given for the tram application.

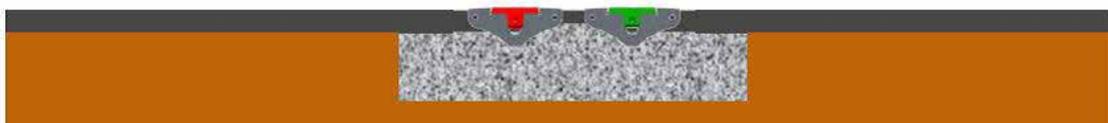


Figure 4-8 Cross-section of road with installed ERS rails [23]

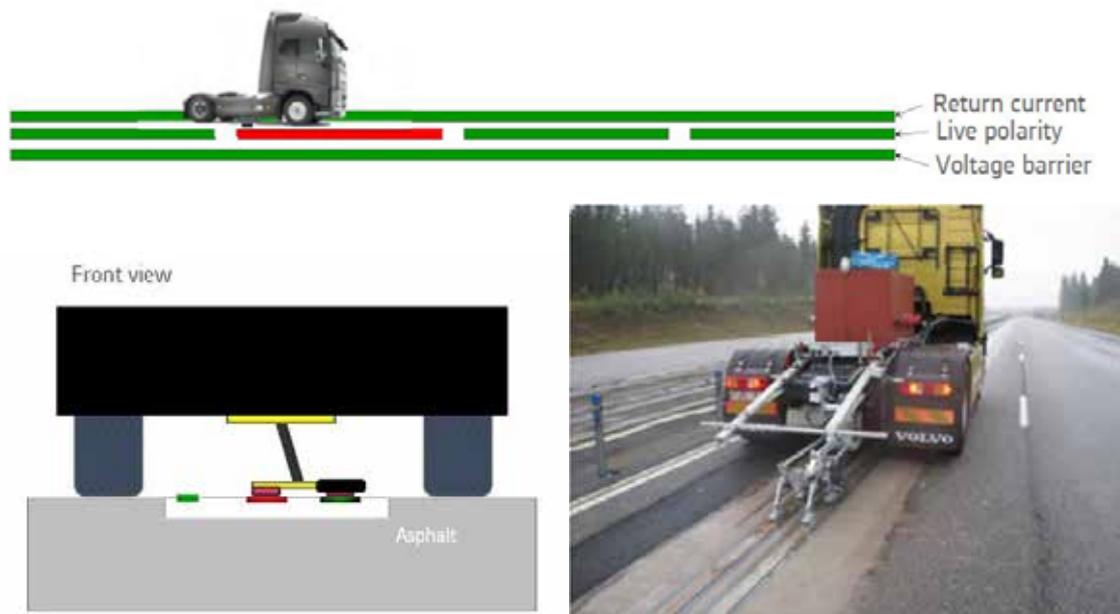


Figure 4-9 Schematic view of the three rails, cross section view of vehicle with a power take-off system when operating on the ERS, and picture of vehicle with double collector shoe during operation on an ERS test track [23]

Another adaptation considered for ERS applications compared to the tram systems, is that it can be relevant to use a third rail in the road surface as an additional grounded barrier between the energized conductor and the road surface. Thus, the road installation could have a structure as indicated in the upper part of Figure 4-9 [23]. As seen in this figure, the power-take-off-unit will only need contact with the sectioned conductor in the middle and the return conductor. It can also be understood that continuous power supply to the vehicle can be achieved if the power-take-off unit has a double set

of collector shoes with sufficient distance between the front and rear shoe to cover the gap between two consecutive segments of the energized conductor, as indicated by the picture in the lower right part of Figure 4-9.

It can be noted that the introduction of this technology for regular road traffic, potentially utilized by a wide range of vehicles, could imply a significantly higher frequency of use than for the tram application. This could lead to increased challenges related to wear and maintenance of the rail in the road surface. As most of the experience of the APS system for trams is from cities with relatively mild climate, there are also several uncertainties regarding how winter conditions with exposure to sand and salt will influence the wear of the road-side rails as well as the power take-off units onboard the vehicles.

### 4.3 Concept from Elways

Elways is a company started in Sweden by Gunnar Asplund with the purpose of developing a dedicated technology for dynamic conductive power supply to road vehicles [26]. Thus, their concept is developed solely with the purpose of supplying power to road vehicles while driving and do not rely on solutions and methods from other applications. As the system from Elways has been demonstrated with a test-track, the solution was considered in [9] to have reached a TRL level of at least 4 in 2016. With a demonstration facility on a public road constructed during 2017 and operation of a test vehicle started in 2018 [27], the concept can be considered to have reached at least TRL 6 with the expectation to reach TRL 7 during 2018. The main technical aspects related to the power transfer technology are summarized and illustrated in the following.

#### 4.3.1 General description of the Elways concept

The concept of Elways is to provide power from a rail embedded in the road surface. Thus, the energized conductor is only available below the road surface, while the openly exposed parts of the rail is grounded. Thus, the intention of the design is that it should be safe to walk on the road, and on the rail itself, even if the system is energized.

A generic cross-section view of a road with the Elways system installed is shown in Figure 4-10 [26], [28]. The figure shows one rail in each lane, as well as the cables for power distribution along the road. As indicated in the figure, the parts of the rail that are reaching the surface of the road are grounded. The slots in the rails for accessing the conducting bars are supposed to be narrow enough to prevent all contact with energized parts, beyond deliberate actions. According to information provided during a visit to the test site utilized by Elways at Rosersberg, the conductors are placed in the lower part of one side of the slot (and not at the bottom as indicated in Figure 4-10) [29]. Thus, also the bottom of the slots is grounded, and contact for effective power transfer should only be achieved with a specially designed power-take-off unit which enter the slots and has a spring-supported mechanism for applying appropriate contact pressure to the sides of the slots.

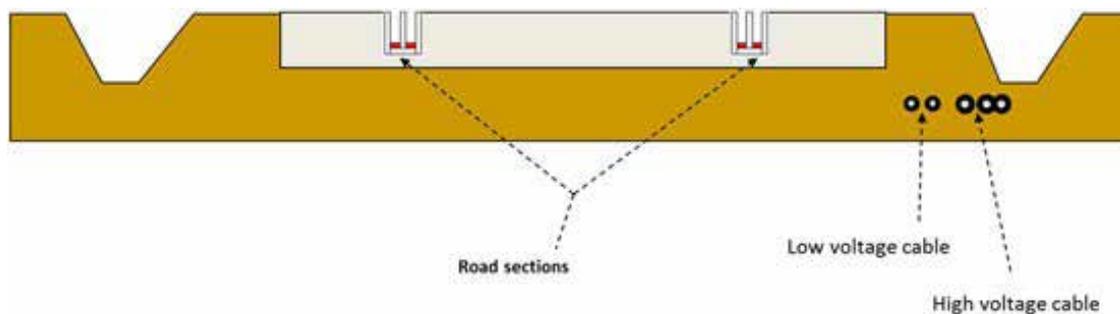


Figure 4-10 Cross-section of road with Elways' concept for power supply to moving vehicles [26]

### 4.3.2 Power distribution for the Elways concept

Since the system is designed for avoiding that energized conductors exposed on the road surface, it is not considered necessary with the same level of sectioning and on-lines supervision of the vehicles as for the ERS solution from Alstom. However, the rails are installed in sections of 50 m that are isolated from each other and supplied by a switch [29]. Thus, the sections should only be energized in case of arriving vehicles, but there will be more relaxed timing constraints for the operation of the switching compared to the ERS solution from Alstom. An overview of the power distribution system is shown in Figure 4-11. It can be noted that there is short isolated segment between the sections, but in a similar way as for the solution from Alstom, a power-take-off unit with two collector contacts at a distance larger than the isolated segment can probably ensure continuous power supply to a moving vehicle.

Each section of the rails is drained at the end, where also the power supply has to be connected, to avoid water accumulating in the slots. The system can also include heating of the rails if needed for liquifying snow or ice during winter conditions.

Contrary to the solutions from Siemens and Alstom, the concept developed by Elways is based on distribution of AC voltage to the moving vehicles. Currently a distribution voltage of about 800 V RMS is used [29], although it can be assumed that the system can be easily adapted to any relevant voltage level within the low voltage range (i.e. below 1000 V RMS). Thus, the power distribution system shown Figure 4-11 can be kept quite simple, with regular AC contactors or circuit breakers for connecting/disconnecting each section. This will also inherently allow for bidirectional power flow of each sub-station, if this is allowed at the interface of the high voltage distribution system. As for the other conductive solutions, it is assumed that the power rating can easily be scaled to reach the practical demand for each section. The distance between the transformer substations can also be relatively flexible and should depend mainly on issues related to cost and complexity of cabling and protection systems, but a distance of a few km between each transformer station is indicated by the designers of the system [29].

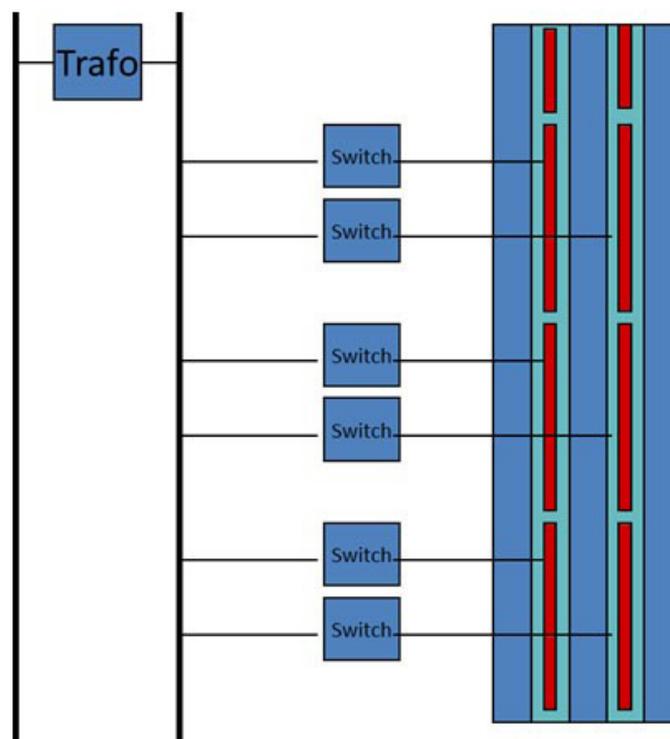


Figure 4-11 Power distribution system for rail sections of the solution from Elways [26]

Currently the system from Elways is designed for 200 kW power transfer per 50 m section. However, the power rating could be easily increased if that would be considered necessary. It can also be assumed that the system can be adapted for DC power supply if needed.

### 4.3.3 Power take-off and interface with vehicle propulsion system

As for the other rail-based systems for roadway power supply, the Elways concept depends on active positioning of the power-take-off unit. In this case, the positioning system must also be able to make the sliding contacts find and enter the slots in the rails. A picture showing the demonstration of one of the developed solutions when mounted on a regular car is presented in Figure 4-12. Further discussions of the challenges related to design and control of the positioning system are also available in [31], which is a student work resulting in another variety of the mechanical positioning system for the power-take-of unit as shown in Figure 4-13.

As already mentioned, the power-take-off-device must enter the slots of the rails, and the sliding contacts entering the slots must be designed to ensure good contact to the conducting bars in the rails without short-circuiting the energized elements to the grounded frame of the rails. There is not much public information available about the sliding contacts, but according to [29], the contacts elements are made of graphite and will be the main part of the system which will be exposed to wear during regular operation. Thus, the sliding contacts on the power-take-off unit mounted on the vehicles should be changed with regular intervals. This implies that they should be designed for easy replacement and low cost.



Figure 4-12 Demonstration of power transfer on the Elways test-track at Rosersberg [30]



Figure 4-13 Power-take-off unit with position control from a student project at Chalmers [31]

As mentioned, the Elways concept is based on distribution of AC voltage to the vehicles. This implies that there will have to be a single-phase rectifier designed for the full power transfer capability, and probably with galvanic isolation, on-board the vehicles. In general, the use of a single-phase AC supply can be considered a disadvantage for the power conversion system on-board the vehicles, since this implies the need for relatively large single-phase rectifiers in each vehicle. Such single-phase rectifiers will usually have lower power density and require more space on-board the vehicle than a DC-DC converter for interfacing between the propulsion system and a DC distribution system.

Until 2017, the demonstration site at Rosersberg was mainly operated with conventional vehicles where the actively controlled power-take-off unit and additional electric loads have been mounted on the vehicle just to demonstrate the power transfer capability. However, a demonstration project with an electric truck, with power supply from the system while operating in a regular traffic environment close to Arlanda in Sweden was constructed during 2017 and started regular operation in 2018. A modified DAF truck is used for this demonstration, equipped with on-board battery storage, an electric traction system based on individual motors for each wheel, and a power conversion system for interfacing to the power supply from the rails [29].

## 4.4 Concept from Elonroad

ElonRoad is a company started in Lund in Sweden with the purpose of developing technology for on-road power supply to electric vehicles. In the same way as for Elways, their concept is developed solely with the purpose of supplying power to road vehicles while driving and do not rely on solutions and methods from other applications. The solution from ElonRoad has been demonstrated in laboratory environments and is considered by [9] to have reached a TRL level of 3. However, a demonstration on a 120 m of test-track started operation during 2017, and this can be considered to have brought the technology to at least TRL 4. Currently, less technical information is available regarding the ElonRoad concept than the solutions from Alstom and Elways, but the technical concept is summarized and illustrated in the following.

### 4.4.1 General description of the ElonRoad concept

The concept of Elonroad is to provide power from rail sections mounted on the road surface. Thus, the general principles of the concept is similar to the ERS solution from Alstom. However, the design of the rail sections as well as the integration with the road surface is different. Pictures of the designed rail system are shown in Figure 4-14. The rails are about 5 cm high and 30 cm wide and are designed for being mounted on top of the road surface to ensure easy and less intrusive installation. The sides of the rails are inclined so that they can be smoothly crossed by vehicles changing lanes. Since the sections are placed on top of the road surface, it can be allowed for water to pass under the rails, as shown in the picture below [32].



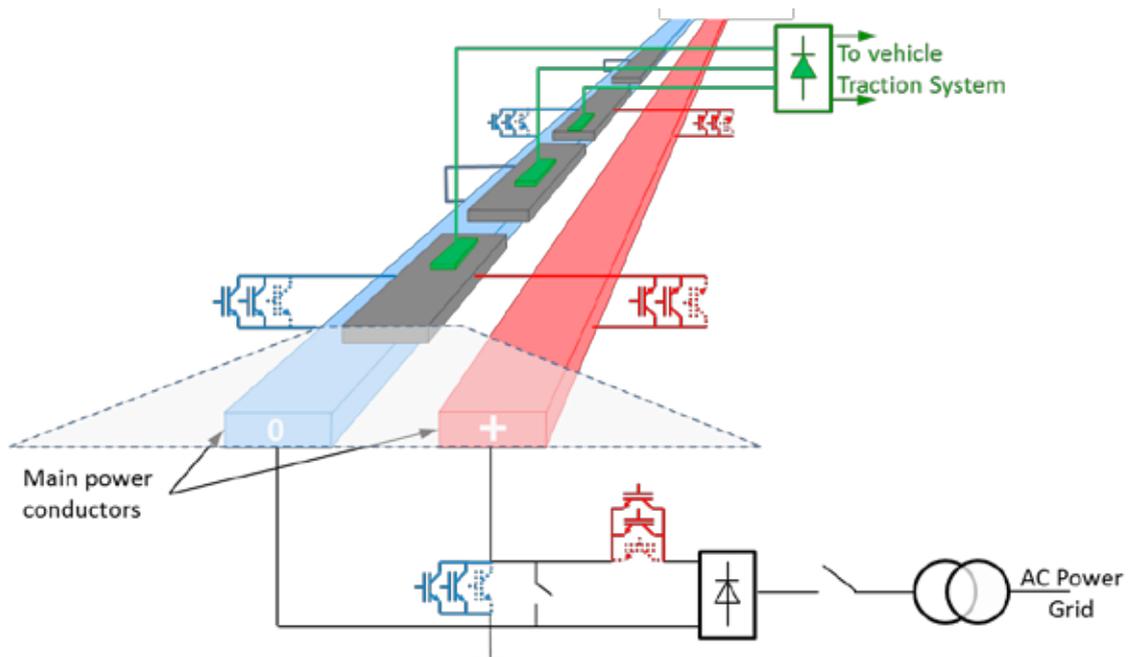
Figure 4-14 Conductive rail elements from Elonroad [32]

It can be noted that Elonroad is also considering a version of their technology that can be integrated in the road surface with only a very small elevation in the range of a few mm [25]. Thus, such a system might be expected to have a similar impact on the surface of the road as the concept from Alstom, but it might be expected to be less integrated in the cross section of the road and allow for a simpler installation.

#### 4.4.2 Power distribution for the Elonroad concept

Limited technical information has been publicly available regarding the power distribution system assumed for the concept from Elonroad. It is stated by [32] that every second section can provide a positive voltage when a car is passing over it. Thus, it might be assumed that every section before/after the active section will provide the ground return. Furthermore, it is assumed that a simpler activation mechanism than used in the concept from Alstom can be applied, and that there will be less need for integrating communication and detection systems in the solution.

