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Maturity of power transfer technologies for electric road systems

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Abstract

Drawing on the method associated with Technology Readiness Levels (TRLs) and previous efforts, this article provides a maturity assessment of several electric road system (ERS) technologies with focus on the power transfer technology subsystem, and the transition context is also discussed. ERS involves electric power transfer from the road to the vehicle while the vehicle is in motion and could be achieved through different technologies such as rail, overhead line, and wireless solutions. ERS is a technology area with immense potential to reduce fossil fuel dependency, reduce greenhouse gas emissions, reduce air pollution as well as reduce noise in urban environments, while increasing energy efficiency in the transport sector. There are numerous promising ERS development and demonstration projects globally since several years. However, the investment cost for large-scale deployment of ERS is considerable and decision makers will require knowledge about how mature different solutions are compared to other transportation solutions.

Keywords: dynamic charging; ERS; maturity assessment; technology readiness level; TRL; transition

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1. Introduction

An electric road system (ERS) enables transfer of electric power from a road to a moving vehicle for both propulsion and charging of battery. ERS is a technology area with immense potential to reduce fossil fuel dependency, reduce greenhouse gas emissions, reduce air pollution as well as reduce noise in urban environments, while increasing energy efficiency in the transport sector. The power transfer can be achieved through different technologies from road to vehicle, such as rail, overhead line, and wireless solutions. The implementation of ERS at national and international levels is likely to work together with the application of other solutions for cleaner and fossil-free transportation. There are several ongoing studies and demonstration projects around the world which have the aim to explore different technologies, business cases and user perspectives as for example discussed by Börjesson and Gustavsson (2018), Gustavsson et al. (2017), Gustavsson et al. (2019), Jelica et al. (2018), Sundelin et al. (2016), Tongur (2018), and the World Road Association (2018).

An implementation of a particular ERS solution will involve considerable investments and imply a significant transformation of transport systems, e.g. regarding how road vehicles are designed and used. Decision makers therefore needs to be ensured that the chosen ERS solution works satisfactory and fulfils its promises, i.e. is mature for the intended purpose. This is no different from past technology transitions. Different ERS technologies are evolving and are becoming more defined and mature systems, but how to assess the maturity of a solution and how can different solutions be compared? This article investigates two research questions:

- How can the technical maturity of different ERS solutions be assessed?
- What is the technical maturity of different power transfer solutions for ERS?

The basic technologies for electric power transfer from the road to vehicles in motion have been developed through various research and development projects across the globe as further described below. ERS is currently tested and demonstrated in several forms at test facilities and on public roads, and there starts to be a lot of available knowledge. However, the various ERS solutions are still a long way from constituting large-scale deployed and widely-used systems. A reoccurring assessment of the technical maturity of ERS is useful for various stakeholders, such as decision makers, road authorities and technology developers.

This topic of maturity of electric road systems has previously been covered by Sundelin et al. (2016) and Gustavsson et al. (2017). The present article aims to revisit the topic in the context of transition to sustainable transports, and to provide a maturity assessment of ERS power transfer technologies as understood by the authors using open information available in June 2019 and complementing discussions with developers.

2. Electric road system solutions

Currently, there are three main concepts for road electrification: overhead conductive lines, conductive rails in a road surface, or wireless solutions. All these concepts have their advantages and disadvantages and are being developed and marketed by different actors.

Demonstration projects currently under way will test ERS on public roads and in real-life environments, addressing various legal, political, economic, and efficiency aspects of ERS. Public road tests would provide decision makers and investors with a foundation for further investments that would bring ERS to commercial operation as e.g. described by Lindgren (2019), Gustavsson et al. (2019) and the World Road Association (2018).

Below, we examine the state of the art of ERS as well as various projects and developments being undertaken by international ERS actors. The concepts are illustrated in Fig. 1.

