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Reducing the environment impact of large battery systems with Electric Road Systems

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Executive Summary

A radical transformation of the transport industry is required in order to achieve a fossil fuel free vehicle fleet and to reach the greenhouse gas emissions goals, and electrification plays an important part. An electric road system (ERS) is a road which supplies power to electric vehicles travelling on it and comes with several benefits, such as extended driving range, reduced need for batteries and flexibility and convenience for the driver who no longer needs to stop to recharge. Research shows that the reduction in battery sizes can be up to 70% and, as a consequence a significant reduction of CO2 emissions, in comparison to a Battery Electrical Vehicle (BEV) designed for fast charging.

Keywords: Battery electric vehicle (BEV), charging, infrastructure, extended range electric vehicle, wireless charging

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1. Electrification of road transport

Decarbonization of road transport is a fundamental step towards significant reduction of the global CO2 emissions. Electrification of road transport facilitates CO2 reduction, to the extent that the electric energy used is generated from sources with a low CO2 intensity. Since renewable electric energy generation in a global perspective is expected to grow significantly over the near few years [[1]] with photovoltaics potentially being the dominating electric energy source already in 2027, electrification of road transport is a promising path to CO2 reduction.

Electrification of road vehicles is however challenging from several viewpoints. The electric propulsion itself is an improvement compared to combustion-based propulsion, since an electric traction systems is significantly smaller, lighter and more efficient than the corresponding combustion traction system. The challenge lies in the way energy is transferred to and stored on board an electric vehicle.

The electric energy transfer can be made in three different ways:

1. The on-board battery energy storage can be filled by direct transfer of electric energy, called charging. The charging rate is limited by the on-board battery energy storage capacity to receive electric power. This capacity is usually related to the energy storage capacity and expressed in the unit “C”, where C=1 refers to a charging power that fills an empty battery in 1 hour. C=2 is twice as fast and thus fills the battery in 0.5 hours. Modern full electric vehicle batteries are designed to store large amounts of energy and are capable of

being charged at a rate of C=2…3, but this ability is tapered as the battery is charged approaching C<0.5 for an almost full battery. This means that a full charge of an electric vehicle battery takes place with an average C-rate near C=1 corresponding to one hour. Part recharging can be made faster, typically from 10% to 80% of full battery in about 20 minutes, like the Korean car OEM Kia EV6 [[2]], corresponding to C=2.3. This is referred to as fast charging. If longer charging times is allowed, like night-time then the C-rate is much lower.

2. An alternative is to replace an empty battery with a full one, called battery swap. There are several automotive OEM's on both commercial vehicles and private cars, like the Chinese car OEM NIO [[3]], that are designed for a systematic battery replacement in just a few minutes in dedicated battery swapping stations. The empty battery is then recharged in the battery swapping station at a lower C-rate than would have been needed with fast charging. On the other hand, the batteries located in the battery swapping stations represent an additional amount of battery units in excess of those installed in the vehicles. The total amount of battery packs will inevitably be higher in a road transports system based on battery swapping, but it is not evident that the total battery capacity is higher, since many vehicles can be equipped with relatively small batteries suitable for daily commuting and swap to bigger batteries for long trips only.

3. A continuous supply of electric energy can be provided at least for parts of a travelled distance on a public road. This kind of energy transfer can be referred to as an "electric road system" - ERS, and replaces partly the role of fast charging. While on an ERS energy can be provided both for propulsion of the vehicle and for charging of an on-board battery. The need for on board energy storage is reduced. It can be shown [[4],[5],[6]] that even with a fraction of a main road system equipped with ERS, the battery capacities installed in most road vehicles can be reduced by 50%-70%.

This paper reports on the experiences of building and using an advanced ERS, with several different road vehicle types.

2. Electric roads

An electric road refers to a road that includes some kind of technology that facilitates electric energy transfer from the road to the vehicles driving on it. Several different technologies in several different forms of implementations can be considered.

The energy transfer can be made in a conductive way, meaning that some kind of sliding contacts are used. This is the oldest form of continuous electric energy transfer to vehicles, used in trains, trams and trolley buses since a century and in late years subject to intense development.

The energy can also be transferred in an inductive way, via a high frequency magnetic field that connects a transmitting part, usually installed just beneath the road surface and a receiving part installed in the vehicles, usually underneath the vehicle body.

The energy can finally be transferred via high frequency electric fields, but this alternative is related to challenges with voltage levels that make the alternative practically unrealistic.

