Dynamic Charging Technologies for Electric Vehicles

Petr Velek

CTU in Prague, Faculty of Transportation Sciences

Abstract

The expansion of electromobility in freight transport is limited by performance parameters and the price of existing batteries in electric freight vehicles. Using dynamic charging systems is the way to efficiently operate electric freight vehicles. The dynamic charging technology for road vehicles is the subject of intensive research today, selected dynamic charging applications are tested in real road traffic in the world. The paper presents the functional principles of technologies for dynamic charging of electric vehicles, contact (conduction) charging systems, and non-contact (wireless) charging systems. The paper initially summarizes the reasons of public interest in electromobility, as a tool for reducing harmful emissions of conventional car transport, and explains the contribution of dynamic charging systems in the effort to decrease these emissions. The paper continues by presenting individual types of dynamic charging technologies and discusses test systems of these technologies implemented in the world. The paper concludes with a comparison of investigated dynamic charging technologies. While conduction charging systems are at an advanced stage of development, and generous projects of overhead catenary systems for charging of trucks are being prepared, wireless charging systems remain in the phase of designing.

Keywords: electric vehicle, dynamic charging system, overhead catenary, power rail, inductive charging

Introduction

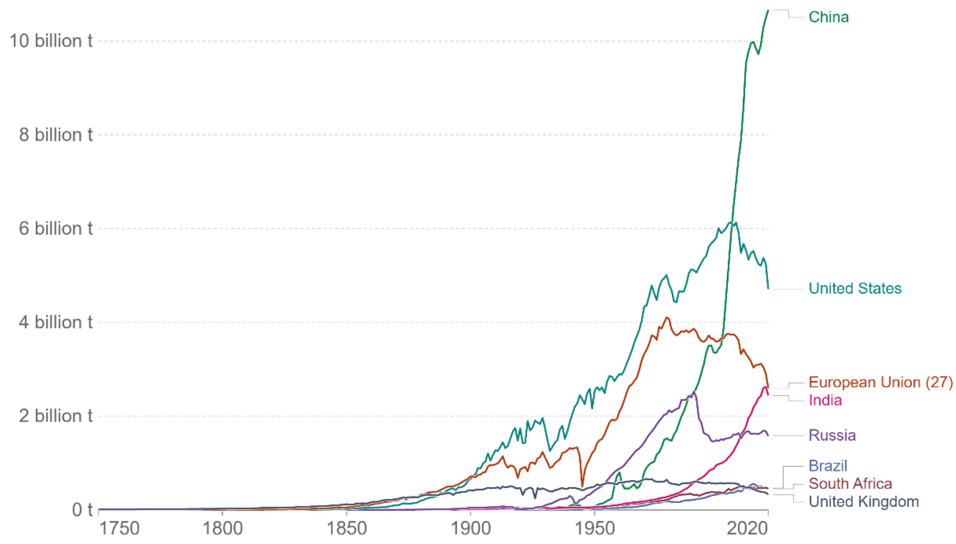
In addition to emission standards for the combustion of carbon fuels and to financial support for vehicles with biofuel engines, electromobility is an important and, in the context of predicted growth in transport performance, a necessary means of significantly reducing pollutants emitted by transport. The development of electromobility is conditioned by a reliable and sufficiently capacitive infrastructure of system equipment for recharging electric vehicles. Charging certain categories of vehicles, especially long-distance trucks, is generally inefficient due to the insufficient performance of existing charging stations and the limited capacity of truck batteries. A suitable way of recharging heavy electric vehicles can be found in the dynamic charging systems, technology proven in the operation of rail vehicles and currently developed and tested for road vehicles. Selected dynamic charging systems may in the future also be suitable for charging standard passenger vehicles. The aim of the paper is to get acquainted with the functional principles of the basic dynamic charging technologies for road vehicles and to describe the implemented systems using the dynamic charging technology in real road traffic in the world.

1. Reasons for the development of electromobility

The interest of public administrations in expanding electromobility is based on public strategic plans to ameliorate the climate and the related goal of reducing greenhouse gases and other pollutants emitted by transport. The UN countries have expressed their will to reduce greenhouse gas emissions through the Paris Agreement negotiated in 2015. The 192 countries ratifying the Paris Agreement have pledged to reduce greenhouse gas emissions by 2030 to the level of 55% of the volume of greenhouse gas emissions in 1990. Of the most emitted greenhouse gases, the transport sector is largely responsible for carbon dioxide emissions; in 2018, the transport sector globally emitted approximately 20% of all CO_2 emissions (Ritchie, 2020).