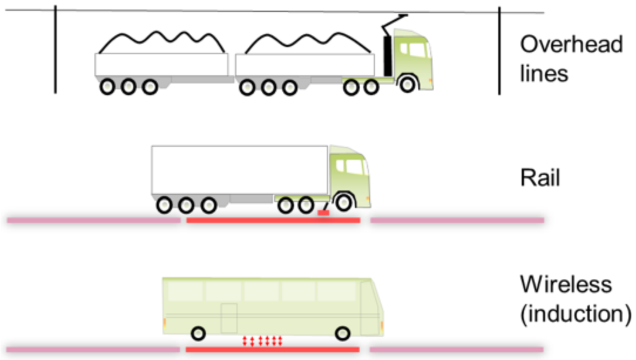

Fig. 1 The three main concepts for road electrification and power transfer to moving vehicles.

2.1. Overhead-line solutions

An overhead line solution uses conductive wire lines (also known as catenaries) above the vehicle to provide the energy. The energy is transferred to the vehicle by means of a power receiver device (sometimes called a pantograph) installed on top of the vehicle, and which follows and detaches automatically from the overhead lines.

Siemens has worked with overhead catenary lines, and its technology named eHighway has been tested on a 2 km closed test track east of Berlin, Germany. Full vehicle integration has been made with heavy trucks from both Scania and Volvo Group. The Siemens solution has been demonstrated since June 2016 together with Scania trucks by Region Gävleborg along 2 km of the E16 highway outside Sandviken, Sweden. The eHighway solution has also been demonstrated during 2017 by South Coast Air Quality Management District together with three different trucks along one mile of an urban road in the City of Carson in Los Angeles County, California, USA. The German federal government funds the construction of three future demonstrations of overhead lines along public roads (A 1, A 5 and B 462), which will be successively put into operation from 2019 onwards.

2.2. Rail solutions

A rail solution for conductive energy transfer from roadway to electric vehicles uses conductive rails installed in the road to provide the needed energy. The energy is transferred to the vehicle via a power receiver pick-up arm installed beneath the vehicle, and which follows and detaches automatically from the rail.

Alstom has a service-proven power system for tramways called APS which supplies electricity through a third rail at ground level and eliminates the need for overhead lines (in order to meet new requirements for tramways in urban areas). The APS product is used in many cities for energy transfer during movement and has been used as a foundation when Alstom has developed its ERS system that involves two rails in the road surface level. AB Volvo has developed power receiver pick-up arms for heavy transport vehicles and tests have been made at a Volvo test site in Sweden. The vehicle integration was performed as part of the Slide-in research project described by Hjortsberg (2018).

The rail solution from the company Elways involves one rail with two trenches where the conductive parts are placed down in the trenches. The rail and a customized power receiver pick-up arm integrated into a medium sized truck have, since April 2018, been used for demonstration of electrified shuttle transports along a public road in the vicinity of Arlanda Airport, outside Stockholm, Sweden. The Elways solution has had many years of development and tests in various environmental conditions.

Elonroad is a solution with a rail that consists of short segments in sequence. The rail is intended to be installed on the road surface and rises about 5 cm and has slantwise sides. The power receiver device has at least three contacts. Tests are ongoing in a closed environment in southern Sweden and demonstrations along an urban public road in the city of Lund will start within a year. A new design with the rail in the road surface level is being developed.

In addition, Honda R&D in Japan has worked with an ERS lane on the side of the road and performed tests of high-power charging at high speeds as described by Tajima et al. (2018).

2.3. Wireless solutions

A wireless solution uses a magnetic field to provide the energy. Electric current in primary coils installed in the roadway create magnetic fields which induces current in a secondary coil installed beneath the vehicle.

The commercial company OLEV, a spin-off of the university KAIST in South Korea, has developed technology for wireless power transfer to buses as described by Suh et al. (2011) and Ahn et al. (2013). Its solution has been tested on a public road inside KAIST's Daejeon campus since 2012. Since 2013, a bus route of 24 km traversed by a few buses has been in operation in Gumi with a total of 144 m of installed coils.