The energy can be transferred from different directions. Conductive ERS exist in at least three different forms:

1. Conductive transfer from above the vehicle via catenary lines about 6 meters above the road, like with Siemens eHighway [[7]]. This technology is derived from train technology and suitable for supplying electric trucks, but does not work with smaller electric vehicles like cars.

2. Conductive transfer from the side of the road, like Honda's system [[8]], where the vehicle connects conductively to a continuous parallel 2-pole supply on the side of the road via an arm extended from the side of the vehicles. The system is originally developed with racing in mind and Honda has shown ability to transfer over 400 kW in 200 km/h.

3. Conductive transfer from the road surface where the vehicle connects conductively to either a continuous parallel 2-pole supply, like with Alstom [[9]] or Elways [[10]] technologies or an alternating 2-pole supply like Elonroad's [[11]] technology.

Inductive energy transfer from the road where a set of coils in the road create a local high frequency magnetic field vertically directed from the road that is linked to receiving coils mounted under the body of the vehicle. The Israeli company Electreon [[12]] manufacture an example of this technology.

2.1 Safety

There are many safety aspects to consider related to ERS. The *electric safety* means that there should be no risk related to touching the electric road itself or a vehicle that is connected to an electric road. Touch protection of the ERS itself is accomplished by making the live conductors inaccessible by hanging them high above ground like with catenary wires or covering them with the vehicle. Touch protection of the vehicle is accomplished by a doubly isolated and galvanically separated energy transfer from the ERS to the vehicle, combined with a isolation fault monitoring system on board the vehicle.

Mechanical safety refers to the road friction for those ERS technologies that involve an installation in the road surface, that is the conductive ground-based technologies. In those cases a pattern is engraved in the contact tracks that is small enough to not interfere with the sliding contacts but provide enough grip to the rubber in the wheels.

Thermal safety refers to the situation that occurs when a vehicle has been standing still on a piece of conductive ERS while charging. The contact points are heated by the charging current and the contact temperature is kept at safe levels by a combination of air cooling and delayed departure after a standstill charging session [[13]].

Electromagnetic safety has two sides; I) The magnetic field that extend outside the vehicle with inductive ERS must not exceed levels that can be dangerous for living beings and II) The electro magnetic compatibility (EMC) as radiated emissions should respect civil and military standards.

2.2 Some consequences of different charging technologies

Experience shows that, with a fast charging based road transport system, there is a need for a ratio of 1:100 or denser of {fast charging spots: BEV fleet} for cars [[14]]. In Sweden, with about 5 million cars, that corresponds to about 50 000 fast charging spots. Distributed along about 15000 km National and European roads this corresponds to at least 3.3 fast chargers per kilometre, or rather at least 100 fast chargers ever 30 km in average across Sweden. Along the bigger roads with higher traffic much higher numbers of fast chargers per station must be installed. With higher need for {fast chargers: BEV} ratio but lower vehicle number makes allocation of fast chargers for commercial vehicles a similar challenge.

Modelling shows that, with an ERS based road transport system, about 3000 … 4000 km of the 15000 km National and European roads would need to be covered with ERS [[5]] to facilitate "non-stop" travelling across the country with vehicles that need 50% - 70% less batteries than with a fast charger based system,

These conclusions highlight two challenges with electromobility; I) The huge number of fast charging stations needed in a fast charging based system, and II) The significant reduction of the amount of batteries needed and eliminated need for fast charging stations if ERS technology is applied.

2.3 Related CO2 emissions

Figure 2-3 shows the CO2 emissions from battery manufacturing (assuming 60 kg CO2/kWh battery capacity) and driving cars and trucks with a fully electrified vehicle fleet in Sweden with the battery amount needed for a fast charger based system (left bar) and an ERS based (right bar). Notice that the CO2 from driving (orange field) is the same for both, that the CO2 from battery manufacturing is NOT negligible in comparison to driving in either case, that the CO2 from battery manufacturing is significantly reduced with ERS and finally that the CO2 emissions form battery manufacturing is dominated by the car batteries. The conclusion is that with full electrification of road vehicles, the choice of charging technology has a profound impact on the CO2 emission, indirectly via the reduced battery need.