According to [25], the contact surface of road-side sections from Elonroad consists of a series of 1 m. long contact surfaces with 15 cm isolation in between. Every second contact surface is always on ground potential. The other surfaces can be energized by semiconductor switches as the vehicles pass by, but are connected to ground in the absence of vehicles. The structure of the road-side sections is illustrated in Figure 4-15. The switching mechanism for the sections that can be energized are supplied from a busbar at 650 V DC [25].

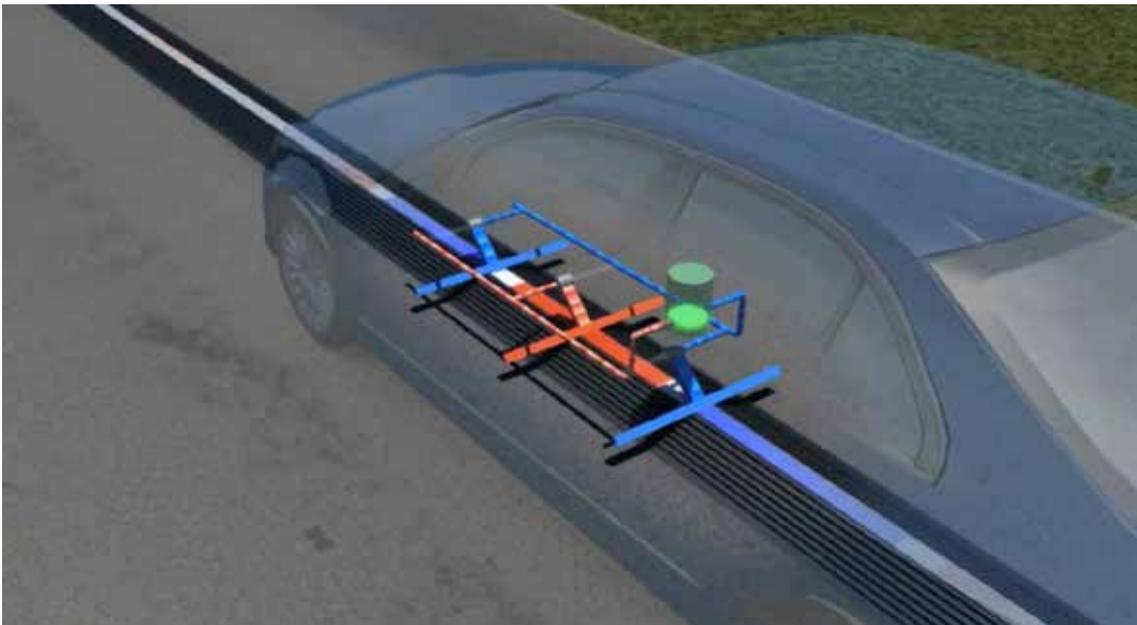


**Figure 4-15 Electrical schematic and power distribution strategy of the Elonroad concept [25]**

It is stated by [32], that the solution from Elonroad is designed for power transfer up to 240 kW per section. However, as for the other solutions for conductive power transfer, it should be possible to increase the power transfer capability by limited redesign, if necessary.

#### 4.4.3 Power take-off and interface with vehicle propulsion system

Limited information is available about the planned power-take-off system for the ElonRoad concept, and it is stated by [32], that the infrastructure is intended to be open for vehicle manufacturers to design their individual concepts and designs for power-take-off equipment. However, an indication of how the system could work is given by Figure 4-15 and Figure 4-16. As can be understood from Figure 4-15, each sliding contact of the power-take-off system will receive either 0 or 650 V DC, and the voltage at each contact will alternate as the vehicle moves. It is indicated that the on-board power take-off equipment will have three sliding contacts, and since each of these contacts will receive a square-wave voltage signal alternating between 0 and 650 V, there is a need for a "3-phase" rectifier onboard the vehicle [25].



**Figure 4-16 Illustration of power-take-off for a moving vehicle from the Elonroad concept [32]**

This illustration in Figure 4-16 seems to indicate that the use of single elevated conductor sections at 5 cm above the road surface can make it possible to design power-take-off systems with relatively wide sliding contacts. Due to the elevation and the fact that there will not be two conductors in parallel along the road, this solution could imply a lower need for active lateral position control of the power take-off units than for the solutions from Alstom. However, if small, narrow, sliding contacts are preferred from design considerations regarding space, weight and/or safety, similar requirements for active positioning of the power take-off system as for the concept from Alstom would be required.

## 4.5 Overview of research and demonstration activities on road-surface power supply

All the reviewed concepts for conductive dynamic power transfer from the road surface have been demonstrated in laboratory environments or on test-tracks, and further demonstration projects in public road environments are currently being planned. Below follows a summary of the ongoing demonstration activities:

### Alstom ERS

- The system was demonstrated on a test-track at Hällered in Sweden, in cooperation with Volvo, as part of the in Slide-in electric road system project [21], [23]. This demonstration was mainly based on equipment constructed for the tram application.
- Upgraded equipment with dedicated design of the rail sections for ERS applications are under construction by Alstom, and is intended for potential use in a demonstration project on a section of a highway in France during the coming years [23].
- Alstom is in cooperation with Volvo participating in an ERS project for busses under planning in Gothenburg [23].
- Alstom is participating in the preparations of a potential demonstration project in France referred to as EWAY Corridor Vallée de la Seine [23]. However, the technology to be selected for future demonstration is not confirmed.

### Elways

- The Elways concept has been demonstrated on a test-track at Rosersberg, close to Arlanda Airport, in Sweden [26], [28]. The test track was established with 200 m of rails in 2012, and extended with additional 150 m in 2015.
- A demonstration on a public road near Arlanda was constructed during 2017 and has started operation in 2018.

### Elonroad

- The concept from Elonroad has mainly been tested in a laboratory environment. However, a 120 m test-track is currently in operation outside Lund in Sweden
- Elonroad is involved in a testbed referred to as Electrivillage in Mariestad, Sweden, where the technology should be tested in a public road environment within a few years.

## 4.6 Summary of status for on-road power supply from rails

The status of technology for on-road power supply to moving vehicles can be summarized as:

- This class of technology is based on various concepts for integrating conductive rails in the road surface for utilizing sliding contacts to transfer power to moving vehicles. Although technology for sliding contacts is well established, the various concepts require different designs of the power-take-off units and have different approaches for ensuring safety by avoiding that energized conductors are exposed in areas with public access.
- All three reviewed concepts depend on relatively short sections for integration in the road surface, and corresponding mechanisms for energizing the system only when it should supply a moving vehicle. It can be assumed that the need for short sections will increase the cost and complexity of the power distribution system compared to solutions for overhead lines. The solution from Elways is designed to allow for the longest sections in the range of 50, while the solutions from Alstom are based on sections shorter than 10 m. The solution from Elonroad is based on very short sections with length of 1 m, but with alternating polarity along the road.
- The main functional difference of these concepts compared to solutions with overhead lines, is that they can be designed for operation with vehicles of various sizes. Thus, it should be possible to use the same infrastructure for cars, as well as for smaller delivery trucks and other small commercial vehicles, in addition to large vehicles with higher power demand, like busses and trucks for long-haul transport. However, it might be considered a disadvantage of the solution from Alstom that power transfer to the vehicle will only be allowed at speeds above a threshold value. Thus, the presented solution is mainly suitable for highway applications and cannot be

directly applied in street crossings or general city environments. However, by applying shorter sections, it might be possible to partially introduce the same system in city environments with lower vehicle speeds than assumed for highway applications

- All the three reviewed concepts have been demonstrated by experimental testing, although there are differences in the progress towards demonstration on public roads.
- The development of the concepts from Alstom and Elways have started earlier than the development of the Elonroad concept. Thus, more information and experience is currently available, and they have reached further in the progress towards practical demonstrations. Thus, the solutions from Alstom and Elways are currently considered to have TRL 4. However, they are assumed to reach at least TRL 6 as soon as practical demonstrations on public roads have been completed. Such testing of the Elways concept has started during 2018. The concept from Elonroad was considered to have TRL 3 in 2016, but successful demonstration on a test-track during 2017 has brought also this solution to TRL 4.
- A relevant challenge for utilizing the same concept for a wide range of different vehicles is expected to be the implementation and integration of the power-take-off units. The solution from Elways will require precise active position control for connecting to the infrastructure, but the sideways control might be relaxed or disabled during normal driving since the power take-off unit will be guided by the rail in the road. The solution from Alstom will depend on more accurate position control for the power take-off-units also during normal operation. The concept from Elonroad, depends on short conducting sections in the road-side rails which have alternating polarity and are elevated above the road surface. Since there will never be two parallel contacts in the road-side rail, this solution might allow for some flexibility towards identifying potential trade-offs between the width of the onboard sliding contact and the accuracy of the sideways position control since.
- In theory, all the three different concepts could be used by the same types of vehicles with slightly different interface of the sliding contacts on the power-take-off units. However, there is no standard or common agreement for the voltage and the electrical interface on the vehicles. The solution from Alstom is for instance based on distribution of 750 V DC to the vehicles, while the solution from Elonroad is distributing 650 V DC. However, it appears that Elways is distributing AC power to the vehicles. Although it can be assumed that the system from Elonroad can easily be adapted for 750 V, also this system needs a rectification from alternating voltage onboard the vehicle, due to the alternating polarity of the road-side sections. Thus, there might be different requirements for the power converter interfaces for integration with the on-board propulsion system and energy storage of the vehicles.
- The solutions with AC distribution can inherently allow for bidirectional power flow if allowed by the AC grid. However, AC distribution implies different requirements for the power conversion system on-board the vehicles. For the DC-based solution from Alstom, as well as for the system from Elonroad, it is assumed that some modifications will be needed for enabling bidirectional power flow at the substation level. However, bidirectional power flow would be only relevant under very specific conditions, which in practice would be associated with steep slopes and high traffic in only the downhill direction.
- No severe technical limitations related to the power transfer systems are foreseen for demonstration of the different concepts, as all functions required for operation can be achieved with conventional and available technology. Thus, it can also be expected that systems can be implemented in large scale if they will be sufficiently tested and demonstrated to comply with safety regulations and other public requirements, and if there will be acceptance for integrating required power-take-off-units on the vehicles to utilize the infrastructure.
- For application under winter conditions, and especially during Norwegian coastal climate, it can be assumed that the main concerns with all three solutions will be the integration in the road surface, and the reliability as well as the maintenance requirements under various road and weather conditions. Although solutions for handling snow and ice are considered in the design of the systems, it is not certain how the lifetime and reliability will be influenced by winter conditions and frost movements in the road, and/or by leakage currents and increased corrosion due to salt on the road surface.

## 5 Power transfer from conducting rails along the road-side

In addition to the concepts presented for power supply from overhead lines or from conductive rails integrated in the road surface, Honda in Japan has also recently presented a system for conductive power transfer from a rail integrated in the safety fence along highways. This concept has until now been mainly presented in Japanese, so there is limited information available in English. However the main concept is briefly introduced in the following, based on two available publications presented in English within the Society of Automotive Engineers (SAE) [33], [34].

### 5.1 General description of concept proposed by Honda

The concept under development by Honda is based on power take-off with a mechanically controlled arm that can be extended from the vehicle to the power supply rail integrated in the safety fence along the road, as shown in Figure 5-1. A more detailed illustration of the power take-off system is shown in Figure 5-2.



Figure 5-1 Pictures of dynamic charging system developed by Honda when installed on an electric vehicle in operation on a test track [34], [35]

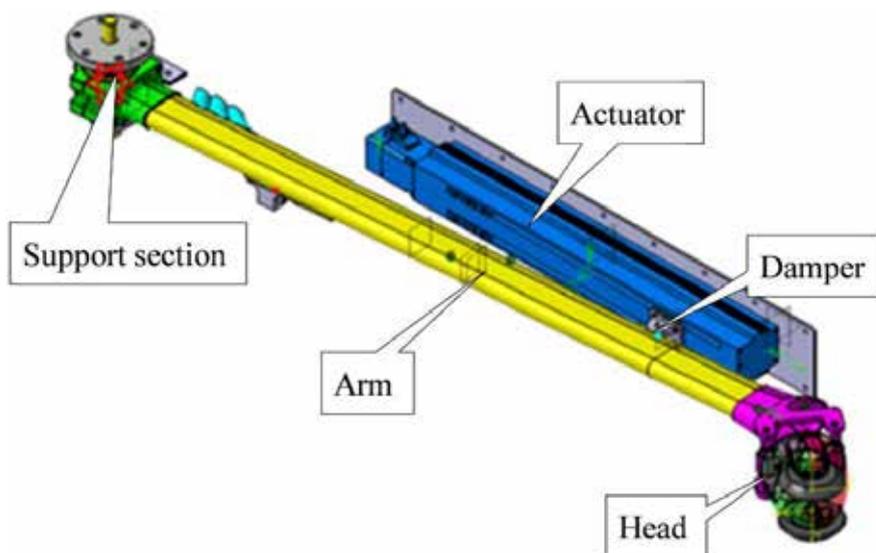


Figure 5-2 Power take-off system developed by Honda for integration in light electric vehicles for dynamic transfer of power during high speed driving [34]

As for all the other concepts for dynamic conductive power transfer, the power take-off system needs to establish a sliding contact with two conductors. In this case, the contact point is two rolling contacts (referred to as "twin roller") with a conic shape which helps to self-align the position of the power take-off arm when it is pushed towards the conducting rails integrated in the safety fence, as shown in the more detailed illustration in the left part of Figure 5-3. A picture of the contact point or "head" of the power take-off arm is shown to the right hand side of Figure 5-3. The rolling contact points are connected to the main conductors of the power take-off arm by regular brushes.

From the available descriptions and pictures, there does not seem to be any regulation of the vertical position of the power take-off arm, as it seems to be integrated in the car with a fixed position and some flexibility to adapt to the vertical position according to the mechanical guidance structure. Thus the system does not seem to be explicitly designed for vehicles with significant variation in suspension load (i.e. large difference in ground clearance between fully loaded or empty vehicle) or with significant suspension movements during regular driving. This seem to make the control of the power take-off system simpler but less flexible than for the concepts with conducting rails in the road surface. However, systems with vertical position control could be easily developed, resulting in a system with similar complexity and challenges of position control as for the systems with power take-off under/below the vehicle.



**Figure 5-3** Illustration of two-phase sliding for power supply from the side of the road, [34], and closer picture of the power take-off unit when in operation [33]

Beyond the explanations and illustrations in [33], [34], very limited information is available in English regarding the design considerations of the stationary infrastructure integrated in the safety fence and the construction of the power take-system. However, the conducting rails in the safety fence are most likely based on very similar considerations as for the overhead lines in terms of dimensioning as well as wear and tear. It should also be mentioned that the location on the side of the road and the elevation from the road surface should ensure less problems with wear and tear due to pollutions like sand and dust on the road, and would avoid any problems with operation due to water on the road surface. Furthermore, it is a significant advantage that the concept does not depend on integration in the road surface, which could ease installation and avoid that the infrastructure causes problems and significantly increased maintenance cost for the road. Thus, the system could be expected to be more reliable than the system integrated in the road surface, although safety aspect could be questionable since the conductors on the side of the road will be relatively easily accessible.

## 5.2 Overview of research and demonstration activities

Very limited information is available in English regarding the plans for demonstration and further development of the concept promoted by Honda. From the available publications, it is clear that the system has been implemented on a relatively long test track and has been integrated in several electric vehicle prototypes, allowing for testing the system during driving at high speed. According to [34], the system has been tested for a distance of at about 300 m at various speeds, up to a maximum speed of 156 km/h. However, no information is available about any future plans for qualification and full-scale demonstration on a public road section.

It should also be mentioned that the results presented by Honda have been obtained with a regular electric vehicle (i.e. a passenger car), and that the available information does not discuss in detail the application for heavy vehicles and freight transport. However, the intention seems to be to develop a system with capability for supplying high power levels at high speeds, which would make the system generally applicable for heavy duty transport.

## 5.3 Power conversion and distribution system for rail by the side of the road

The system proposed by Honda has been presented with gradually increasing power levels. The initial proposal seems to have been designed for 100 kW power supply capacity with a dc-voltage of 375 V, and with vehicle speeds up to 70 km/h. However, the results from the demonstration activity presented in [34] are obtained with a system designed for supplying 180 kW to the vehicle at 600 V dc, for speeds up to 156 km/h. Furthermore, the development target presented in [34] is a system capable of supplying 450 kW to a vehicle at 750 V dc, for speeds up to 200 km/h. The power conversion stages in such systems will be the same as for all other solutions based on dc power distribution and will not be discussed in further detail here.

It can be noted that some details regarding the power supply system used for the demonstration facility used to obtain the documented results are included in [34]. This system seems to be based on a large-scale stationary battery storage system capable of supplying high power to the moving vehicle. However, this can be assumed to be a solution chosen for practical reasons at the test site, since supply of high power to the vehicle is demonstrated with only one vehicle for short periods of times. Thus, there could be no need for a full-scale installation with a continuous capacity of power supply from the main power system equal to the maximum power transfer capability to the vehicle. However, if such a system should be installed on a public road with multiple users, it would be expected that the power distribution system and the integration with the high voltage distribution network would be very similar to what has been discussed for the other solutions.