Bombardier has been conducting research on dynamic wireless power transfer as an evolution of its Primove commercial static solution. The system has been integrated into a Scania truck and tested in 2013 on an 80 m closed test track in Mannheim, Germany, as part of the Slide-in project described by Hjortsberg (2018).

The large EU project FABRIC has built two facilities for demonstrations of dynamic wireless power transfer: a test track outside Torino, Italy, using a Fiat van and power transfer technology developed by SAET group and the university Politecnico di Torino, and the Vedecom test track in Satory, France, using a Renault van and power transfer technology based on a commercially available static wireless solution from Qualcomm. The FABRIC project concluded its demonstration activities at the end of June 2018[†].

A test track for dynamic wireless power transfer has been completed at Utah State University using technology developed by WAVE. A system in the range from 25 kW to 40 kW can be tested using a 20-seat passenger bus[‡].

In recent years the Israeli company Electreon (previously Electroad) has been known for its ambition to enable large scale adoption of pure electric buses by developing a dynamic wireless electrification system for urban transportation. Tests are ongoing in a closed environment in Tel-Aviv and demonstrations along a public road in the vicinity of the town of Visby on the Swedish island of Gotland will start within a year.

3. Methodology

3.1. Maturity of complex systems

A technology whose scientific background is well understood is in this context considered to be mature, regardless of how long it has been in use. The ability to assess technology maturity of complex systems is important for acquisition planning, which calls upon a systematic method for such assessments.

Technology maturity is an important variable of the model called Gartner hype cycle[§] that aims to graphically distinguish publicity and hype from adoption and commercial viability of a technology. The diffusions of innovations model is closely related to the adoption life-cycle of a technology and describes how innovations are communicated and marketed into the society as described by Rogers (2003) and Moore (2014). However, while the Gartner hype cycle and the diffusions of innovations models are related to the spread of a technology into the society, they are not suitable for an assessment of the reliability and usefulness of a technology for a certain application.

NASA invented Technology Readiness Levels (TRLs) in the 1970s and made further developments in the 1980s and 1990s as described by Banke (2010). Other organizations have continued the development and the U.S. Department of Defense (DoD) has with its guidance for Technology Readiness Assessment (TRA) described "a systematic, metrics-based process that assesses the maturity of, and the risk associated with, critical technologies" (2011). Technology Readiness Assessment (TRA) is today an established method of estimating the maturity of a technology system for a given application. The first step in a technology readiness assessment is to analyze the different elements of the system and identify the critical technology elements (CTE). The next step is to estimate the maturity of each CTE for the application following a well-defined TRL scale. Finally, an aggregated maturity estimation using the TRL scale is made for the system. The definitions of the nine levels are as follows:

[†] https://www.fabric-project.eu/
[‡] https://select.usu.edu/evr/
[§] https://www.gartner.com/en/research/methodologies/gartner-hype-cycle

TRL 1. Basic principles observed and reported.
TRL 2. Technology concept and/or application formulated.
TRL 3. Analytical and experimental critical function and/or characteristic proof of concept.
TRL 4. Component and/or breadboard validation in laboratory environment.
TRL 5. Component and/or breadboard validation in relevant environment.
TRL 6. System/subsystem model or prototype demonstration in a relevant environment.
TRL 7. System prototype demonstration in an operational environment.
TRL 8. Actual system completed and qualified through test and demonstration.
TRL 9. Actual system proven through successful mission operations.

The U.S. Department of Defense has also developed Manufacturing Readiness Levels (MRLs) intended for production contexts (2011). However, the technology and manufacturing perspectives are not the only relevant perspectives while assessing the potential and possibility for large-scale deployment and usage. Market and social acceptance are for example also important as discussed by Gustavsson et al. (2019).