The evolution of CO_2 emissions for selected regions is shown in figure 1. In the context of industrial development, CO_2 emissions have been growing steadily in Europe and the USA since the mid-19th century; in other economically important regions, CO_2 emissions increase with a latency of 70-100 years. In European countries and the USA, the growth of CO_2 emissions in the 1980s slowed down, resp. stagnated due to the increasing share of nuclear energy in the energy mix of these countries. Since 2000, measures have been taken in the EU and the USA to reduce greenhouse gas emissions. The decrease in CO_2 emissions in Russia in the 1990s was linked to the country's political and economic transformation and a decline in industrial production and trade. In China, contrary to developments in Europe and the US, CO_2 emissions continue to rise continuously. With more than 10 billion tons, CO_2 emissions in China today are the highest in the world, per capita they are less than half the level in the US, per GDP they are significantly lower than in India or Russia. Today, the European Union has a higher GDP weighted by CO_2 emissions than the United States.

Figure 1: Evolution of CO_2 emissions in selected countries



Source: Global Carbon Project, ourworldindata.org

The major share of CO_2 emissions from the transport sector comes from road transport, the share varies from country to country depending on the degree of motorization and the share of the emission-free car fleet. In the USA and other developed countries, the share of CO_2 emissions from road transport in the volume of all CO_2 emissions from transport in 2010 was 60 to 80%. (Albuquerque, 2019)

Table 1: CO_2 emissions in selected countries in 2019

	CO_2 emissions (mil. t)	CO_2 emissions per capita (t)	CO_2 emissions per mil. $ of GDP (t)
China	10,490	7.34	0.73
USA	5,260	15.99	0.25
EU (27)	2,910	6.51	0.19
India	2,630	1.92	0.92
Russia	1,680	11.51	1.00
Brazil	486	2.30	0.26
South Africa	476	8.07	1.23
United Kingdom	369	5.43	0.13

Source: ourworldindata.org, worldbank.org
(note - GDP at current prices)

The volume of services in the field of transport is predicted to be three times the current value in 2050; the increment of services in transport will not be able to be diverted to emission-free railway transport, despite the planned increases in the capacity of electrified railway lines. The reduction of greenhouse gas emissions from road transport will not be achieved otherwise than by using vehicles with alternative powertrains, i.e. electric vehicles and vehicles with biofuel engines, in order to ensure existing road transport performance. The wider interest in electric vehicles is still limited by their insufficient performance parameters; the range of electric vehicles, their charging time, and purchase price are not offset by very low operating costs compared to conventional vehicles with internal combustion engines. The persistent weaknesses of electric vehicles due to the unsatisfactory properties of used batteries, their prices, capacity, size, and limited reserves of metals mined for their production are solved, among others, by offering hybrid vehicles with electric and internal combustion engines whose effects on reducing harmful emissions are only partial. Obstacles to a wider and faster substitution of the performance of conventional vehicles with fully electric vehicles can be solved by electric vehicles using roads equipped with dynamic charging systems on their routes. The use of a dynamic charging system allows the electric vehicle to be equipped with less capacitive and cheaper batteries and, in the case of long journeys, to significantly reduce the unproductive vehicle charging time at the charging station. Electric vehicle charging systems are divided into contact (conduction, wire) charging systems, with a traction line overhead or built into the road, and contactless (wireless) systems with energy transmitters, usually embedded in the road. In the literature, the term "electric road" (eWay, route électrique) is used for dynamic road charging systems.

2. Conductive dynamic charging systems for electric vehicles

Since 2016, the overhead catenary systems for charging electric freight vehicles have been tested in real operation in Europe. At the same time, the dynamic charging technology for electric vehicles using the traction line embedded in the road is being developed and examined in several test projects on marginal or isolated roads, e.g. in Sweden.