## 5.4 Summary of status for conductive rail by the side of the road

The status of technology for power supply to moving vehicles from conducting rails integrated at the side of the road can be summarized as:

- The technology is based on conventional and well-proven concepts, although it relies on a position controlled arm for the power take-off
- The technology has been demonstrated by Honda in Japan on a dedicated test-site.
- Limited information is available in English, but the concept has been demonstrated only for small EVs. However, the development target for the concept is to reach a power capability of 450 kW which would also be in the suitable range for heavy duty vehicles.
- It is expected that such systems can be quickly implemented if there is will for investment
- A main disadvantage is expected to be safety issues related to energized conductors that will most likely be easily accessible along the road.

## 6 Comparative evaluation of concepts for dynamic conductive power transfer

A brief comparison of the advantages and disadvantages for the various concepts for conductive dynamic power transfer is shown in Table 6.1 together with a summary of the technology status. It should be noted that this simple evaluation is mainly based on considerations regarding the technology for power transfer and the practical applicability of such systems in various vehicles. Issues related to practical integration along the road, including challenges in construction, operation and maintenance of roads with such infrastructure will be considered in a separate memo within the ELinGO-project.

**Table 6-1 Comparative evaluation of concepts for dynamic conductive power transfer**

	Advantages	Disadvantages	Technology status
Overhead lines – Siemens	<ul style="list-style-type: none"> <li>- Simple system</li> <li>- Based on mature technology</li> <li>- No impact on road surface</li> <li>- Proven operation under wide range of weather and climate conditions</li> </ul>	<ul style="list-style-type: none"> <li>- Only suitable for large vehicles</li> <li>- Visual impact</li> <li>- Active positioning of power-take-off</li> </ul>	<ul style="list-style-type: none"> <li>- Ready for utilization</li> <li>- TRL 7 by 2018 and no technical obstacles expected to reach 8/9</li> <li>- Low risk for pilot projects</li> </ul>
Rail solution – Alstom EPS	<ul style="list-style-type: none"> <li>- Limited visual impact</li> <li>- Experience with similar technology for trams</li> <li>- Can be used for smaller vehicles</li> </ul>	<ul style="list-style-type: none"> <li>- Energized conductor in road surface</li> <li>- Short rail sections and high number of switches</li> <li>- Complicated system for energization according to vehicle position</li> <li>- Need for active positioning of power take-off unit</li> <li>- Concerns regarding reliability and maintenance requirements</li> <li>- Low friction on conductors</li> </ul>	<ul style="list-style-type: none"> <li>- Based on available components</li> <li>- Currently around TRL 4</li> <li>- Adaptations needed for large-scale utilization</li> <li>- Uncertain reliability in Norwegian conditions</li> <li>- Limited design possibilities for avoiding increased wear of conductors and road surface during winter conditions</li> </ul>
Rail solution – Elways	<ul style="list-style-type: none"> <li>- Limited visual impact</li> <li>- Can be used for smaller vehicles</li> <li>- No energized conductors at road surface</li> <li>- Based on simple and rugged components</li> </ul>	<ul style="list-style-type: none"> <li>- Need active positioning for connecting to road-integrated rail</li> <li>- High expected wear on vehicle-side conductor</li> <li>- Concerns regarding reliability and maintenance requirements</li> </ul>	<ul style="list-style-type: none"> <li>- Based on simple technology</li> <li>- Currently around TRL 6</li> <li>- Uncertain reliability in Norwegian conditions, especially in case of salty and humid environment</li> </ul>
Rail solution – Elonroad	<ul style="list-style-type: none"> <li>- Limited visual impact</li> <li>- Only single sliding contact in the road surface with alternating polarity for each section</li> <li>- Limited need for integration in the cross-section of the road</li> <li>- Potentially limited need for sideways positioning of power take-off units</li> </ul>	<ul style="list-style-type: none"> <li>- Energized conductor in road surface</li> <li>- Short rail sections and high number of switches</li> <li>- Concerns regarding reliability and maintenance requirements</li> </ul>	<ul style="list-style-type: none"> <li>- Currently TRL 4</li> <li>- Further trials expected</li> <li>- Uncertain reliability in Norwegian conditions</li> </ul>
Rail solution – Honda	<ul style="list-style-type: none"> <li>- Similar advantages as surface-integrated solutions in terms of applicability and efficiency</li> <li>- No installation in the road surface</li> <li>- Potentially simpler position control of power take-off system</li> <li>- Possibly longer sections</li> </ul>	<ul style="list-style-type: none"> <li>- Safety in case long sections are energized</li> <li>- Safety issues related to arm for power-take-off</li> </ul>	<ul style="list-style-type: none"> <li>- Demonstrated on dedicated test-track</li> <li>- Limited information available in English</li> <li>- Main concerns are related to safety and practical applicability</li> </ul>

## Part II - Technologies for Dynamic Inductive Power Transfer

### 7 Introduction to technologies for dynamic contactless power transfer

Currently, several different concepts and design approaches are being pursued for obtaining technology for dynamic contactless power transfer that do not depend on a mechanical and electrical contact point between the moving vehicle and the infrastructure. In general, contactless transfer of electric power can be based on magnetic fields (i.e. inductive power transfer) or electric fields (i.e. capacitive power transfer). Since solutions for capacitive power transfer will usually have lower power capacity and/or require significantly shorter mechanical distances between the transmitting and receiving sides, they are usually not considered for high power contactless solutions intended for electric vehicles. However, it can be mentioned that hybrid solutions with combined inductive and capacitive power transfer have been recently proposed for stationary contactless battery charging of electric vehicles [36]. It should also be noted that some technologies for wireless or contactless power transfer are referred to as coupled magnetic resonance systems. However, it has been demonstrated that such systems can be considered as a special case of inductive power transfer. Furthermore, the concepts based on considerations of magnetic resonance are usually designed so that they require more space and volume than can be conveniently integrated in electric vehicles. Indeed, all the concepts that have been demonstrated for dynamic contactless power transfer in applications for electrification of transport are based on the principles of inductive power transfer. Thus, only such solutions will be discussed in the following.

The various solutions for dynamic inductive power transfer that have been proposed in scientific literature and/or have been developed towards practical demonstration systems are based on several different design strategies and system configurations. It is also difficult to find a clear and general classification of concepts for dynamic inductive power transfer, since such a classification will mainly depend on which part of the system is considered. However, the common feature of all these systems is that they share the same basic functionality of contactless inductive power transfer and usually have the same main elements, as briefly reviewed in the following

#### 7.1 Basic functionality of inductive power transfer

A simplified sketch of a general system for inductive power transfer to an electric vehicle is shown in Figure 7-1. The basic principle of the power transfer is that current in a coil integrated in/below the road surface generates a magnetic field. The magnetic coupling (i.e. mutual inductance) between the transmitting coil in the road and the receiving coil integrated in the vehicle determines to which extent this field influences the receiving coil. The rate of change of the magnetic field generated by the transmitting coil generates a voltage in the receiving coil, which drives the current into the on-board power conversion system and by that transfers electric power to the vehicle. Due to the coupling between the coils, the current in the receiving coil is also influencing the magnetic field and generates a counter-induced voltage in the transmitting coil. Thus, the system operates with alternating currents (AC), and the frequency of operation has significant impact on the design and power transfer capability of such a system.

In general, the physical principles determining the operation of inductive power transfer systems are the same as for a conventional transformer, with the main difference that the coupling between the transmitting and receiving coils is much lower than in a conventional transformer for power system applications due to the significant airgap between the two coils. A discussion of the basic principles for wireless inductive power transfer in electric vehicle applications, including the basic equations for analysing an inductive power transfer system in a similar way as a transformer, is presented in [38].

More information about the historical background of dynamic inductive power transfer systems for moving vehicles and how this general idea and its basic system configuration can be traced back to the 1890s is available in [39], [40], [41] [42]. A range of other potential applications of technology for inductive power transfer are also discussed in [42].

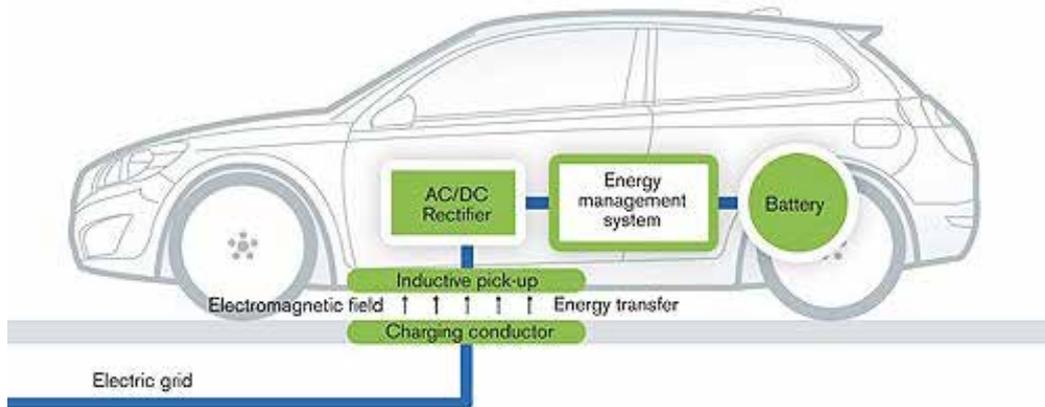


Figure 7-1 General illustration of concept for inductive power transfer to an electric vehicle [37]

## 7.2 Main elements of inductive power transfer systems

An illustration identifying the main elements of a system for dynamic inductive power transfer to an electric vehicle is shown in Figure 7-2. This figure indicates how such a system usually will have a larger area of transmitting coils integrated in the road, and a smaller receiving coil integrated in the vehicle. The figure also indicates how such a system depends on power electronic converters for regulating the power transfer and that the system includes a capacitive compensation network on both sides of the airgap

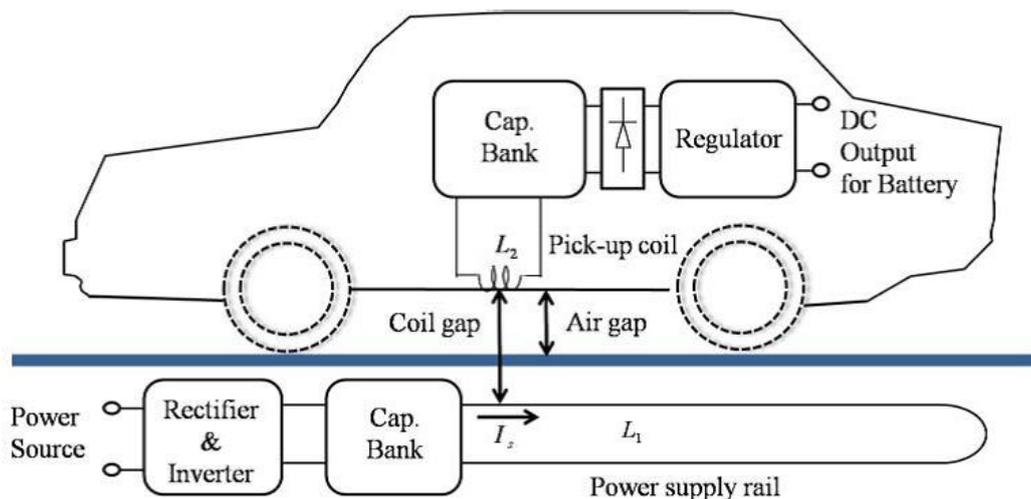


Figure 7-2 General overview of system for inductive power transfer to an electric vehicle [40]

The capacitor banks indicated in Figure 7-2 are usually necessary in systems for contactless inductive power transfer due to the large airgap between the transmitting and receiving coils. Since the large airgap causes a relatively low magnetic coupling between the coils, only a part of the magnetic field generated by a coil can contribute to the power transfer. Compared to a traditional transformer, this

implies that the magnetizing inductance becomes relatively low and the leakage inductance becomes high. Therefore, the inductive power transfer between the coils will consume a significant amount of reactive power, which corresponds to a significant phase shift between the voltage at the terminals of the coils and the current flowing in the coils. The reactive power required by the coils, and the corresponding reactive current, must be supplied by the source and/or the load-side to support the power transfer across the airgap. If this reactive power should be supplied by the power converters on the transmitting and/or receiving sides, the required current rating and resulting cost of the converters would increase correspondingly. Thus, the reactive power is usually supplied by capacitors. The capacitors are usually designed according to the equivalent inductance of the coils on each side of the system to obtain a specific resonance frequency, where the reactive power supplied by the capacitors is equal to the reactive power consumed by the coils for inductive power transfer. When the system is operated at this frequency, the resonance in the system will ensure that the currents at each side of the system can be kept in phase with the voltage (i.e. unity power factor operation), which eliminates the need for supplying reactive power from the converters in the system. The resonance between the coil inductance and the capacitors also reduces the equivalent impedance between the sending and receiving sides of the system, which is also helping to increase the power transfer capability compared to an un-compensated system.

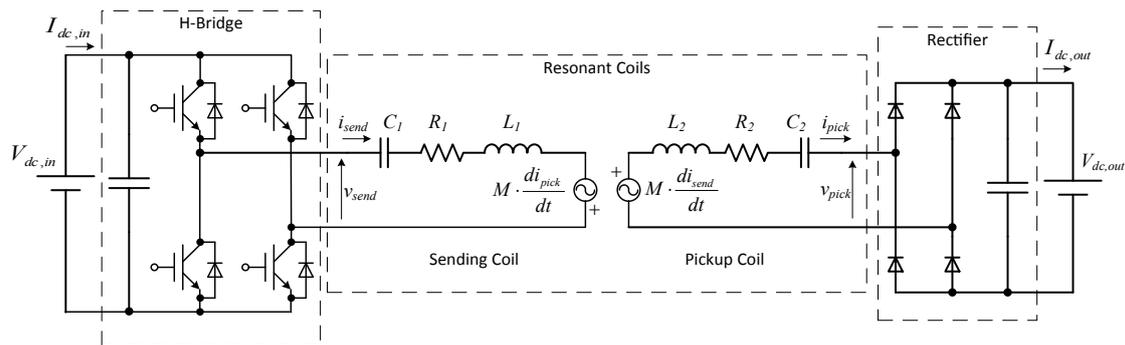
The capacitive compensation networks of systems for inductive power transfer can be configured in several different ways, and the selection of the most suitable configuration also depends on the topology of the power electronic converters in the system as well as the application the system is designed for. For the simplest and most basic compensation network, the main choice is to determine if the compensating capacitor is connected in series or in parallel with the coils. Considering that there should be a compensation network on both sides of the system, there are four basic options for design of the compensation network: Series-Series (SS) compensation, Series-Parallel (SP) compensation, Parallel-Series (PS) compensation and Parallel-Parallel (PP) compensation [43]. However, a large range of higher order compensation networks, containing multiple capacitors and/or inductors for interfacing to various types of converter topologies, have been studied, as for instance discussed in [44].

Although there are several options for the design and selection of compensation networks and power electronic converters for inductive power transfer systems, a simple system configuration with SS-compensation is often found to be the most suitable. The SS-compensation network is inherently suitable for interfacing with the most common power electronic converter structures, based on Voltage Source Converter (VSC) topologies. Furthermore, since the SS-compensation supplies reactive power in series with the coils for the inductive power transfer, this configuration implies that the coils will operate with the same current but have a higher terminal voltage than the power converters controlling the system. Thus, the system can be based on standardized low-voltage VSC converters for controlling the operation and the power flow of the system, while the coils and compensating capacitors are designed for higher voltages. Since there are not significant problems in increasing the voltage rating of the insulation for the coils and capacitors, and the higher voltage imply thinner copper wires while the cost and losses of power electronic converters for high frequency operation is usually lower for low voltage ratings, the SS-compensation topology can lead to suitable design trade-offs for the overall system.

As an example, the detailed topology of an inductive power transfer system with SS-compensation is shown in Figure 7-3. This figure shows how the capacitors on both sides of the system are connected in series with the coils. The sending-side coil is in this case supplied by a conventional voltage source converter, which is a two-level H-bridge configuration with the same topology as commonly used for a wide range of other applications. For high power systems, the H-bridge converter will be usually designed with Si-based Insulated Gate Bipolar Transistors (IGBTs), while systems with lower power and voltage rating will often utilize Metal-Oxide Semiconductor Field Effect Transistors (MOSFET). However, MOSFET devices based on Silicon Carbide (SiC) with similar voltage rating as Si

IGBTs and lower losses are currently emerging, and are expected to become applicable for reducing losses in various applications of inductive power transfer.

In the case shown in Figure 7-3, the converter on the receiving side is a passive diode rectifier, but a similar H-bridge as on the sending side could also be used on-board the vehicle if it is desirable to have active control also on the receiving side. Alternatively, a DC-DC converter could be introduced between the terminals of the diode rectifier and the on-board dc-bus or battery storage system.