3.2. Application of TRA and the TRL scale on electric road systems

The TRA method has proven to be a useful method for assessing the technical maturity of ERS, as shown e.g. by Sundelin et al. (2016) and Gustavsson et al. (2017). The present work has therefore started with a system description (Section 4), followed by an identification of the critical technology elements (Section 5), and concluding with maturity estimations following the TRL scale (Section 6).

One important part of the methodology work has been to examine how the TRL definitions and descriptions from U.S. DoD's TRA guidance shall be applied to an ERS context, i.e. determine useful and clear meanings of "relevant environment", "operational environment", "system model", and "system prototype". The result is as follows:

TRL 5. Component and/or subsystem validation along test track and subject to any realistic weather condition.
TRL 6. Demonstration vehicle propelled by power from ERS equipment along test track and subject to any realistic weather condition.
TRL 7. Demonstration vehicle with prototype power receiver, running at typical operational speeds along a public road during any realistic weather condition, and propelled by power provided by a prototype power transfer subsystem installed in vehicle and deployed along the public road.

In addition, for TRL 8 the U.S. DoD's TRA guidance gives the following useful description "Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. […]".

4. System hierarchy of ERS

To perform a TRA the system needs to be described in detail. In general, an electric road system consists of five different subsystems as illustrated in Fig. 2 and described below.

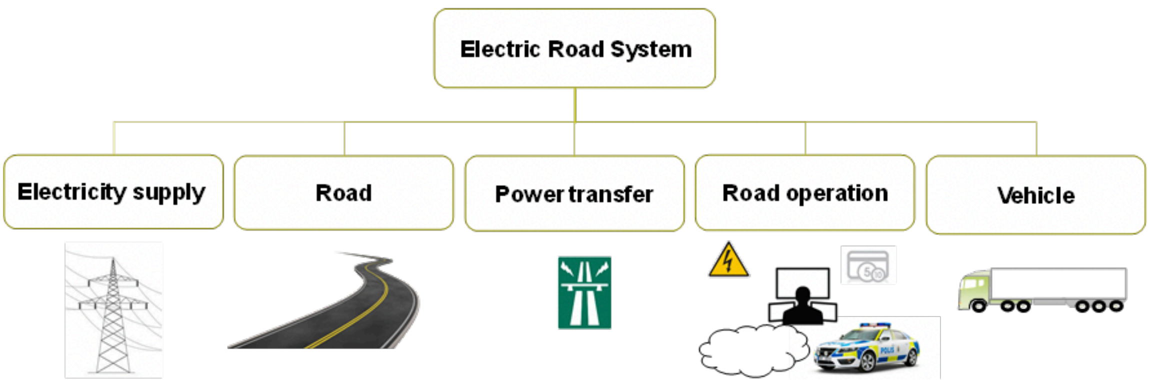

Fig. 2 Overall system layout of ERS with five subsystems.

The *electricity supply* consists of transmission, distribution and management components. Transmission includes how the electric power flows from the generation sources over long distances. Distribution is how the power flows through a grid to the power transfer subsystem. The management component controls the operation and balance the energy.

The *road* subsystem consists of pavement, barriers and auxiliary components. The pavement includes the actual structural body and road markings. Barriers includes both safety and noise protection components. Auxiliary components are road signs and other necessary roadside components.

The *power transfer* subsystem is divided into three components: road power transfer, vehicle power transfer and control. The road power transfer component consists of in-road and/or roadside equipment that handles detection of the vehicle and transferring of power from the road. Vehicle power transfer controls safe activation and operation of a power receiver, and measures transferred energy after successful acknowledgment. The control component monitors the energy handover and system operation.

The electric *road operation* subsystem controls the energy management of the overall system, provides user information and handles payment and billing. This subsystem also handles access and lane control of the road based on vehicle identification.

The *vehicle* subsystem includes the necessary component that converts the power from the power transfer subsystem into either propulsion of the vehicle or to energy storage. A control component provides user information, fleet management and vehicle positioning.