2.1 Overhead catenary lines

The overhead catenary line system enables the transmission of electricity from the public grid via a pantograph to a moving electric vehicle. Significant results in the development of overhead catenary technology for road vehicles are achieved by the Siemens mobility company, whose overhead catenary solution for electric freight vehicles has been used in 5 overhead catenary test systems on busy roads worldwide, 3 in Germany, one in Sweden and one in the USA. The overhead catenary line technology for the pantograph power supply is based on a long history of experience with electric traction on railway lines.

The Siemens mobility overhead catenary infrastructure consists of a system of substations, supplying the trolleys with 670 V DC, and two-pole catenary wires suspended on cantilever masts. The contact wires are suspended at a height of approx. 5.0 m, approx. 1.0 m above the highest permitted truck height. The distance between the masts is between 20 and 60 m. The overhead catenary line is divided into sections with a length of approx. 1.5 km, at the interfaces of which the overhead catenary lines are run in parallel to ensure continuous power supply to the vehicle. The overhead catenary is equipped with catenary wire breakage detectors.

Electric freight vehicles operated in the overhead catenary line system are equipped with a pantograph for taking electricity from the overhead catenary lines. In the Siemens mobility overhead catenary line system, a retractable pantograph is installed on the roof of the driver's cab, together with sensors for detecting the catenary wire above the pantograph. The pantograph extends and connects to the catenary wires automatically while the vehicle is moving without the need to decelerate. The contact of the pantograph with the overhead wire is via two sliders equipped with two carbon strips. The electrical energy taken from the catenary supplies the vehicle's electric motor and is also used to recharge the electric vehicle's battery. Vehicles also recharge batteries with energy recovered during braking. For operation outside the trolley line, trucks can be equipped with an additional internal combustion engine, including LNG, biogas, hydrogen. (Rudgarster, 2021; ELISA, n.d.; FESH, n.d.)

Overhead catenary line systems with Siemens mobility technology implemented in real road traffic are further presented individually.

a) *System FESH – Feldversuch eHighway Schleswig-Holstein*

The overhead catenary line system in Schleswig-Holstein was set up on the A1 motorway in the 5 km section between the exits Reinfeld and Lübeck on the Lübeck-Hamburg route. The motorway section in question serves transit traffic from Germany to Scandinavia, the Baltic countries, and Russia and, with an intensity of 8,000 trucks per day, it is one of the motorway sections with the busiest truck traffic in Schleswig-Holstein. The motorway in the section with the overhead contact line has three lanes in each direction. The project was initiated by the Government of Schleswig-Holstein, technical and knowledge support for the project is provided by the Research and Development Centre of the University of Applied Sciences in Kiel, the Technical University of Dresden, and the University of Heilbronn. The project is funded by the Federal Ministry of the Environment, Nature Conservation and Nuclear Safety. The motorway section in question is suitable for scheduled tests due to the intensity of truck entries into the system and the high traffic density of vehicles of different groups on the motorway. The operation of substations in the FESH overhead catenary line system is specific in that it rectifies a high proportion of electricity from renewable sources.

The FESH system was put into operation in autumn 2019, data collection for accompanying research is planned to end in 2022. The accompanying research aims to analyse the operation of the substation system working with electricity from a specific mix of sources, investigate the effects of wind on overhead wires and also, for example, to examine the psychology of drivers in the overhead catenary line system exposed to unusual objects on the motorway. The primary research goals of the FESH system are to evaluate the system's impacts on the environment (investigation of harmful gas emissions, noise, other effects on local fauna), to evaluate changes of the project's existential causes, and to assess the functionality and efficiency of recharging technology. (Rudgarster, 2021; FESH, n.d.)

Figure 2: The overhead catenary line system in Hesse

Source: ehighway.hessen.de

b) System ELISA – Elektrifizierter, Innovativer Schwerverkehr auf Autobahnen

The test system of the overhead catenary line in Hesse was implemented under the name of ELISA on the A5 motorway in the 5 km section near Frankfurt am Main between the exits Langen / Mörfelden and Weiterstadt. The construction costs of the project were EUR 14.6 million, the costs were covered by the Federal Ministry of the Environment, another EUR 15 million is budgeted for the accompanying research. The project is being carried out in cooperation with the Technical University of Darmstadt. The motorway section with an overhead catenary line is characterized by a very high intensity of traffic, up to 135,000 vehicles per day with a share of heavy freight traffic of 10%, the lane of the motorway has 4 lanes in each direction. The overhead contact line is supplied via two substations in Bornbruch West and Gräfenhausen West. The system operates 5 electric freight vehicles commuting on the route between the Cargo-City loading yard at Frankfurt am Main Airport and the Darmstadt industrial zone. The construction work of the overhead contact line lasted from May to November 2018, the system was put into operation in May 2019, the accompanying research of the overhead catenary line system is scheduled to be completed in 2022. (Rudgarster, 2021; ELISA, n.d.)