**Figure 7-3 Inductive power transfer system with SS-compensation supplied by a H-bridge VSC and operated with a passive diode rectifier on the receiving side**

### 7.3 General challenges and design trade-offs for dynamic inductive power transfer

In general, the topologies and principles of operation for stationary and dynamic inductive power transfer systems are very similar. However, systems for dynamic inductive power transfer impose some specific conditions and challenges compared to stationary applications. Some of the more specific design options relate to the integration in the road structure, the selection of coil layouts in the road and how the system can be designed that can allow for simple and cost-effective construction and installation. However, the most suitable solution for such detailed issues depends on many aspects, and there is currently a continuous and rapidly progressing development in components, materials and design methods for such systems which can significantly influence the cost and design trade-offs of such systems. Thus, detailed discussion of such issues is beyond the scope of this document. However, the general challenges that all systems for dynamic inductive power transfer will meet is the selection of how long each coil section in the road should be, how power should be distributed to each section and how the control of the system should be organized to ensure that regulations for emissions of electromagnetic fields are respected while losses of the system are minimized. An illustration of a configuration for one coil section when supplying one vehicle is shown in Figure 7-4, for one of the solutions discussed in [41]. As seen in the figure, the system contains the same main elements as the more generalized structure shown in Figure 7-2. However, considering a case with multiple vehicles on a road with inductive power transfer capability, Figure 7-5 indicates how different lengths of the primary coils in the road will influence the integration with the vehicles. The figure also indicates that there will be trade-offs regarding the length of the road-side coils as well as how large share of the road distance that should be equipped with inductive power transfer capability. Indeed, it is possible to integrate road-side coils in most of the road distance, but this will lead to high cost of installation. Considering that the vehicles in any case will have a certain on-board energy storage, it could be cost-effective to install infrastructure for dynamic inductive power transfer in only parts of the road distance. However, integration of coils in a lower share of the road distance will lead to increased power rating of the coils to be installed, since the same energy will have to be effectively transferred during a shorter distance and a shorter time.

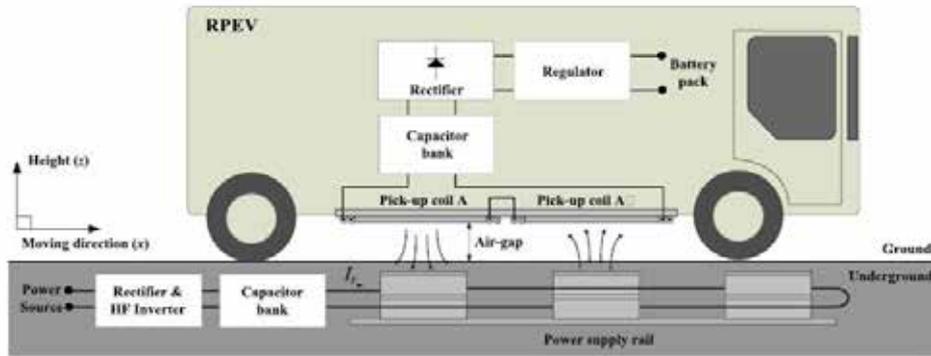


Figure 7-4 General overview of system for inductive power transfer to an electric vehicle [41] (RPEV refers to "Roadway Powered Electric Vehicle")

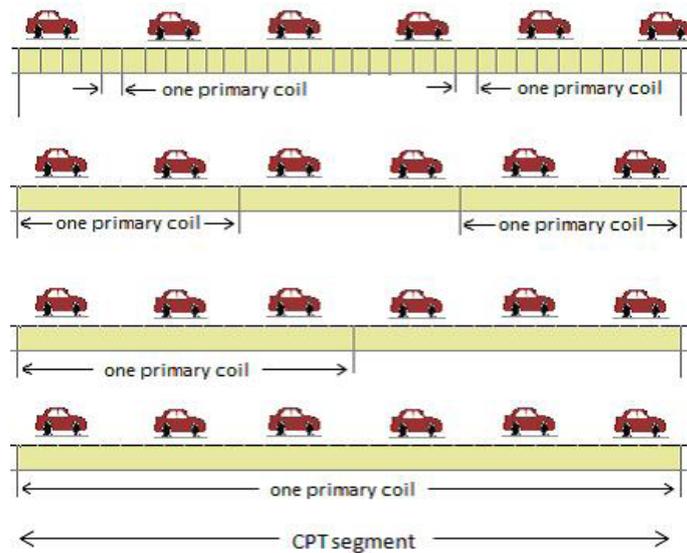


Figure 7-5 Illustration of integration with traffic for various lengths of road-side coils [45]

Indeed, systems with very short coils will ensure that each coil will only supply one vehicle at the time. For longer coil sections in the road, more vehicles can be supplied from the same section. In general, the solution with very short coils can achieve high efficiency for power transfer when the vehicle is in the position directly above the ground coil. However, the speed of the vehicle will imply that limited energy will be transferred from each ground-side coil to the vehicle, and that the vehicle will be in the position that allows for maximum power transfer in a very short time. This also implies that power will only be transferred to each vehicle in short pulses, and each road-side coil will also supply only short pulses of power. Furthermore, the use of many small coils will imply a higher need for copper in the road-side coils than longer coils that can provide power transfer to the same vehicle for a longer time. On the other hand, very long coil sections will imply that long sections of the road will be magnetized without any vehicle to receive power. This will lead to higher losses since current will flow in long distances without transferring power, and can also lead to concerns about compliance with requirements for electromagnetic regulations in the parts of the road where there is no vehicle receiving power. In general, it can be possible to optimize the length of the road-side coils, as discussed in [46]. However, the most suitable length will depend on the expected speed of the vehicles, the selected coil configuration, the operating frequency, the power transfer requirements and several other design trade-offs for the overall system. Thus, it is expected that the ongoing progress in research and development of components and system solutions for dynamic inductive power transfer will significantly influence the results of such optimizations during the coming years, and it is difficult to draw a simple conclusion regarding what can become a preferable solution.

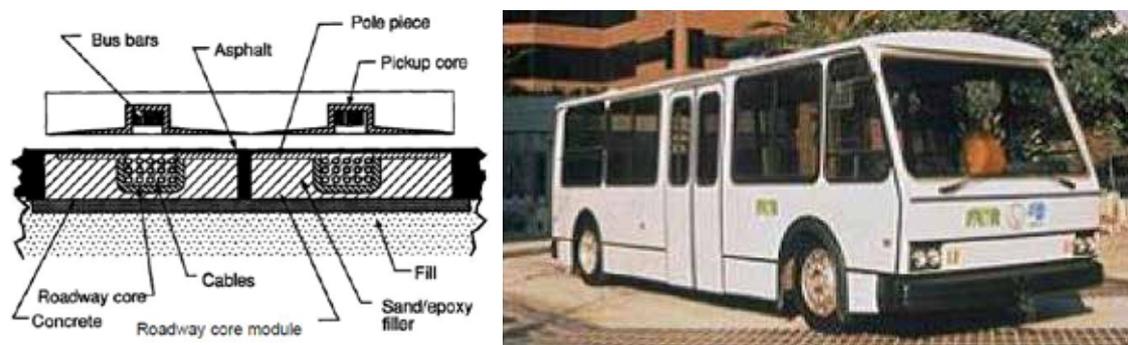
## 8 Overview of major research activities and demonstration projects

In general, numerous academic and industrial research groups are currently pursuing various concepts for dynamic inductive power transfer, and several companies have started to promote different solutions. A relatively updated overview of the most significant research activities and initiatives is presented in [40], [41], and a comprehensive list of demonstration projects in Europe related to dynamic charging systems and/or opportunity charging along the routes of public transportation systems is presented in [47]. However, a summary and description of the main research activities is presented in the following to give more overview and easier access to information within the ELinGO-project.

### 8.1 Origin of modern research activities on dynamic inductive power transfer

A review of the historical background for development of dynamic inductive charging systems is presented in [40], [41], showing how the general idea behind this concept can be traced back to a patent from 1894. However, it would pass a long time before the general technology development led to the availability of the power electronic technology and digital control techniques which systems for inductive power transfer depend upon today.

The first steps towards modern research activities on dynamic inductive power transfer were initiated in California around 1976 by the Lawrence Berkeley National Laboratory, motivated by the oil crisis in the 1970s [40]. This initial activity led to the design of an 8 kW prototype intended for a car, but was not developed into a fully operational system. The activity was later continued into "the Santa Barbara Electric Bus Project" in 1979 [40], but after these first initiatives, very limited research activities were conducted on dynamic inductive charging for the next 15 years. However from 1992, The University of California, Berkeley, hosted a program for "Partner for Advanced Transit and Highways (PATH)," which resumed the research activities on dynamic inductive charging. This program led to the development of a system with a rating of 60 kW with 7.6 cm airgap, operating at 400 Hz. The system reached a power transfer efficiency of about 60 %, and experienced several practical limitations and problems, mainly due to the relatively low operating frequency of 400 Hz which led to heavy on-board coils and significant acoustic noise. A very high excitation current was also needed in the road-side installation due to the low operating frequency, which contributed to the relatively low efficiency of the system.



**Figure 8-1** Cross-section of system for dynamic inductive power transfer, and picture of the first operational prototype bus tested for the system [48], [40]

In parallel to the activities in California in the early 1990s, significant research activities on inductive power transfer were started by Prof. John T. Boys at the University of Auckland, New Zealand. The initial research activities within this group were dedicated towards material handling and factory

automation systems, as discussed in [49]. The applications in factory automation have been commercialized by Daifuku in Japan and by Conductix Wampfler in Germany. Later, significant research activities related to stationary charging of electric vehicles have been pursued, and the commercialized factory automation system from Conductix Wampfler seemed to have formed the basis for the system for in-route (opportunity) charging of busses deployed in Torino and Genoa, Italy, since 2002 [50]. Thus, a dominant part of the initial research activities on electric vehicles at the University of Auckland were focussed towards stationary charging systems, and these initial developments are not further reviewed in the setting of the ELinGO-project.

## 8.2 KAIST and the Korean Railroad Research Institute

A significant research and development effort related to dynamic inductive charging was initiated in South Korea from around 2008. The activity, which was started by the research group of Prof. C. T. Rim at KAIST, has led to several demonstration projects and also deployment of vehicles in operation in several cities in South Korea. Thus, the technology has partly and gradually been transferred to the company "Green Power" [51], which is responsible for the commercial development and construction of systems based on this technology.

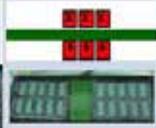
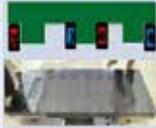
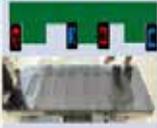
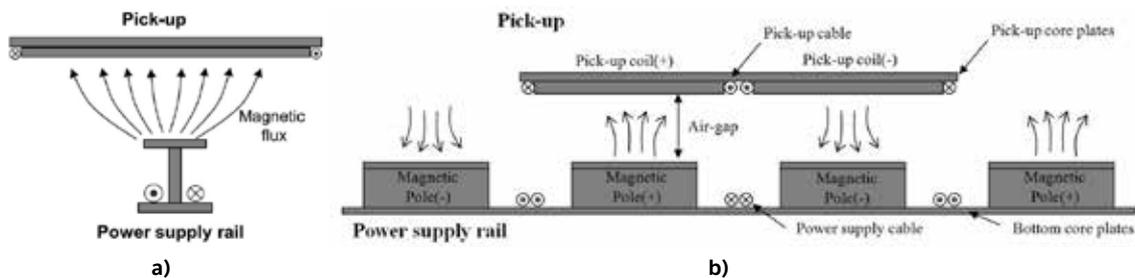
	1 G (Car)	2 G (Bus)	3 G (SUV)	3* G (Bus)	3* G (Train)	4 G (Bus)
Date	Feb. 27, 2009	July 14, 2009	Aug. 14, 2009	Jan. 31, 2010	Mar. 9, 2010	2010– (under development)
Vehicle						
System Spec.	air-gap= 1cm efficiency= 80%	air-gap= 17cm efficiency= 72%	air-gap= 17cm efficiency= 71%	air-gap= 20cm Efficiency=83%	air-gap= 12cm efficiency= 74%	air-gap= 20cm, efficiency= 80%
	All the efficiencies are measured by AC grid voltage to on-board battery terminals					
EMF	10mG	51mG	50mG	50mG	50mG	<10mG
Power Rail (width)	 20cm	 140cm	 80cm	 80cm	 80cm	 10cm
Pick-up						
Power	3kW / pick-up	6kW / pick-up	15kW / pick-up	15kW / pick-up	15kW / pick-up	25kW / pick-up
Weight (Pick-up)	20kg	80kg	110kg	110kg	110kg	80kg
Size	55x18x4 cm <sup>3</sup>	160x60x11 cm <sup>3</sup>	170x80x8 cm <sup>3</sup>	170x80x8 cm <sup>3</sup>	170x80x8 cm <sup>3</sup>	80x100x8 cm <sup>3</sup>

Figure 8-2 Overview of the first 4 generations of developed OLEV concepts by KAIST [40]

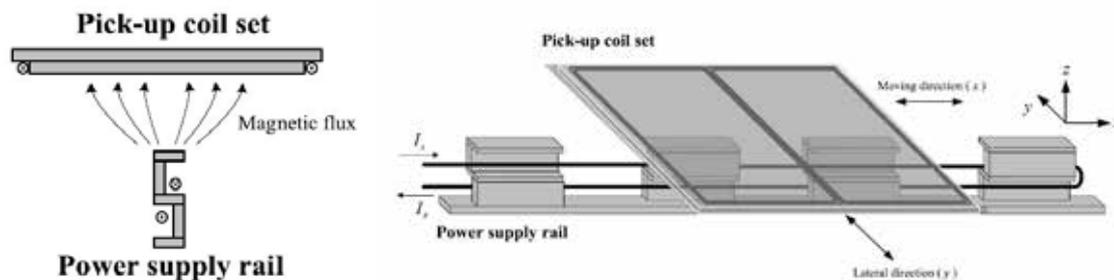
The OLEV concept has been developed in several generations, as reviewed in [40], [41], where various solutions for the road-side installation have been pursued, resulting in various characteristics and performances. An overview of key information regarding the first 4 generations of OLEV technology is presented in Figure 8-2 [40]. Among these various designs, the case referred to as 3+G has been utilized in at least 6 busses which are currently in regular operation, and in 3 light rail trains which operate in the Seoul Grand Park. The same concept has also been further developed in cooperation with the Korean Railroad Research Institute (KRRRI) to reach a power level of about 800 kW, which has been demonstrated for the potential application of a high-speed train [52].

The third generation OLEV concepts are based on road-side sections with an E-type (or W-shaped) magnetic core, as illustrated in Figure 8-2. However, the 4th and 5th generation of OLEV technology developed by KAIST are based on a different approach for road-side coil design, with relatively short sections having alternating polarity, as also sketched in the rightmost column in Figure 8-2. A more detailed illustration of this system, with what is referred to as I-type supply rail, is shown in Figure 8-3. The main motivation of pursuing this system configuration instead of the more traditional E- (or W-) core design approach, has been to obtain a very narrow installation in the road. This is argued to ensure simpler and faster installation in the road and a lower cost of the overall system.



**Figure 8-3 Schematic illustration of 4<sup>th</sup> generation OLEV technology based on I-type power supply rail with alternating polarity, shown as a) cross-section of the system and b) view from the side [40]**

A further development of the concept from the 4<sup>th</sup> generation of OLEV technology has been presented as a 5<sup>th</sup> generation, based on what is referred to as an S-type power rail. This concept is illustrated in Figure 8-4, where it can be seen that the name refers to the cross-section shape of the magnetic core. In this case, the alternating polarity of each core element is obtained by changing the orientation of the S-shaped core, while the conductor is just passing through the cores to further simplify the installation and avoid the need for winding the conductors around the core elements. This leads to an even narrower cross-section in the road, and the system is referred to as having an "ultra-slim S-type" power rail, since the rail is only 4 cm wide.



**Figure 8-4 Schematic illustration of 5<sup>th</sup> generation OLEV technology based on S-type power supply rail with alternating polarity, shown as a) cross-section of the system and b) view from the side [40]**

It can be noted that all the developed OLEV concepts seem to be operating at a frequency of 20 kHz. However, it is noted in [40] that a 6<sup>th</sup> generation of the technology is under development, with the main intention of ensuring compliance with the new standard SAE J2954 for stationary inductive charging of electric vehicles. Indeed, it is expected to be a significant advantage and potential future requirement that systems for stationary and dynamic inductive power transfer to electric road vehicles should be compatible. The standard for stationary inductive charging is specifying an operating frequency of 85 kHz, which also implies different design considerations and trade-offs than the previous OLEV systems operating at 20 kHz. Thus, it is indicated that a 6<sup>th</sup> generation of the OLEV technology will be based on core-less rails, without any rigid magnetic structure in the road. However, this concept has not yet been developed to the stage of large-scale experiments or demonstrations.

### 8.3 Bombardier Primove

Bombardier in Germany has been developing technology for inductive power transfer for electric transportation since around 2010. The main applications have been for stationary opportunity charging of public transportation systems like trams and busses. The technology has been demonstrated at multiple locations in Germany, and busses with in-rout inductive charging are now in operation in at least 4 locations in Germany as well as in Södertälje in Sweden [53]. The same basic technology seems to be applicable also for dynamic charging, which has been demonstrated by Bombardier for an 800 m track of a tram in Augsburg, Germany, and for a truck in Augsburg, Germany, as part of the Swedish "Slide-in electric road project" [53], [54].