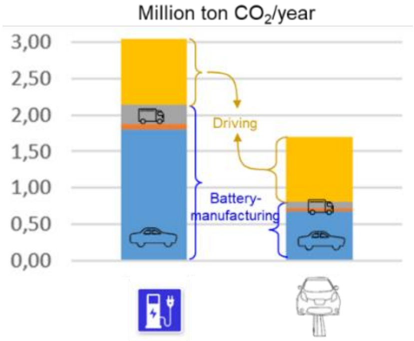

Figure 3-3 CO2 emissions from BEV's with a full electrification of cars and heavy-duty trucks in Sweden

3. The Evolution Road project

The objective of the Swedish electric road system project called EVolution Road, is to demonstrate a technology that makes it possible to reduce greenhouse gas emissions from transportation by electrification without big batteries or a very large number of fast charging stations. EVolution Road is a pre-commercial demonstration project with partners from the industry, academia, and public sector in Sweden. The consortium tests and demonstrates a road based conductive ERS on behalf of the Swedish Transport Administration. A one-kilometer ERS has been implemented and is tested in the city of Lund with technology from the Swedish company Elonroad. The ERS consists of a conductive rail immersed in the top layer of the road surface. The solution ensures highly efficient transfer of power and offers the charging ability to all types of BEVs. In addition to power supply, the ERS includes smart technology controlling access, safety, smart billing, data, and more.

3.1 The Elonroad system principle

The ERS technology developed by Elonroad AB is a longitudinally segmented ERS. This means that the contact surfaces are arranged as illustrated in Figure *3-1*. The left side of the figure illustrates the connection to the power grid, the rectification, some switchgear for safety and the track that internally has two main conductors (illustrated blue and red) carrying about 600 VDC. The dark grey contact surfaces transfers the power to the vehicle via minimum three sliding contacts (illustrated in green). The contacts surfaces are arranged such that every second of them is always connected to electric zero and the remaining are either connected to electric zero or to 600 VDC by means of transistors integrated in the road.

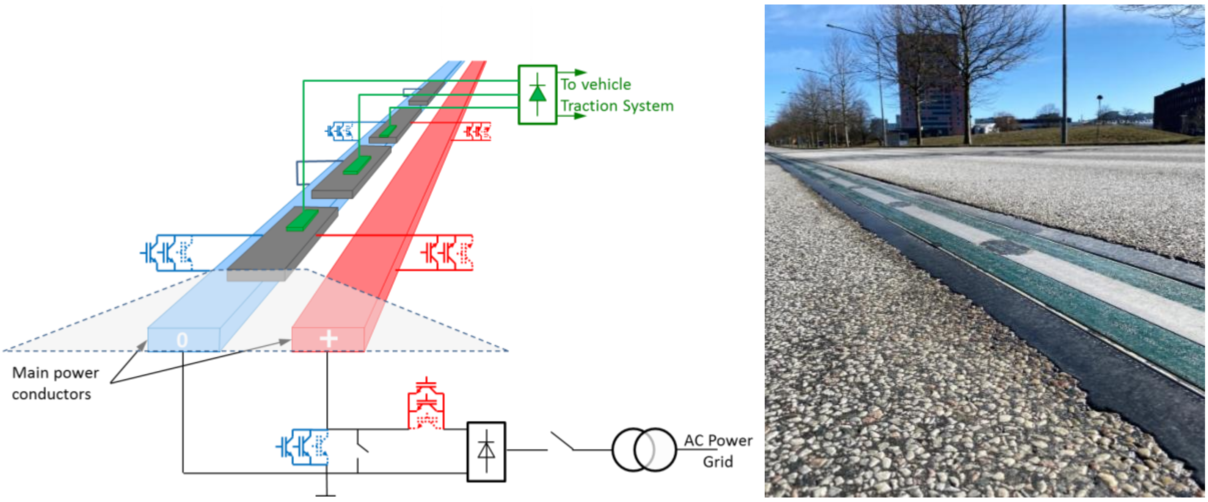

Figure 3-1 Left: The Elonroad principle, Right: a photo of the Elonroad ERS

The ERS is rectangular in cross section and built in 10 meter sections that are integrated in a groove in the road and secured by a bitumen mass. Figure *3-2* illustrates the installation process. The installation is fast, simple, and secure. A 40 cm wide and 6 cm deep groove is milled in the top layer of the road. Rails are then placed in the groove hanging on bars, leaving them level with the surrounding asphalt. The remaining space is filled with a bitumen-mass that fixes the rail to the road itself and the bars are removed. The whole process takes very little time and has no negative impact on the underlying layers of the road body. Once installed, the visual impact of the road is very limited.

Figure 3-2 Left: Installing the ERS, Right: Moulding the ERS into the groove in the road.