5. Critical technology elements of ERS power transfer

Through an analysis of the different elements of a general electric road system, the critical technology elements can be identified. The analysis shows that all subsystems are critical in order to ensure high quality service and high uptime of the total system, but the power transfer subsystem is found to be the most fundamental for the ERS concept and also includes electrical hazards and the least proven components. The generic technology elements of the power transfer subsystem are displayed in Fig. 3.

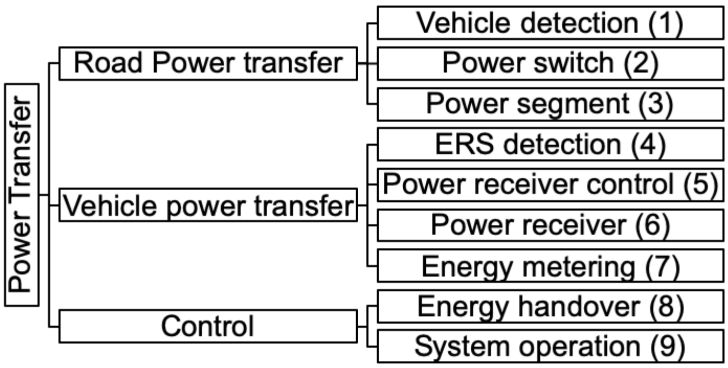

Fig. 3 Generic view of the power transfer subsystem.

When the vehicle enters the electric road (3), the vehicle and the performance of equipment is detected (1). A sensor on the vehicle detects the power supplier (4), and controls (5) the movement and position of the power receiver device (6). In normal operation the power is switched on, but can at any time be switched off in case of emergency or failure detection (2). When the energy receiver is successfully connected to the power supplier, the current control of the power transfer is handed over to the vehicle through overvoltage protection and fuses (8). The energy metering (7) and system performance is monitored in an operation and control centre (9).

The electrification of long-haul freight transportation has been the driving force ERS and continues to be the focus for several activities. Studying the available technologies reviewed in Sec. 3, we find that the Swedish demonstration project with an overhead-line technology has been going on since more than three years and that it provides lot of public information. This case is therefore used to map the generic technology elements of the power transfer subsystem as displayed in Fig. 4. However, this does not exclude other technologies since road electrification can be utilized for various kinds of vehicles, e.g. trucks, buses and cars, even though not all types of ERS technologies are suitable for all kinds of vehicles.

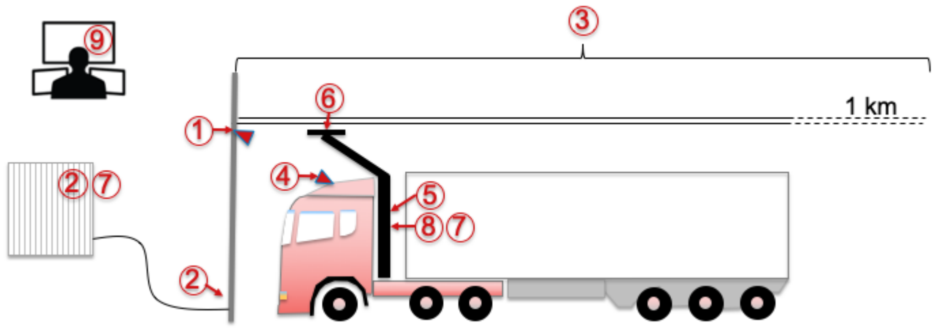

Fig. 4 Mapping of the power transfer subsystem technology elements to the Swedish demonstration project with an overhead-line solution. A energy meter (7) can be installed at different locations depending on the solution.

Focusing on the novel application of power transfer from a road to a moving vehicle in a reliable manner and avoiding electrical hazards, the understanding of the authors is that the critical technology elements are power switch, power receiver control, power receiver and energy handover.