**Figure 8-5** Picture of test vehicle operating on the 800 m track for demonstrating Bombardiers concept for dynamic inductive power transfer, and picture of the receiving-side coil when installed on the vehicle [54]

In general, limited technical information about the technology developed by Bombardier is publicly available. However, the system operates at a frequency of 20 kHz, and is rated for transferring at 200 kW to the vehicle. Various information is given regarding the airgap of the system, but it appears to be in the range of 6 cm for trams and up to about 10 cm for the tested truck-application [40], [54]. However, for road vehicles, the airgap distance is mechanically controlled by the pick-up system on the vehicle. For busses with stationary charging, the pick-up system might be lowered to the ground during charging, while a minimum clearance from the road surface is ensured for dynamic power transfer applications.

According to the information presented in [54], the technology from Bombardier is based on a three-phase system configuration for the road-side installation. The pick-up system on-board the vehicle is a three-phase winding with multiple taps, which is connected to a diode rectifier. Thus, the input to the rectifier can be switched between several tap positions for controlling the rectified voltage. This controllability is assumedly coordinated with the mechanical position control of the pick-up system. The dimensions of the on-board pick-up systems is 2×1 m for a 200 kW unit.

Although limited technical details regarding road-side installation of the system from Bombardier is available, some information is presented in [54]. The general structure of the test-track utilized for obtaining the results presented in [54] is shown in Figure 8-6. From this figure, it can be seen that three-phase windings are used in the road installation, and that the sections are 20 m long. The test track described in [54] had 4 sections which are each supplied by a three-phase inverter from a regulated 750 V dc distribution system. The winding layout of the road-side system is forming a distributed three-phase pattern (sometimes referred to as "Meander Type" coil) without any need for multiple turns on each magnetic pole of the winding. The road-side installation is about 20 cm deep, including an asphalt layer of 4 cm for covering the installation, and 80 cm wide. It is noted in [54] that longer sections of at least 25 m could be reasonable for reducing the cost of the system.

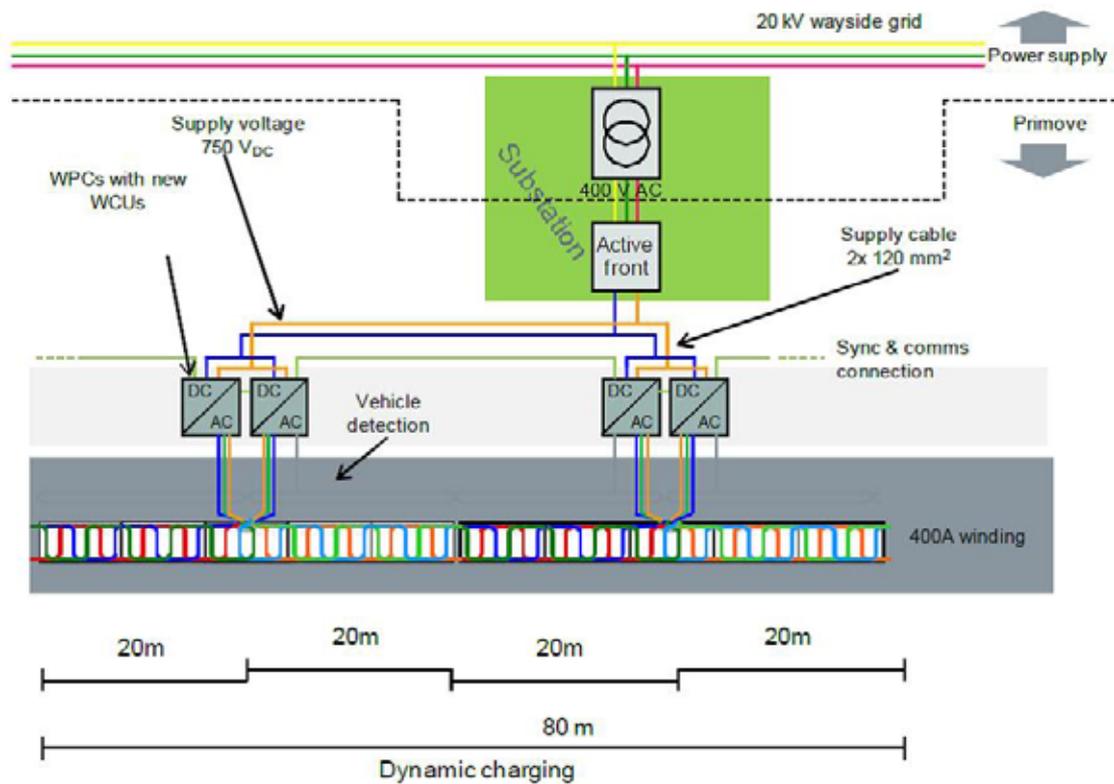


Figure 8-6 Schematic view of power supply system and road-side installation of the test track for dynamic inductive charging of trucks described in [54]

## 8.4 Other European initiatives for dynamic inductive charging

Many European research groups are currently working on various topics related to technology for inductive power transfer, and the research and development activities related to dynamic inductive charging is also increasing. However, only few of these activities have led to development of complete systems and/or technology demonstrations with power levels in the range of what is required for heavy road vehicles.

A large part of the open research activities related to inductive charging in Europe have been organized within EU research projects, first in the "UNPLUGGED" project [55] which ended in 2015 and later in the "Fabric" project [56], which is scheduled to end in 2017. Within these projects CIRCE / Endesa has been developing technology for stationary as well as dynamic charging of electric vehicles, which has also been integrated as a part of the regional VICTORIA-project [40], [55], [56].

As part of the VICTORIA-project, the developed technology for 50 kW inductive power transfer at 26 kHz has been installed in a 10 km bus route in Malaga, with two points for static in-route charging and a 100 m section for dynamic charging [57]. It is not specified what is the exact length of the road-side coils for the installation in Malaga, but concepts by 1 m length as well as configurations with significantly longer road-side coils have been investigated for case studies in the mentioned projects.

In the EU project "Fabric," two additional demonstration projects for dynamic inductive charging are under development, one in France and one in Italy. The test site in France is located in Satory near Versailles where a system for 20 kW power transfer will be tested on a 100 m track. Limited technical information is currently available regarding this test system, but according to information collected in [58], the technology to be used in this demonstration is provided by Qualcomm (previously HALO IPT). This technology is assumed to be based on research results from the University of Auckland. Thus, according to information from [40], this system is most likely based on multiple rectangular coils for the road-side installation. The Italian test site within the EU Fabric project is located close to Torino. The system is intended to be rated for 20 kW, but information collected in [58] indicates that also higher power levels up towards 100 kW might be considered. The technology is assumedly developed from concepts for induction heating provided by SAET EMMEDI [56], [58], [59].

In addition to the demonstration activities mentioned above, the INTIS laboratory in Lathen, Germany has established a test centre with a 25 long road-side power supply system. This system has a frequency of up to 35 kHz and a power capability of 30 kW for air gap distances of about 10 cm [41], [60]. The research team at this laboratory seems to be conducting internal developments of various concepts for dynamic inductive power transfer, as well as providing consulting and testing services. Several other companies are also starting to promote solutions for dynamic inductive power transfer, as for instance ElectRoad in Israel [61]. However, most of these commercial initiatives appear to be mainly positioning themselves with respect to future business opportunities, without revealing any detailed information that can be assessed from a technical perspective.

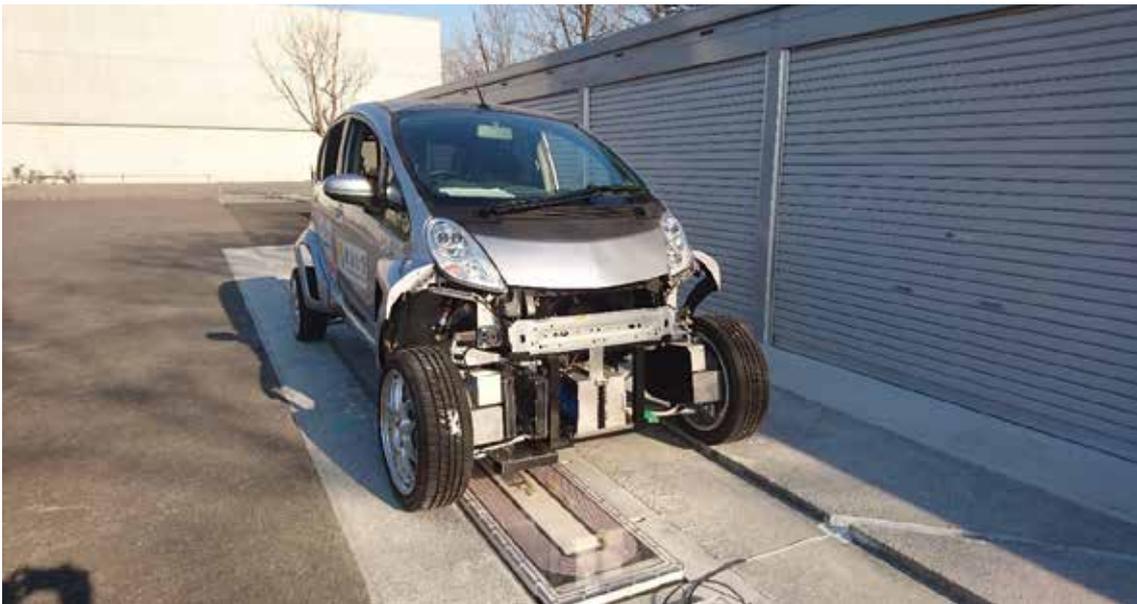
Beyond the technical developments and demonstrations discussed above, multiple research organizations and governmental institutions around Europe have conducted feasibility studies as well as technical and/or economical assessments of various solutions for dynamic inductive charging as a potential solution for future e-mobility with reduced emissions. The analysis presented in the slide-in electric road project in Sweden [54] is maybe the most technically detailed analysis with respect to case studies and detailing level of the information from a specific technology provider. However, a thorough general evaluation of the potential challenges and benefits of deploying technology for dynamic inductive charging, including identification of critical issues for further development and testing, has been prepared for Highways England [62]. As already mentioned, an overview of pilot projects and potential implications of technology for dynamic power transfer to moving vehicles has also been prepared in The Netherlands [47]. The ElinGO project is operating within the same context as these reports, for summarizing technology status and development trends as basis for future strategic decisions regarding how emissions from road transportations can be reduced according to recent political targets.

## 8.5 Activities in Japan and China

Significant research activities on inductive power transfer beyond the already mentioned initiatives in South Korea are also going on in other Asian countries, especially in China and Japan. In China, several University-based research groups are currently actively publishing results from studies of various concepts for inductive power transfer, including the authors of [46]. However, any potential plans for full-scale demonstrations of technology for dynamic inductive charging in China are not easily available in English. Similarly, limited information about any national plans within Japan are available in English. However, what is known from easily accessible scientific publications is that the Japanese Railway Technology Institute and the University of Tokyo are conducting relevant research activities on dynamic inductive power transfer.

The Japanese Railway Technical Research Institute (RTRI) has for instance developed a reduced scale prototype of a system for railway applications which has been evaluated on a test track. The system was designed for a power transfer capability of 300 kW, for preliminary testing the transmitting side coil was scaled down to 50 kW. However, the test was based on pick-up coils rated at 16.7 kW, and the system configuration for full power transfer of 300 kW was based on 18 pick-up coils. Thus, only the sending side coil was scaled down for the tests reported in [63]. The reported experiments were based on a test-track with a 13.2 m long section integrated in a standard Japanese railroad track, and also the pick-up coils were integrated in a rail vehicle according to the regular specifications of rolling stock on the Japanese railways. The system was operated at 10 kHz and had an airgap distance of 7.5 cm

The research activities at the University of Tokyo have addressed multiple aspects of various solutions for dynamic inductive power transfer, and several of these concepts have been demonstrated by simplified laboratory experiments. However, a test-track has recently been established within the University Campus at Kashiwanoha for the particular application of dynamic inductive power transfer to an electric vehicle with a wireless in-wheel motor. Thus, the system is originally designed with two parallel coil sections in the road-side, which transfer power individually to each wheel of the vehicle, as shown in Figure 8-7. However, the infrastructure is built so that testing of different concepts is possible with minor adaptations. At present, a road-supply system is available featuring a 750 VDC local distribution to 24 individually-controlled inverters working at 80kHz. Each inverter unit is rated for 12 kW of continuous power transfer.



**Figure 8-7 Inductive charging infrastructure under development at The University of Tokyo, Kashiwanoha campus, for testing of the wireless in-wheel motor concept (Photo: G. Guidi).**

## 8.6 Activities in USA

Also in USA, the main research activities related to inductive power transfer have until now been dedicated towards stationary inductive charging of electric vehicles. However, some activities in dynamic inductive charging are emerging, especially at the Oak Ridge National Laboratory (ORNL) and at the Utah State University. At both these institutions, the activities related to dynamic inductive charging have originated from the activities on stationary inductive charging.

Due to this background, the concepts pursued by ORNL have been based on small road-side coils of similar size as the on-board pick-up coils, with either rectangular or circular shapes, as shown in

Figure 8-8. The experiments for dynamic power transfer to vehicle prototypes as shown to the right-hand side of Figure 8-8 have been conducted at quite low power levels, with the main experiments reported for 1.5 kW at an operating frequency of 22 kHz and an airgap distance of 10 cm.



**Figure 8-8 Experimental facilities and tests at Oak Ridge National Laboratory (ORNL) [64]**

At Utah State University, further activities in inductive charging of electric vehicles have been supported by the establishment of an Electric Vehicle and Roadway test facility. Limited detailed information about this facility is currently available, but it will be utilized for testing of technology for dynamic inductive charging with power levels up to about 50 kW and airgap distances up to more than 35 cm [58], [65]. As this test facility and the associated research activities are related to Utah State University, future scientific publications that will reveal some more information about the concepts for dynamic inductive charging currently under investigation might be expected during the coming years.

It should also be mentioned that the International Transportation and Innovation Center (ITIC) in Greenville, South Carolina has been established as a test facility for sustainable vehicle technology, including technology for dynamic inductive charging [66]. Limited technical details about the activities at this facility are openly available, as part of the activity is also intended for providing commercial or confidential testing services. However, it can be noted that ITIC is also involved in the development of the possible testing facility for electric transportation technology at Hell Arena in Stjørdal, Norway.

## 9 Summary and discussion of demonstrated concepts for dynamic inductive power transfer

As can be understood from the information presented in section 7 and 8, the range of relevant initiatives within research and demonstration activities related to dynamic inductive power transfer around the world is quite diverse. Thus, a significant number of various research groups involved in these activities are pursuing several different concepts. Since limited information has been published regarding the most industrially oriented demonstration projects, and since several research groups focus on different aspects of the technology, it is difficult at the current stage of technology development to present clear and simple comparisons between the various concepts based on publicly available information. However, some key information regarding the most important systems that have been or are planned to be demonstrated under relevant conditions are summarized in Table 9.1. From this information, it can be noticed that it is only Bombardier and the Korean Railroad Research Institute (KRRRI) that have demonstrated full-scale systems with the power levels required for heavy road transport. However, the different generations of the OLEV technology from KAIST has been utilized in several demonstration projects and is also in regular operation on busses, although with significantly lower power levels than demonstrated by KRRRI or Bombardier.

In general, the concept of Bombardier is quite different from the various generations of OLEV technology from KAIST, since Bombardier uses a distributed three-phase winding while the OLEV concepts are based on a single-phase configuration. Furthermore, as discussed in [54], the adaptation of the dynamic charging concept from Bombardier to trucks has been based on a mechanical lifting device for controlling the position of the on-board receiving coil during operation. The mechanical position control of the receiving coil serves two purposes: firstly, it allows for the coil to be lifted into a higher position for protection when it is not in use, and secondly, the position control is used for regulating the magnetic coupling and by that the voltage induced in the coil, according to the operating conditions. Additionally, the receiving coil also has several different tap positions that can be connected to the output terminals, implying that the induced voltage to be rectified on-board can be regulated by changing the tap position of the coil. Thus, the concept from Bombardier has two relatively slow methods that can be utilized for controlling the power transfer to the moving vehicles. For the concepts originating from KAIST, it seems instead that the power transfer is fully controlled by the power electronic conversion systems and that there is no mechanical or electromechanical control involved. In general, it can be assumed that any position controlled, movable, installation on-board the vehicle can be a disadvantage under Norwegian winter conditions with frost and ice, and possibly with salty snow or water along the road leading to a corrosive environment. In this respect, the concepts from KAIST could have advantages with respect to robustness and reliability compared to the solution from Bombardier, although these advantages could come at the cost of a slightly reduced efficiency. However, it can also be expected that the system from Bombardier could be designed to avoid the mechanical position control by introducing additional power electronic control stages on-board the vehicle.

In general, it can be expected that most of the concepts under development can be scaled to higher power levels by pursuing appropriate research efforts and ensuring sufficient investments in suitable demonstration facilities. Still, the different concepts will have various advantages and disadvantages. Thus, a brief discussion of potential interoperability between various solutions and some important corresponding research questions regarding various systems are given in the following section.