3.2 The power receiver – the "pick up"

In order to draw power from the longitudinally segmented ERS, at least three sliding contacts are needed to provide a continuous power flow from the ERS to the vehicle. The device containing the sliding contacts is referred to as the "pick up". It is a mechatronic device that is capable of lowering/raising the sliding contacts and to apply a specific mechanical pressure on the individual contacts.

It has turned out that there are benefits with having more than three sliding contacts. The road is normally not perfectly clean and small objects like grains of sand can lift the sliding contact and in the worst case break the current path to the rectifier causing an arc. This problem can be mitigated by I) splitting one sliding contact in several parallel smaller contacts and II) having more than three sliding contacts on one vehicle. Both these measured provide alternative paths for the pickup currents and secure that no arcing will be initiated. Figure *3-3* shows close-up photos of two different pickups.

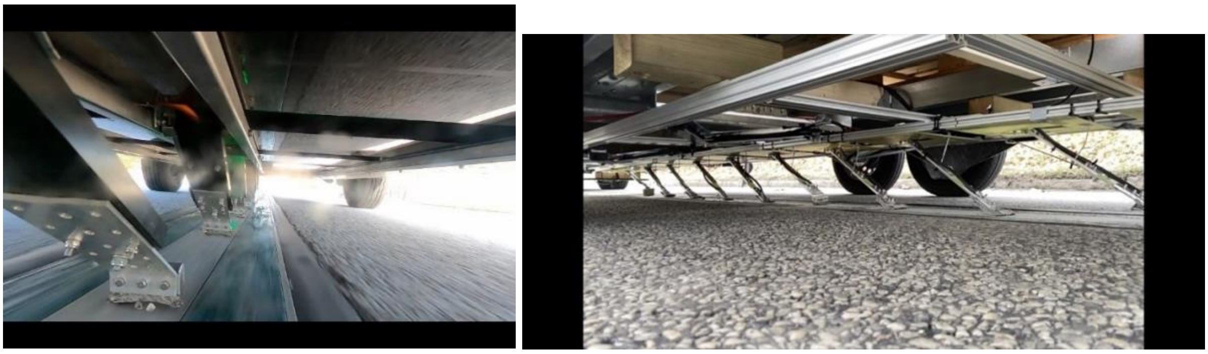

Figure 3-3 Different views of the sliding contacts of two different pick ups

3.3 Electric power transfer tests

The ERS is designed to transfer up to 300 kW to a vehicle even with a full flow of vehicles in normal traffic. This high power level is mainly intended for heavy trucks and not expected to be drawn by cars that rather are expected to draw up to 50 kW from the ERS.

Two types of tests are referred here; I) one where two vehicles are using the road at the same time and II) one where a dummy load on a trailer is designed to draw 300 kW from the road.

The two-vehicle test shows that the road is able to provide individual supply to several vehicles. In this case the Nissan Leaf drew 12 kW and the City Bus 210 kW simultaneously.

The dummy load test turned out to limit the power to 265 kW. The reason that the ERS could not provide the expected 300 kW is related to the rectifier station that is a bit under-dimensioned for this load level.

Figure 3-4 Left: A Nissan Leaf and a City bus drawing power at the same time
Right: A dummy load trailer with pick up for the ERS

3.4 Friction tests

A piece of the Elonroad track has been installed in a public road in northern Sweden, to subject it to more extreme winter conditions. This road has also been used for friction testing under winter conditions by a company specialised in such measurements. The friction on the route has so far been equivalent to the surrounding road, where the friction on the conducting tracks has been passed in 12 out of 13 measurements (the surrounding road has failed in more measurements). At the time the rail was failed, the deviation was marginal.

3.5 Efficiency calculations based on tests

The Evolution Road ERS system as well as the test vehicles are modelled in detail regarding all electric circuit parameters. Figure 3-5 left illustrates the electric system on a high level only. The grid transformer, the rectifier, the cables from the rectifier to the road, the ERS tracks as well as the sliding contacts and rectifier are all modelled in detail. The real ERS is also equipped with high precision and high sampling rate measurements systems that can measure voltages and currents in the interfaces A…E in Figure 3-5.