6. Technology Readiness Assessment of ERS power transfer technologies

A maturity assessment following TRA "by the book" requires access to subject matter experts and supporting information such as test data. Instead, the authors have in the present work made a simplified technology readiness assessment of different ERS power transfer technologies using public information available in December 2019.

The maturity estimations below have followed TRL definitions adapted for an ERS context as given in Section 3.2. The basis for the assessment is the application of ERS for heavy duty vehicles operated at speeds normally occurring on country roads and highways, and subject to realistic weather conditions for Northern Europe. At the moment, only two ERS technologies have been demonstrated for this application and during at least one summer and one winter season. The progress of these demonstration activities has been reported by Region Gävleborg (2018) and eRoadArlanda (2018), respectively. These two demonstrations and also other projects have been closely followed by the authors.

6.1. Overhead-line solutions

System prototypes of the overhead-line technology from Siemens have been demonstrated for over three years along a public highway as reported by Region Gävleborg (2018). The first system prototype version has TRL 7 and there are components such as the overhead lines that are believed to have TRL 8. However, the power receiver and its control have recently been redesigned due to lessons learned. The new system prototype version has TRL 6 and needs to be demonstrated during winter conditions before the system can said to have completed TRL 7.

6.2. Rail solutions

Alstom ERS has TRL 5 since the power transfer components have been integrated and validated to work together at a test track. There is no public information about demonstration of vehicle propulsion. It is however believed that Alstom is able to perform a quick maturity development.

The Elways technology has at least TRL 6 since a system prototype have been demonstrated for more than one year along a public road as reported by eRoadArlanda (2018). The wear of the power receiver is however at the moment not acceptable for long-term operation and TRL 7.

The Elonroad technology has TRL 5 since the power transfer components have been integrated and validated to work together at a test track. The new design with the rail in the road surface level has TRL 4.

The Honda technology with an ERS lane on the side of the road has TRL 4 when considered as a system. Some technical components have TRL 5.

6.3. Wireless solutions

The technology from Bombardier has TRL 5 since the power transfer components have been integrated and validated to work together at a test track. Some components have however not been fully integrated in the vehicle.

The OLEV technology is found to have TRL 7 for the application of urban buses, even though the available test result information is limited and there might be challenges that imply TRL 6 in reality. The technology has TRL 4 for long-range and high-speed applications.

The technology from WAVE and the technologies studied in the FABRIC project have not been considered due to lack of available information.

The Electreon technology has TRL 4. A rapid maturity development is expected in order to be able to perform demonstrations in an operational environment within a year.

7. Conclusion

Electric Road System (ERS) is a technology concept that has the potential to heavily reduce fossil fuel dependency and deliver several benefits for the climate, environment and people. The investment cost to implement ERS will be high and decision makers will require knowledge about how mature different solutions are compared to the conventional and alternative technologies.

The maturity level of ERS can be assessed using the established Technology Readiness Assessment (TRA) method using well-defined TRL definitions. However, this requires access to subject matter experts and supporting information such as test data. One important part of the methodology work has been to examine how the TRL definitions shall be applied to an ERS context, i.e. determine useful and clear meanings of general wordings.

In this article an assessment outline has been performed in order to make a comparison of ERS maturity possible. To be able to perform a TRA a system description is required, but since we lack the detailed information a generic system hierarchy was used.

The review of current ERS project shows that there are many ongoing activities and many of the projects will most likely take large steps on the TRL ladder within the coming years. To gain confidence it is essential that test and validation results becomes open for public review.

The TRL mapping of current ERS projects around the world shows that the maturity level of some of the critical technology elements are high, but that some elements have lower maturity and some of the technologies have not yet been used to propel a vehicle.

The performed assessment in the present work cannot be regarded as a complete TRA "by the book" due to lack of access to necessary information. The TRL findings reflects the authors' opinion based on the available public information in December 2019 and will change when new information becomes available. Despite these shortcomings of this assessment, it is believed that the results regarding the maturity of power transfer technologies for electric road systems are valuable for decision makers.

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