**Table 9-1 Summary of available information regarding the main demonstrated concepts for dynamic wireless power transfer**

Concept	Main electrical performances				Comment
	Power level	Frequency	Airgap distance	Efficiency	
KAIST – OLEV 2G	60 kW (10 × 6 kW pick-ups)	20 kHz	17 cm	72 %	Planar U-type rail, 140 cm width I-type pick-up coil Announced in 2009
KAIST – OLEV 3+G	14 kW	20 kHz	20 cm	83 %	Planar E-type (W-type) rail, 70 cm width Double planar pick-up coils. Applied in at least 6 operational busses and 3 (light rail) trains Announced in 2009
KAIST – OLEV 4G	27 kW	20 kHz	20 cm	74-80 %	I-type transmitting rail with alternating poles, 10 cm width Double planar pick-up coils Lateral tolerance up to 24 cm Announced in 2010
KAIST – OLEV 5 G	22 kW	20 kHz	20 cm	71 %	S-type transmitting rail with alternating poles, 4 cm width Double planar pick-up coils Lateral tolerance up to 30 cm
KAIST – OLEV 6 G		85 kHz According to SAE standard for stationary charging			Coreless supply rail (planar coil without magnetic core) Design target of interoperability between stationary and dynamic charging Assumedly similar power level and efficiency targets as earlier generations
KRRI – South Korea	800 kW – 1000 kW (4 × 200 kW pick-ups)	20 kHz	5 cm	83 %	Based on KAIST 3+G concept adapted to trains Development since 2012 Test track with 128 m long transmitting rail
Bombardier	200-250 kW	20 kHz	8.5-10 cm	78-90 %	Mechanical adjustment of pickup position Tested for speeds up to 70 km/h Three-phase ground-side winding – “meandering type” Segment lengths of 20 m, Pick-up system of 2x1 m On-road installation is 20 cm deep, incl. 4 cm asphalt layer over the winding
VICTORIA / Endesa	50 kW	26 kHz	15-20 cm	85 %	Development activities since 2013. Demonstration on bus route in Malaga with 8 sections for dynamic charging and two points for stationary charging 80 cm wide coils with 30 % lateral tolerance
INTIS	30 kW	30 kHz	10 cm	-	Test track of 25 m Double U-type transmitting rail
UTokyo	2x12 kW	85 kHz	12 cm	89-93 %	Test track of 6 sections of 200x30 cm with two parallel planar coils for concept of wireless in-wheel motor of electric vehicles
RTRI - Japan	50 kW 3 × 16.7 kW pick-ups	10 kHz	7.5 cm	70-85 %	Single turn winding in rail-side segment Two loops, of ~40 cm – total width of 80 cm Design for 300 kW by 18 × 16.7 kW pick-ups
ORNL	1.5 kW	23 kHz	10 cm	75 %	Circular pads , 33 cm diameter
Fabric – France / Qualcomm	20 kW Potentially 40 kW		12.5 cm - 17.5 cm	80 %	Information related to demonstration within EU Fabric project Indicated lateral tolerance of 20 cm
Fabric – Italy	20 kW × 3 – 100 kW	10-150 kHz	25 cm	70-80 %	Track with 3 sections Indicated lateral tolerance of 50 cm
Utah State University	30-50 kW	20-140 kHz	25-38 cm	90 %	Development target for demonstration on test track under construction

## 10 Critical challenges in design and research on dynamic inductive power transfer

Although the wide range of different concepts for dynamic inductive power transfer makes direct comparison of performances difficult, most potential design solutions have similar challenges for further development. Furthermore, future large-scale utilization of such technologies will depend on standardization of the infrastructure and the systems on-board the vehicles. Standardization that can ensure compatibility between equipment from different manufacturers can be ensured by agreeing on a single concept for electromagnetic design or, alternatively, by limiting the concepts to a range of electromagnetic designs that can be interoperable. It will also be potentially very beneficial to ensure interoperability between concepts for dynamic inductive power transfer and the emerging standards for stationary inductive charging. Additionally, the applicability and utilization of infrastructure could be significantly increased if it can be possible to ensure that vehicles of different sizes and with different power requirements can utilize the same road-side installations.

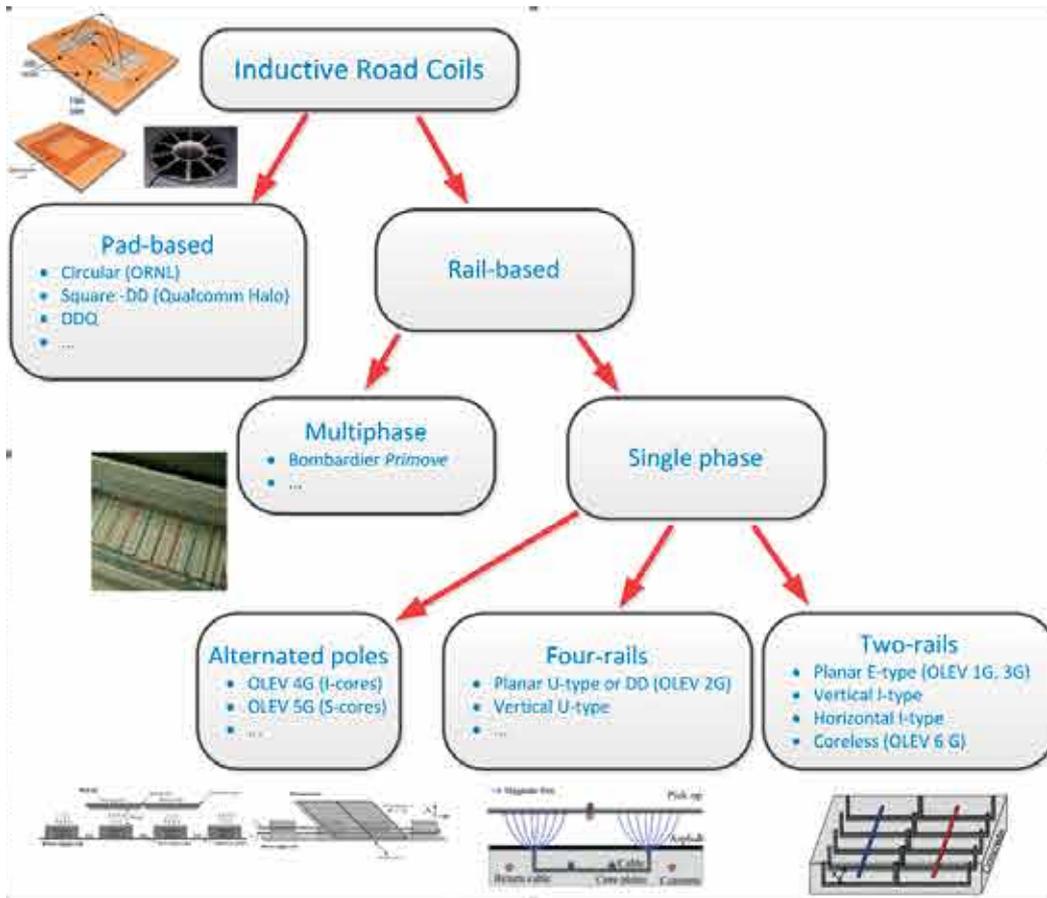
To give a basis for identifying some critical research topics and design challenges that are similar for several different concepts of dynamic inductive power transfer, an attempted classification of the most common concepts is presented in the following. This classification can also be useful as a basis for obtaining a general understanding of the potentials and limitations for interoperability of different concepts.

### 10.1 General classifications of concepts for dynamic inductive power transfer

As already mentioned in section 7 and 8, several publications and reports presenting and summarizing the developments of technology for dynamic inductive power transfer have been recently published [38], [41], [47], [56], [62]. However, none of these publications contain a clear classification or comparison of the various concepts that allows for simple evaluation of the compatibility or potential for interoperability between different solutions. An attempt towards such a classification is illustrated in Figure 10-1. As seen from the figure, it can be relevant to provide a first level of classification by separating between pad-based and rail-based solutions. The pad-based solutions can be generally considered as extensions of concepts for stationary inductive power transfer, as each pad is assumed to be individually controlled by a power electronic converter and can be considered as equivalent to the ground-side coil of a stationary inductive charging system. The rail-based solutions are, on the other hand, considered as systems with longer road-side sections fed by the same power conversion system.

#### 10.1.1 Pad-based concepts for dynamic inductive power transfer

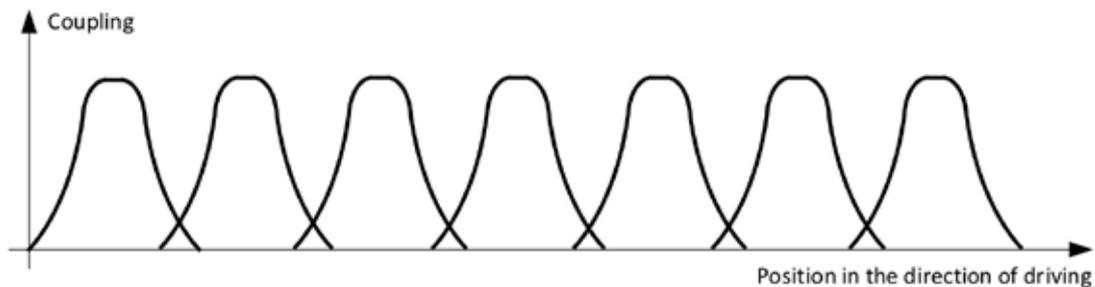
As listed and illustrated for the group of pad-based systems for dynamic inductive power transfer, there are several possible concepts and coil designs that have been tested for this purpose. However, the circular pads as tested and demonstrated by Oak Ridge National Laboratory in several publications [64], are the closest to some of the common solutions for stationary inductive power transfer. However, due to the circular shape of the coils, this solution has its main advantages for stationary applications where the relative position of the ground-side and vehicle-side coils can be fixed. Indeed, operation of such ground-side coils for dynamic charging applications implies that the coupling conditions between the two coils is only at the maximum level at the exact moment when the vehicle-side coil is perfectly aligned above the road-side coil. Thus, such a solution will give poor utilization of materials in the road-side coils, and the average power transfer capability will be significantly lower than the peak power transfer capability.



**Figure 10-1 Possible classification of concepts for dynamic inductive power transfer**

Square-shaped coils, or joined rectangular coils like the DD coil concept from the University of Auckland [67], [68], as shown by a small image at the upper left of Figure 10-1, can give a slightly higher average coupling between the vehicle-side and the road-side coils. Thus, such coil designs can allow for a slightly better utilization of the material in the coils for transferring power to a moving vehicle. However, all the pad-based solutions have the common disadvantage that they will depend on a high number of individually controlled road-side coils. Thus, these solutions require a high number of separate power electronic converters, or a method for switching power electronic converters between the consecutively energized coils while the vehicle is moving along the road, which could significantly increase the cost and reduce the utilization of active material.

For the simplest pad-based solutions, consisting of multiple individual coils placed side-by-side along the road, the power transfer to the vehicle will have significant pulsations depending on the position of the vehicle, with short peaks of power transfer depending on the size and design of the road-side coils. Thus, the average power transfer capability to a vehicle travelling along the road will be significantly lower than the power transfer capability at the moments when the vehicle-side coil has the maximum coupling with the road-side coils. As mentioned, this effect would be most pronounced for circular coils. However, for regular square-shaped or rectangular coils there will also always be vehicle positions where there is very low or no power transfer capability between the road-side infrastructure and the vehicles. A general illustration of how the coupling conditions between the coils, and by that the power transfer capability between the road and the vehicle, can change with the position of the vehicle when passing multiple rectangular road-side coils is given in Figure 10-2. For this illustration, it is assumed that the vehicle has either multiple receiving coils or coils that are large enough to cover parts of two road-side coils at the same time. Otherwise, there would be points along track where no power could be received by the vehicle.



**Figure 10-2 General illustration of the coupling between the vehicle-side and road-side coils, implying the limitation in active power transfer capability, for pad-based solutions or systems with short road-side sections**

It should be noted that it is possible to design the ground-side coils to compensate for the power pulsations indicated by the illustration in Figure 10-2, but this would require overlapping of the coils. For instance, the DDQ concept presented by researchers from the University of Auckland utilizes an in-quadrature coil overlapping two adjacent coils [67], [68]. Thus, power transfer capability between the vehicle-side coil and the overlapping coil on the road-side is the maximum at the position when the power transfer capability from the two other coils is zero. Thus, this design approach can help to reduce the power pulsations along the road if the two adjacent DD coils are arranged along the direction of travel along the road, or it can be used to significantly increase the robustness with respect to misalignment of the vehicle if the DD coils are placed side-by-side within the lane. In any case, the additional in-quadrature coil of the DDQ concept should be expected to introduce additional cost while it will not help to increase the utilization of active material in the road-side installation.

Considering the presented concepts for pad-based road-side infrastructure, it can be understood that these solutions are all likely to cause high costs and low utilization of active material for dynamic charging of electric vehicles. This will especially be an issue for dynamic charging at relatively high speeds, since charging at high speed will require long sections of coil infrastructure to be installed in the road. Indeed, the lower average power transfer over a distance will be due to the pulsations in the power transfer capability to the vehicle, the longer distance will have to have a road-side installation to be able to transfer the same amount of energy to a vehicle at a certain speed. Instead of increasing the share of the road length that has ground-side coils installed, the maximum power ratings of the system could be increased. However, this would also increase the required size, weight and cost of the installation on-board the vehicles. Thus, none of these options seem to be preferable for power transfer to vehicles at high speed. Still, these concepts can be very relevant for quasi-stationary applications or "opportunity charging," at points along the road where the vehicles are expected to stop, for instance at intersections or in road sections with frequent slow-moving traffic.

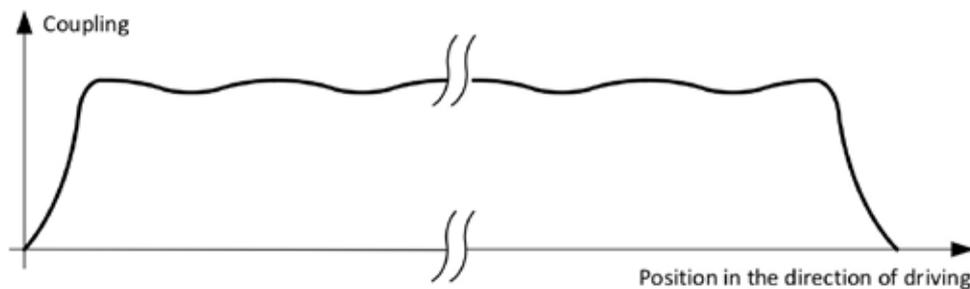
### 10.1.2 Rail-based concepts for dynamic inductive power transfer

For the rail-based solutions indicated in Figure 10-1, a relatively wide variety of concepts have been proposed. However, the use of single-phase or multi-phase coils is a significant difference between these concepts, allowing for a further sub-classification as indicated in Figure 10-1. As indicated in the figure, the concept of a distributed three-phase winding has been used by Bombardier, and a schematic illustration of how the ground-side coil winding of this solution can be configured is shown in Figure 8-6, but limited technical information has been made publicly available regarding the design and implementation of their solution. However, the concept of three-phase rail-based (meander-type) solutions has been recently studied by a research group in IK4-IKERLAN in Spain [70]. Still, the concept of single-phase rail systems has been more widely applied, including for instance by all the different generations of the OLEV-concept from KAIST as shown in Figure 8-2.

The main difference between three-phase and single-phase ground side coil installations is that the distributed three-phase (meandering) winding allows for constant power transfer capability to a single on-board receiving coil, independently of the vehicle position. Single-phase solutions are, however, including many different possible configurations with potentially quite different characteristics. It is especially relevant to separate between the systems having alternating poles in the road-side sections, and the systems having two rails (E-core) or four rails (U-core) with relatively long road-side sections. The concepts with alternating poles in the direction of travel can have similar position-dependent variations in the power transfer capability to a single receiving coil on the vehicle side as the pad-based solutions. However, on-board pick-up systems with more than one coil (i.e. equivalent to DQ or DDQ concepts) can be designed to ensure constant power transfer to the vehicle from such systems. Single phase rails with alternating poles also have similarities with pad-based systems, since each pole could be considered to correspond to a single pad. Since the rail-based solution ensures that longer sections containing a high number of poles are excited simultaneously, this solution will not have the drawback of requiring a high number of power electronic converters for controlling each individual pole in the road-side infrastructure.

The concepts with two or four rails can generally be considered to represent relatively long coil sections with a magnetic designed based on either an E-core (commonly referred to as a W-core by OLEV concepts using this type of coil design), or a U-core. These solutions usually have road-side coils with bars of magnetic material intended to guide the magnetic field or they can be based on planar coils with a flat back-plate core. For such solutions each road-side coil, and by that each pole, is usually significantly longer than the vehicle-side coil. Thus, the power transfer capability between the infrastructure and the vehicle will generally have a shape as indicated in Figure 10-3. Thus, the power transfer to the vehicle can usually be kept constant when the vehicle-side coils is within the section of the road-side coil, ensuring close to maximum coupling conditions. However, there will always have to be a transient in the power transfer when the vehicle enters over or leaves a road-side coil.