By both measurements and simulation an operating case is illustrated in Figure *3-5* right. It is a City Bus that charges at about 40 kW while standing still from about 7 seconds to 33 seconds when an acceleration starts and lasts until the bus leaves the ERS at about 56 seconds. The figure shows the measured (“m” in the legend) and simulated (“s” in the legend) losses between the different interfaces A…E. While standing still charging, the bus draws about 40 kW and the total losses are about 2.5 kW, corresponding to a charging efficiency at about 94%. When accelerating the power peaks at 180 kW when the losses are 8.5 kW corresponding to an efficiency at about 97%. These figures are not surprising in any way. When comparing to static fast charging it should be noted that when driving, some of the power used by an ERS vehicle is supplied directly to the wheels, not stored in the battery. This gives the total efficiency of an ERS system a benefit compared to a system where all energy has to be stored in the traction battery.

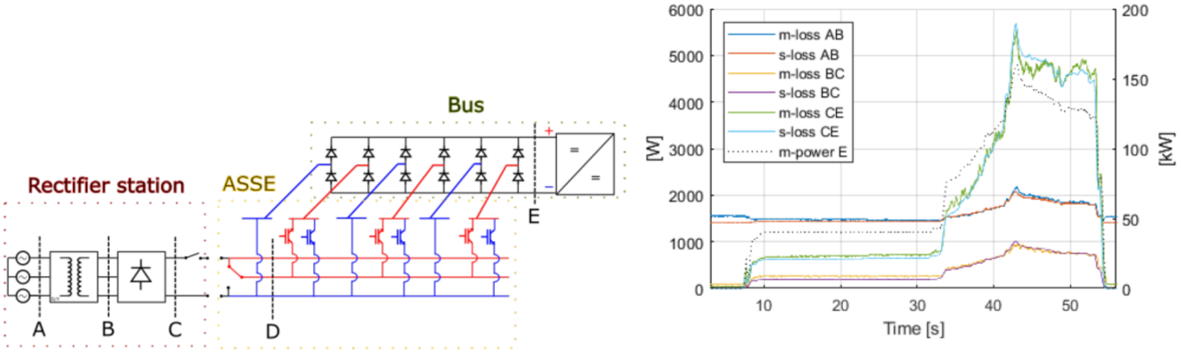

Figure 3-5 Left: High level electric ERS model Right: Measured and simulated data

3.6 Other tests

The Evolution Road project is performing a lot of tests on a regular basis. Electric safety test, EMC tests, acoustic noise tests are example of tests that are made but not reported here for space limitations.

The electric safety tests show that the safety solutions used in a Trolley bus works equally well in the ground based ERS used in all the tests and no hazardous chassis potential has been measured.

The EMC tests have shown very low/undetectable levels of electromagnetic radiations emanating from the ERS technology.

The acoustic tests were performed a summer night with very little traffic. The test object was the city bus illustrated in this paper and no measurement could indicate any noise from the sliding contacts that exceeded the background noise from the bus itself.

4. Environmental perspective

The ERS is constructed mainly of aluminium, with contact-surfaces of stainless steel and insulation made out of rubber. The project is currently evaluating the economic upside of recycling and will have more details further on, but it is already clear that recycling of the whole system after use offers no practical obstacles and that the metal-value of the ingoing parts far exceeds the cost of recycling. A major driver behind the project is the need to lower the overall need for batteries in a future with mostly BEV's. An important argument for an ERS—based infrastructure that can service all types of BEV's is that the about 90% of the batteries in existing and future vehicles is and will be in smaller vehicle, and about 10% heavy duty trucks (HDT)s. An infrastructure that only services HDT's will in a lesser way affect the environmental impact of battery production and the complexity of recycling batteries.

5. Conclusions

The design, installation, commissioning, and operation of the ERS in the Evolution Road project is a story of intense development adapting to unexpected conditions. The electric power transfer itself is working as planned. Since the road contains very powerful computers and communication, there is a risk that it is damaged by moisture. Protection against water/moisture penetration is one of the more challenging aspects of constructing an ERS of this type, but is solved. The project is receiving massive international interest and is regularly visited by international groups. The simplicity and elegance of the solution paired with the high electrical capacity of the system is drawing attention and may well change the view on how and where BEV's should be designed and what battery capacity a future electric vehicle actually needs, if this technology is available. A question bordering on philosophical would be: Electricity has no measurable weight, why should the fuel-tank weigh hundreds if not thousands of kilograms?

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Presenter Biography

Anna Wilkens is innovation manager and responsible for communications at EVolution Road. She has been involved in the project from start in 2019, during the different phases of tests, demonstration, development and evaluation of the electric road technology tested in the project. In addition to the electric road project, she is involved in mobility projects where stakeholders from the industry, academia, and public sector aim to find sustainable solutions to future mobility. Anna started her professional career in communications some 25 years ago and has a degree in communications from the University of Lund, Sweden.