It should also be mentioned that there will always be a trade-off regarding the length of the road-side sections for the single-phase as well as for the three-phase rail based solutions. Indeed, very long sections will imply that a large area will be magnetized for a longer time, when the vehicle is only covering a small part of the section. This also implies that the relative coupling between the road-side and vehicle-side coils will be decreasing with the length of the section, as the vehicle-side coil will be very small compared to the road-side coil. Thus, very long sections will in general reduce the efficiency of the system due to long winding. Very short sections will, on the other hand, imply the need for a higher number of power converters, and will also cause a higher number of transitions between road sections, which will reduce the average power transfer when a vehicle is moving along the road. Thus, as already mentioned in section 7.3 and further analysed in [46], the selection of the length of road-side coil sections will always be a trade-off between several factors. A brief discussion of the most general consequences of changing the length of the sections will be presented in section 10.3.



**Figure 10-3** General illustration of the coupling between the vehicle-side and road-side coils, implying the limitation in active power transfer capability, for solutions with two or four rails and long road-side sections

## 10.2 Potential for interoperability between various designs and coil layouts

The classification of concepts for dynamic inductive power transfer proposed in Figure 10 1 can be a useful starting point for considering the potential for interoperability between various types of coils or road sections. However, it should be first noted that the most fundamental prerequisites for potential interoperability between different concepts is that the systems are designed for the same frequency, and that the control strategies of the road-side infrastructure and the equipment on-board the vehicles are compatible. If these conditions are fulfilled, it can be possible to ensure interoperability between vehicles and road-side infrastructure with different coil designs, if the magnetic field shapes are compatible. An attempt to illustrate how some of the most common types of rail-based or pad-based road-side installations can be compatible with different types of on-board coil designs is shown in Figure 10-4.

The case of a single planar coil on-board the vehicle and an E-core or single planar center-pole winding in the road is shown in the upper part of Figure 10-4. In general, this simple configuration is not directly compatible with solutions having multiple poles in the transversal direction. However, this solution would be compatible with pad-based road-side installations with single rectangular or circular coils. Thus, this solution could also be easily compatible with the typical design of systems for stationary charging, which are usually based on a single planar coil with rectangular or circular shape depending on the power rating and application. Furthermore, the concept could be compatible with systems having alternated poles in the travel direction, as long as the dimensions of the on-board coils are compatible with the distance between the poles in the road-side system. This is indicated with a dotted line in Figure 10-4.

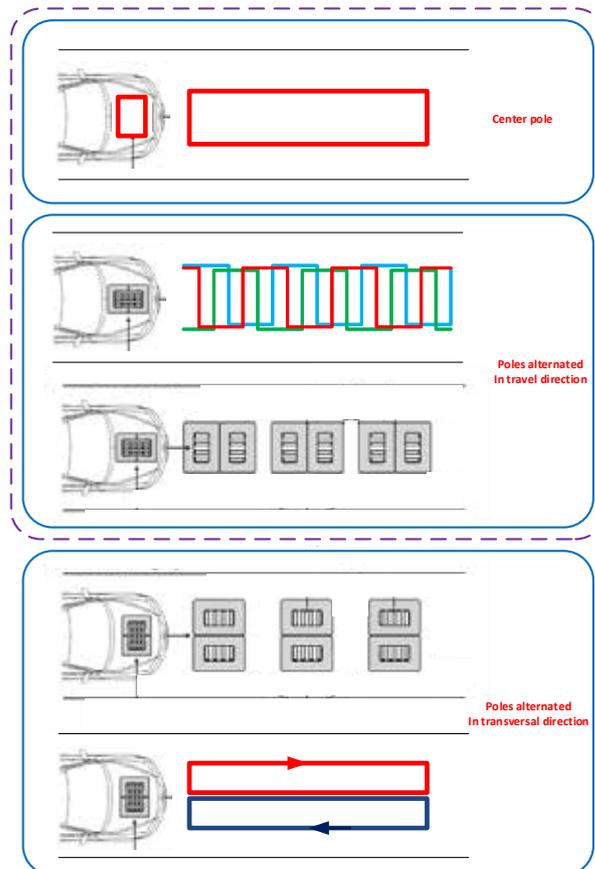


Figure 10-4 Illustration of general road-side and on-board coil configurations classified according to the potential for compatibility between different concepts

In the middle part of Figure 10-4, it is first indicated that at road-side coil section with three-phase distributed windings in general could be compatible with an on-board DD-coil intended for operation on a pad-based road with the two poles of the DD-coils aligned in the direction of travel. Furthermore, this configuration would be quite similar to a system with a single-phase rail-based solution with alternating poles. Thus, it should be expected that the power conversion system with a single coil or with double coils on-board the vehicle could be designed to operate on rail-based installations with distributed three-phase windings, on a road-side installation with single-phase rails and alternating coils, as well as on pad-based installations. As mentioned, this requires that the dimensions of the on-board coils are compatible with the distance between the coils in the road-side infrastructure. A single coil on-board the vehicle would in these cases lead to position-dependent power transfer capabilities for all cases except the three-phase distributed winding, while two or more displaced coils on-board the vehicle could allow for constant power transfer independently of the vehicle position. All these solutions could also potentially be compatible with single road-side coils for quasi-stationary or stationary opportunity charging, although with the same requirement of compatibility of physical dimensions.

The lower part of Figure 10-4 shows how a system designed for operation with a pad-based DD-coil road-side installation, where the two poles of the DD coils are placed side by side, could be made compatible with a road-side installation based on four-rails (or two parallel planar coils) generating two poles with opposite polarity. In this case, operation with dynamic charging on a road with DD-coil based pads would imply that the power transfer capability would depend on the position, while a continuous power transfer could be obtained when operating on a longer road section with the four-rail-based solution. For allowing this kind of interoperability, the control system on-board the vehicle would have to be designed to tolerate the different operating conditions for the two types of road-side infrastructure (i.e. very frequent or less frequency variations in coupling and power transfer capability). However, this should be mainly an issue of practical design and control as long as the magnetic flux patterns are compatible.

Another approach for illustrating the potential for interoperability between vehicle side coils with different size and/or flux pattern than the road-side coils is shown in Figure 10-5. The arrows indicating the general magnetic flux patterns in these illustrations are corresponding to conditions when the current is passing into the plane in the coil windings with black colour and coming out of the plane from the coil windings with red colour.

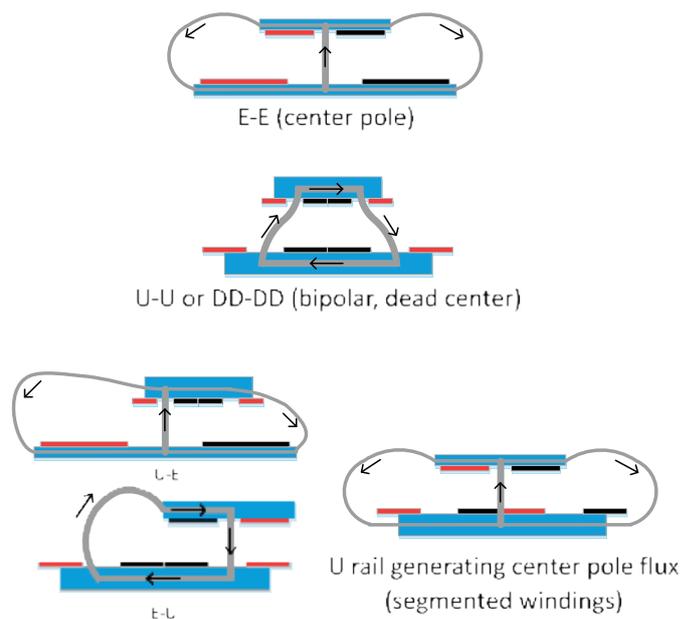


Figure 10-5 Illustration of potential for interoperability of coils with different sizes and different flux patterns

The uppermost illustrations in Figure 10-5 show a simplified indication of the magnetic flux pattern when a smaller sized vehicle-side coil appear above a wider two-rail (E-core or planar winding) road-side coil. As shown by the figure, the flux patterns are generally compatible, as the center-lines of the two coils are appropriately aligned. Although the return-path of the flux on the outside of the winding is becoming longer for the case of a smaller vehicle side coil than what would be the case for equal coils, the field patterns are generally compatible and it would be possible to transfer power, although with increased sensitivity to the sideways position of the smaller vehicle-side coil. However, the longer return path of the flux could be a challenge for the shielding of the magnetic field, which would imply the need for further detailed studies of compatibility with the standards for electromagnetic fields before designing and operating such configurations.

The second illustration from the top of Figure 10-5 illustrates the same conditions of a smaller vehicle-side coil for a bipolar four-rail system (i.e. with U-core or two planar windings). In this case, the main flux path is enclosed along the center of the windings. Thus, this configuration should be expected to have less challenges with stray magnetic field. However, the smaller vehicle-side coil will also in this case imply a higher sensitivity of the power transfer capability with respect to the sideways position, in an even higher degree than for the E-E-configuration shown in the uppermost part of Figure 10-5. As indicated in the figure, the four-rail configuration is generally similar to the DD-coil concept, implying the potential compatibility with the corresponding pad-based road-side solutions, as already discussed on basis of Figure 10-4. This configuration is also referred to in the figure as "dead-center" since the two coils have opposite polarity, causing the magnetic flux in the middle between the winding to become zero.

In the lower left part of Figure 10-5, the expected field pattern when combining configurations with single coils (i.e. E-core or two-rail systems) and double coils (i.e. U-core or four-rail systems) is illustrated. Since the E-core-type windings will have the maximum flux at the middle of the winding, while the U-core configuration will lead to zero flux at the middle of the two coils (i.e. between the windings), a position where the center of the two installations are perfectly aligned in the sideways direction will cause zero coupling between the windings and by that zero power transfer capability. For transferring power between the two coils, the vehicle-side coil should be positioned so that the center of one of the windings will be aligned with the center of one of the road-side windings. Thus, it could be possible to transfer power between the road-side infrastructure and the vehicle if the vehicle is positioned as indicated by the illustrations in Figure 10-5. This operation is similar to the conditions assumed for interoperable power transfer dingle and double coils for stationary inductive power transfer in [69]. Similar operation could also have been sketched for conditions when the total width of the vehicle-side coil is the same as for the road-side installation. However, for the total power transfer capability of the system would be reduced because only one of the windings of the U-type coils can be fully utilized in these conditions.

For the case with a U-type road-side coil and a smaller E-type vehicle side coil, as shown in the illustration at the lower left of Figure 10-4, it could probably be possible to transfer the full rated power of the vehicle-side coil. The reason is that in this particular case, the vehicle-side E-type coil is almost equivalent to one of the windings of the U-type road-side coil. However, this type of operation would imply that a vehicle with a smaller E-type coil will have to be positioned differently in the lane than a larger vehicle with a full-size U-type coil properly designed for the road-side infrastructure. It should also be noted that operation with such configurations, although theoretically possible and potentially interesting from a theoretical point of view, would not be preferable for most practical applications. Thus, the two configurations to the lower left of Figure 10-4 are not likely become common or standardized solutions for ensuring compatibility between different concepts for dynamic inductive power transfer.

The last illustration shown in the lower right of Figure 10-4 shows another possible configuration based on a U-type (four-rail) road-side coil and an E-type vehicle side coil. However, in this case,

the road-side four-rail winding has been reconfigured by changing the current direction in one of the windings. Thus, the two conductors or rails in the middle of the coil will together produce a zero net flux, so that only the flux from the two conductors at the left and right side of the coil will determine the total net flux from the road-side installation. Thus, the U-type coil is effectively reconfigured to an E-type coil which will be compatible with an E-type vehicle side coil in a similar way as for the configuration of the uppermost illustration in Figure 10-4. However, the full power transfer capability of the road-side coil cannot be utilized, and this kind of operation would lead to reduced efficiency since the currents in the middle conductors of the road-side coils will flow without contributing to the power transfer. Thus, also this solution is mainly theoretically interesting as an approach enforce compatibility between two different types of coil windings, but will not be practically preferable solution.

Beyond the cases shown in Figure 10 4, it could be mentioned that the particular case of a DDQ coil on the vehicle side would add additional flexibility for interoperability. Indeed, the two DD windings of such a coil installation would correspond to a U-type configuration, while the Q-winding would correspond to a centered E-type configuration. Thus, for a U-type road, only the DD-windings would be able to receive power, while the Q-winding would be able to receive power from an E-type road-side installation. However, for the case of a E-type (two-rail) road side installation, the two D-coils would have zero coupling with the road-side coil if the vehicle is perfectly aligned in the sideway position, and by that zero power transfer capability. Thus, only the Q-winding would be able to receive power from the road-side infrastructure, which would imply a reduced power transfer capability compared to the total rating of the two DD-windings. Similarly, the Q-winding will have zero power transfer capability if the vehicles is perfectly aligned on a road with a U-type (four-rail) coil configuration, but this will not necessarily imply a reduction of the power transfer capability. These considerations show that a relevant possibility for interoperability of the two combinations shown to the lower left of Figure 10-4 could be obtained by a DDQ-coil on the vehicle side, although the power transfer capability would be reduced for the case of an E-type (two-rail) road-side installation.

It should also be remarked that all discussions presented in this section are based on general considerations without any thorough theoretical or example-based evaluation. Thus, significant further efforts would be required for applying any of the possible configurations that allow for interoperability between infrastructure and vehicle-side installations designed with different types, sizes or power ratings of the coils. Since there is not yet any clear indication of how solutions for dynamic inductive power transfer should be standardized or what principles of coil designs that will become dominant, such considerations have not been widely considered by the individual research groups around the world. However, due to the increasing attention towards technology for dynamic inductive power transfer, and the increasing awareness towards potential challenges of standardization and interoperability between equipment from different manufacturers, it should be expected that future research activities, scientific publications and the emerging initiatives for standardization of technology for inductive power transfer will pay increasing attention to such issues.

### 10.3 Selection of road-section length for rail-based dynamic inductive power transfer

As already mentioned in section 7, the selection of the length of the road-side sections or segments of coils is an important research challenge with significant implications on cost, complexity and efficiency of systems for dynamic inductive power transfer. Thus, several research groups are studying methods for optimizing the section length. However, the detailed studies published until now have considered specific system designs, as for instance the cases discussed in [46]. Although the detailed issues related to electromagnetic design and evaluation of systems with different length of the road-side sections is not relevant for the discussion in this document, a brief introduction to the main impact of changing the length of the coil segments on the efficiency of the power transfer is presented in the following.

For this discussion, a general configuration of a relatively long E- or U-type road-side coils is assumed. Furthermore, the following assumptions are made:

- Only one vehicle-side pickup element is present on each road-side segment at a given time.
- There is negligible coupling between adjacent segments of the road-side installation.
- The coil segments are long enough for the end-winding effects to be negligible when considering variations in the length

If the system is ideally designed and controlled, the peak transfer efficiency can always be expressed as [71]:

$$\eta_{\max} = \frac{k^2 Q_R Q_V}{\left(1 + \sqrt{1 + k^2 Q_R Q_V}\right)^2} \quad (1)$$

$$Q_R = \frac{\omega L_R}{R_R}, \quad Q_V = \frac{\omega L_V}{R_V},$$

In this equation, the subscript  $R$  refers to the road-side coil, while the subscript  $V$  refers to the vehicle-side coil. Thus,  $Q_R$  and  $Q_V$  are the quality-factors of the coils, which can be calculated from the resonance frequency  $\omega$ , the corresponding inductance  $L$  and the equivalent resistance  $R$ , while  $k$  is the coupling factor between the coils.

Changing the track length while keeping the other parameters unchanged has an effect on the coupling coefficient, as well as on the inductance and resistance of the road-side coil. The effects are rather easy to quantify under the assumptions made above, as listed in the following:

- The track resistance is proportional to the track length  $l$ , which can be expressed with reference to an initial length  $l_0$  and the corresponding resistance  $R_{R0}$

$$R_R(l) \approx R_{R0} \cdot \frac{l}{l_0} \quad (2)$$

- The track inductance is proportional to the enclosed area. Therefore, it can be expressed with reference to the initial length  $l_0$  and the corresponding inductance  $L_{R0}$  as:

$$L_R(l) \approx L_{R0} \cdot \frac{l}{l_0} \quad (3)$$

Consequently, the quality factor  $Q_R$  of the road-side coil is approximately independent of the track length. The change in expected efficiency is therefore only caused by the reduction of the coupling factor resulting from increased track length.

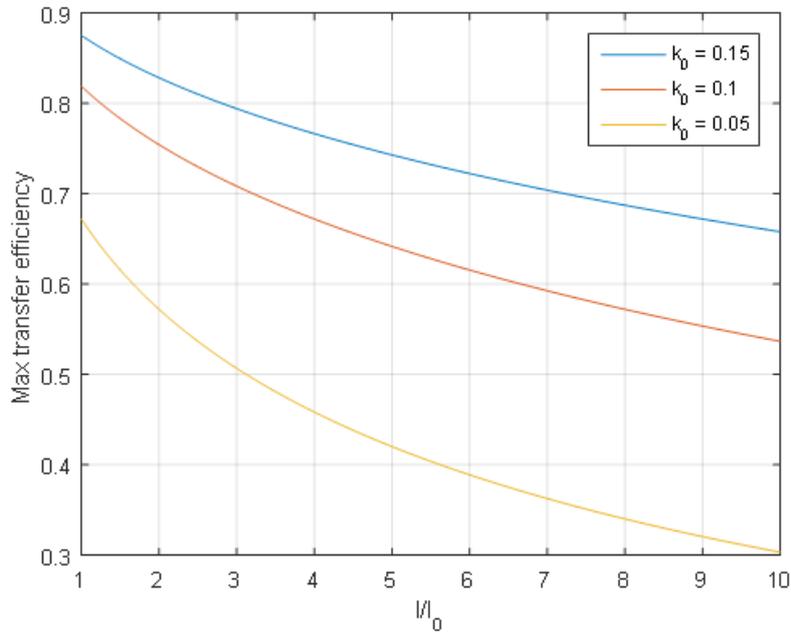
As a convenient approximation, it is noted that for a sufficient length of the track compared to the length of the pickup, the amount of magnetic flux generated by the track current which is linking the pickup is independent of the track length. In other words, the mutual inductance  $M$  is reasonably independent of  $l$ , under those simplifying assumptions. As a consequence, the coupling coefficient will depend on the track length as follows:

$$k(l) = \frac{M(l)}{\sqrt{L_R(l) \cdot L_V}} \approx k_0 \cdot \sqrt{\frac{l_0}{l}} \quad (4)$$

The expected efficiency drop due to increasing track length can therefore be expressed as:

$$\eta_{\max}(l) = \frac{k(l)^2 Q_R Q_V}{\left(1 + \sqrt{1 + k(l)^2 Q_R Q_V}\right)^2} \approx \frac{k_0^2 Q_R Q_V}{\left(1 + \sqrt{1 + k_0^2 Q_R Q_V \cdot \frac{l_0}{l}}\right)^2} \cdot \frac{l_0}{l} \quad (5)$$

To get an idea of the variation in efficiency, some numerical examples are reported in the following figure. A rather good quality factor  $Q_R = Q_V = 100$  is assumed. Several initial values of coupling factors are shown that can be representative of different designs (different gap, track width, coil layout, power rating etc.).

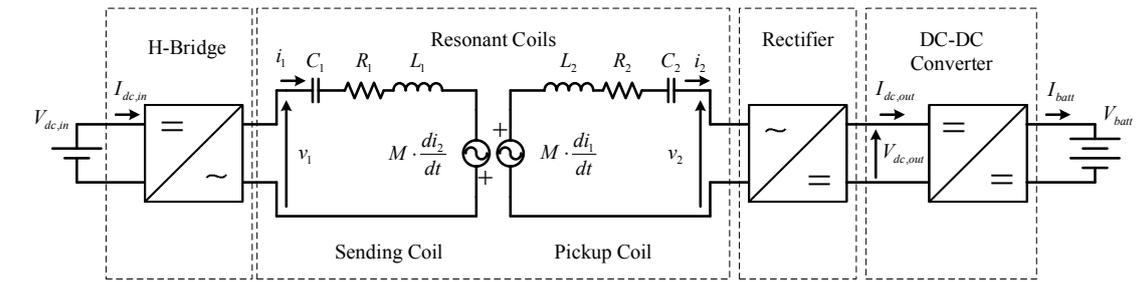


**Figure 10-6 Illustration of maximum power transfer efficiency as a function of relative length of the road-side coil sections, for three different values of initial coupling coefficient**

As seen in Figure 10-6, the maximum efficiency of inductive power transfer between a road-side coil section and a vehicle will decrease with the length of the coil segment. However, a shorter length will imply the need for additional power electronic converters and corresponding power supply installations, which will increase the cost of the system. Thus, as already mentioned, the design of a practical system configuration will rely on a trade-off between several different factors. Although some studies of the optimal track length under specific conditions are already available, significant further efforts towards analysis of this issue is expected from the academic and industrial communities in the coming years.

## 10.4 Control of systems for dynamic inductive power transfer

For considering the general aspects of control and the corresponding challenges that apply to the various concepts for dynamic inductive power transfer, a generalized configuration of the power conversion system is shown Figure 10-7. In this figure, it is assumed that the system has controllable power electronic conversion stages at the vehicle-side (receiving side) as well as on the road-side (sending side). Thus, the voltages at both sides of the resonant coils can be controlled to regulate the power transfer. However, as already mentioned, the solution of Bombardier includes also a mechanical control of the position of the vehicle side coil [54], which will directly influence the mutual inductance  $M$  between the coils, and by that the magnetic coupling coefficient  $k$ . Furthermore, Bombardier has utilized vehicle-side coils with multiple tap positions, which allows for stepwise regulation of the induced voltage on-board the vehicle, and by that power transferred to the vehicle [54]. However, limited details about the control system structures or the implementation and tuning of the control loops are publicly available for the concepts that have been demonstrated with relevant power levels.



**Figure 10-7** General topology of system for inductive power transfer with controllable input and output voltages

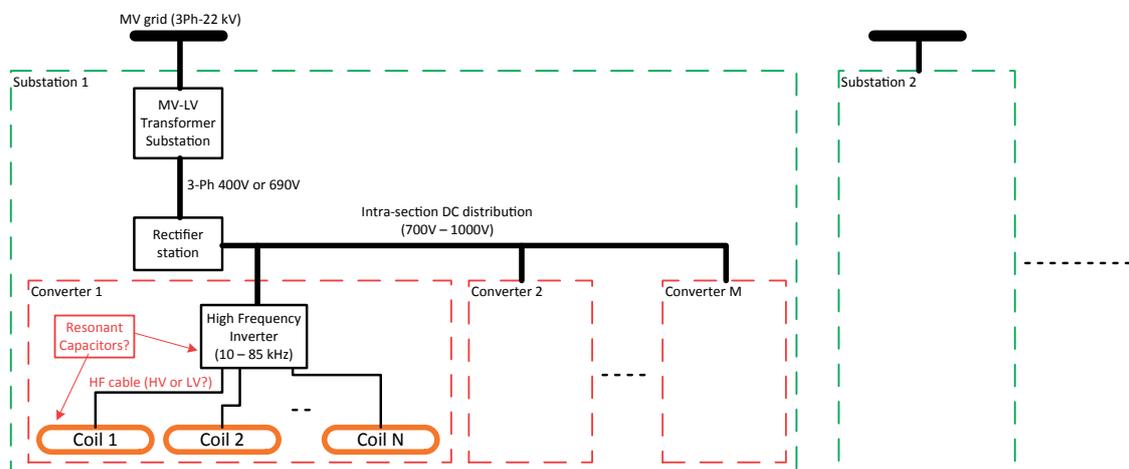
For the OLEV concepts developed at KAIST, some indications of the applied control principles for dynamic inductive charging has been recently published in [72] and [42], and it can be assumed that also most other similar concepts can be operated according to similar control principles. Thus, the sending-side infrastructure is usually controlled to provide a regulated maximum value of the resonant current in the road-side coils, which induces the magnetic field in the vehicle-side coils. With the series-series resonant topology shown in Figure 10-7, the current on the vehicle-side will be strongly associated with the voltage applied on the primary side. Considering the power balance between the sending and receiving side, this implies that the current on the primary side is strongly associated to the voltage on the receiving side. Thus, the power received by the vehicle can be controlled by regulating the vehicle side voltage. Although these general objectives of how the power conversion systems on the sending and receiving sides can be controlled are reasonably well established, it should be assumed that significant research activities are going regarding the practical implementation of the control loops. Thus, further scientific publications and industrial developments should be expected in the coming years related to various methods for controlling the currents and the power flow in systems for dynamic inductive power transfer.

One relevant issue that should be noted regarding the control of systems for dynamic inductive power transfer is the transient response of the power transfer when a vehicle is entering or leaving a road coil segment on the road. For rail-based three-phase or single-phase systems with alternating poles, where the transients associated with the transition between coil segments would not necessarily be significantly different from the transition above each pole, this might not be the most significant control challenge. However, for long coil sections (i.e. E- or U-core road-side coils, corresponding to two- or four-rail systems), this might be a more important challenge. From the vehicle side, the transition from one road-side coil to another will imply that the received power will first drop to zero and then increase to the rated or desired value again. When travelling at relatively high speeds, these transitions will happen relatively quickly, i.e. within some milliseconds, requiring a relatively fast response of the controllers on-board the vehicle. Similarly, the road-side coils should be activated before the vehicle enters the corresponding road-section to ensure that the maximum energy can be transferred to the vehicle. Indeed, it will not be preferable to activate coil sections without any vehicle, since this would imply unnecessary losses in the system, and it would also possibly violate requirements for limitations of electromagnetic fields. This implies the need for detecting the approaching vehicles and quickly controlling the magnetization of the road-side coils when they are needed for transferring power to the vehicle. Furthermore, the operating conditions of the coil will change when the vehicle enters, implying the need for a relatively fast response. Thus, also on this challenge, significant research activity and subsequent academic publications or industrial developments are expected in the near future.

## 10.5 Issues related to in-road power distribution system

In addition to the coils required for the inductive power transfer, the power distribution system and the power electronic converters for controlling the resonant coils will constitute a large share of the total cost of installation along a road with dynamic charging. Thus, there are several relevant questions that should be addressed regarding the design, operation and cost of the power distribution system required along the road to power a system for dynamic inductive power transfer to moving vehicles. However, many of these design challenges will be similar to the challenges of designing cost-effective power distribution systems for conductive power transfer to moving vehicles.

A general illustration of a possible power distribution structure for the road-side infrastructure of a system for dynamic inductive power transfer is shown in Figure 10-8. As seen in this figure, the substation structure for interfacing to a high voltage distribution network is the same as discussed for the conductive solutions in chapter 3, 4 and 5 of this document. Indeed, a similar configuration of transformer stations with rectification to a dc voltage level of in the range of 700-1000 V could be equally applicable to systems for dynamic inductive power transfer. As mentioned in chapter 3, Inductive charging systems could also potentially coexist with overhead lines, and could be powered by the same substation. However, the road-side coil sections for inductive power transfer are expected to be significantly shorter than the sections of the overhead lines discussed in chapter 3. In general, each road-side coil would also have to be controlled independently, implying the need for an individual power electronic converter for each coil section. However, under certain conditions, it could also be possible to switch one converter between multiple coil sections, as indicated in Figure 10-8. Although this might imply the need for additional switches or circuit breakers, it might lead to a more cost-effective solution than the use of individual converters for each coil. Thus, the dc distribution system is expected to be similar to what was presented for the solution of Alstom with short conductive sections in the road surface, although the system for inductive power transfer would depend on power electronic converters (possibly in combination with solid state breakers) for controlling the energization of the sections.



**Figure 10-8 General overview of the road-side power system infrastructure for power supply to the resonant coils of a system for dynamic inductive power transfer**

An additional issue that should be considered for the system in Figure 10-8 is the location of the resonant capacitors with respect to the coil windings. In general, it can be assumed that it is advantageous to integrate the capacitors with the coils, especially since the use of series-series-compensated systems implies that there will be a need for high voltage cables between the capacitors and the coil terminals. Thus, by placing the resonant capacitors together with the coils, low voltage cables

can be used between the converters and the coil sections installed in the road, and only active power must be transferred between a converter and the integrated assembly of capacitors and a coil section. It can also be mentioned that it can be relevant to distribute the capacitance along the road-side coil, especially for very long coil sections, as for instance applied in the long coil section for railroad applications presented in [52]. On the other hand, the integration of the resonant capacitors with the coil windings might be disadvantageous with respect to maintenance and repair when the coils should be embedded in a road structure. Thus, it might be relevant to place the resonant capacitors at an accessible point by the side of the road, or at least to ensure that access can be provided to the installation without the need for breaking the surface of the road. In this respect, there might be several practical issues that will require attention and innovative solutions when designing and installing potential infrastructure for dynamic inductive power transfer.

## 10.6 Summary of research challenges for dynamic inductive power transfer

In general, the already presented concepts and demonstration projects related to technology for dynamic inductive power transfer are clearly indicating that this concept is technically feasible. Although a wide variety of concepts have been proposed and investigated at lower power levels, it can also be expected that most of these solutions could be scaled to the power levels and applications that would be needed for transportation of goods. However, even if it could be theoretically and technically feasible to scale most of the presented concepts to the required power levels, the different concepts have various advantages and disadvantages that would influence their practical applicability. Thus, further research and development efforts are expected to lead towards clearer identification of the most suitable design approaches for various applications. Furthermore, there are also several remaining research challenges that might influence what will be the most preferable solutions for potential large-scale application of technology for dynamic inductive power transfer. Some of the most relevant issues are listed in the following:

- Coil design and selection of optimal coil section length
- Optimization of system configurations, including efficiency, performance and cost associated with coils, capacitors and power electronic converters
- Standardization and interoperability between concepts from different manufacturers.
- Interoperability between road-side infrastructure and vehicles with different coil dimensions and different power requirements
- Control of road-side and vehicle-side conversion stages
- Cost effective design and construction (ac or) dc power distribution systems along the road and integration of the power supply system for the road with the high voltage distribution system

It should also be mentioned that several theoretical and practical issues associated with the physical construction of the road-side infrastructure would require further attention before large scale application under Nordic conditions. Especially, further investigations and research activities should be conducted towards the integration of coil sections in the road cross-section considering the local requirements for road-construction and the impact of winter conditions and expected mechanical movements in the road structure due to frost. However, these issues are only indirectly associated with the electromagnetic design of systems for dynamic inductive power transfer, and are not further discussed in this document.

Although the cost of infrastructure for dynamic power transfer to moving vehicles has not been considered in this document, it should be remarked that systems for inductive power transfer in general suffer from higher costs than solutions for conductive power transfer. This is mainly due to the need for more active material (i.e. copper, ferrite, capacitors, semiconductors etc.), and the need for additional power electronic converters for generating and controlling the high frequency magnetic field utilized in systems for inductive power transfer. Although ongoing research activities

for improvement of the technology for inductive power transfer is not expected to reduce the cost or need of active material to the level of systems for direct conductive power transfer by sliding contacts, the potential advantages of a contactless system can be considered significant. Especially, the advantages in terms of reduced maintenance requirement and simplified system operation that can be expected from a system without any moving parts and where all active components can be encapsulated and protected from mechanical tear and wear can be considered as the main motivations for continued research and development of technology for contactless power transfer.

## 11 Conclusion

This document has presented a general introduction to the electro-technical aspects of technologies for dynamic power transfer to moving vehicles. Thus, two general types of technologies have been reviewed and evaluated, based on:

- i. Conductive power transfer by sliding contacts
- ii. Contactless inductive power transfer by electromagnetic fields.

For conductive power transfer, three different concepts have been evaluated based on:

1. Overhead lines
2. Sliding contacts in the road surface
3. Sliding contacts at the side of the road

The power transfer capability to moving vehicles has been demonstrated in relevant environments for all these three concepts, and there are no concerns regarding the technical feasibility of transferring the power levels required for heavy duty freight transportation. Ongoing demonstration projects for the different technologies have been briefly reviewed, and further information about the various concepts can be found in the references cited in the text. Since power transfer from overhead lines is well established for trains and trolley busses, this concept is considered to have high technical maturity. Although further progress can be expected in the design of the power take-off system and minor practical issues related installation in tunnels or other space-constrained areas are pending practical developments, the technology can already be considered ready for application to freight transportation under a wide range of operating conditions. However, the concept with overhead lines is only suitable for large vehicles, and cannot be utilized by small vehicles like private cars. The concepts based on sliding contacts in the road surface or at the side of the road are can potentially serve a wider range of vehicles but are considered as less mature, since they are either being developed especially for electric road applications or adapted from different applications of similar concepts for trams or subways. Although the basic functionality has been demonstrated, several concerns remain regarding the durability and maintenance requirements of these solutions during winter conditions, with frost, snow, ice and with exposure to salty environments. Further experience can be expected from ongoing demonstration projects in Sweden, but continued research and demonstration activities will be needed for further maturing these technologies.

The technology for dynamic inductive power transfer is currently more diverse than for dynamic conductive power transfer, with several different concepts and design approaches being pursued by different industrial and academic research groups. In this document, a brief introduction to the general principles of dynamic inductive power transfer are first presented, before reviewing the research activities resulting in relevant practical demonstrations. Among the concepts that have been demonstrated in relevant environments, only the solutions provided by Bombardier in Germany or KAIST/KRRI in South Korea have been developed for power levels in the range required for heavy duty freight transportation. However, the demonstrations presented by Bombardier and KAIST/KRRI is clearly demonstrating the feasibility of the technology in general. Thus, it should be expected that most of the concepts and design solutions presented by other research groups can also be scaled to higher power levels, although this would likely require further research and development efforts beyond what has been presented in the available scientific literature. It should also be expected that the significant ongoing development efforts related to dynamic inductive power transfer will lead to improved performance and increasing power levels in the coming years. Thus, some of the critical issues for further research and development of the technology has been reviewed. Especially, it is expected that further attention will be dedicated towards standardization and interoperability of various solutions, since this will be necessary for potential future large-scale utilization of such technology.

## 12 References

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