c) System eWay BW

The project of the overhead catenary system in the federal state of Baden-Württemberg was implemented on the federal road B462 in the section of 3.4 km between Kuppenheim and Gaggenau, 20 km south of Karlsruhe. The system is labelled eWay BW with regard to road category and location. 5 Scania CV vehicles are operated in the overhead catenary line system. Accompanying research will evaluate the economics of transport on the 18 km long route on road B462 between the Obertsrot industrial site and the Kuppenheim logistics centre, provided by various types of trucks, electric trolleys powered by the overhead catenary line system, fully battery electric vehicles, and hydrogen and LNG powered vehicles. There is intensive freight transport on the route section in question, with a load of 510,000 tons of paper transported annually from the Obertsrot factory to Kuppenheim. The evaluation of the operation of road trucks will also be compared with the performance on the parallel railway line. The number of level crossings on the Obertsrot-Kuppenheim route and the Gernsbach tunnel provide opportunities to carry out scheduled tests in terms of specific infrastructure and traffic. One of
the reasons for the non-implementation of a longer overhead contact line on the Obertsrot - Kuppenheim route is the directional conditions of the B462 road, which is not suitable for the installation of the overhead catenary line, e.g. around the town of Ottenau. The total costs of the overhead catenary line system, including the costs of the accompanying research, are EUR 28 million, 94% of which are borne by the Federal Ministry of the Environment. The project is being carried out in cooperation with the Frauenhofer Institute for Systems Research and Innovation (Fraunhofer ISI). The overhead catenary system was put into operation in June 2021, the construction work lasted 13 months, the operational phase of the system is planned for a period of three years. (Rudgarster, 2021; eWay BW, n.d.)

d) Overhead catenary line in Sweden on the E16 motorway

The overhead catenary line system in Sweden was set up on the E16 motorway in the 2 km section between the Kungsgården and Sandviken Västra, 170 km north of Stockholm near the port city of Gävle. It is the first overhead catenary line system of its kind on a public road, the operation of the system started in June 2016, and the first test system in which the operation was terminated in 2021. Three Scania hybrid trucks with a 20 kWh battery were operated in the overhead catenary line system. The source (Lindgren, 2020) reports on the operation of the system after the circulation of electric vehicles for more than 2,000 km for a period longer than 3 years, and according to this source, the experience with the operation of the system is positive. Weaknesses in the functionality of the system were partly manifested in the winter periods in bad weather. Deficiencies in the functionality of the detector for detecting the catenary wires above the vehicle during heavy snowfall have been eliminated. There is still a danger of snow accumulating on the overhead line cantilevers, a pile of snow falling from the contact wires endangers passing vehicles. The challenge is to modify road maintenance vehicles (e.g. milling machines with a hopper conveyor) to suit the lower structural clearance of the road with the overhead catenary. Based on favourable results from the operation of the catenary line test system in Gävle, a 21 km long permanent catenary line project on the E20 between cities Örebro and Hallsberg, approximately halfway between Stockholm and Gothenburg, is being assessed in Sweden. (Widegren, 2022)

e) Overhead catenary line in Los Angeles

The overhead catenary line test system in the USA was set up on the I710 motorway in the 1-mile section in Carson, Los Angeles. Three freight electric vehicles are operated in the overhead catenary line system, one fully electric vehicle, two hybrid vehicles with a diesel combustion engine, resp. with a CNG engine. The cost of the project was $ 13.5 million. The overhead catenary line runs near two major seaports in Long Beach. The motivation to reduce exhaust emissions in California is multiplied by the frequent occurrence of oxidative smog arising from the reaction of exhaust gases and sunlight. (Siemens, 2017)

2.2 Road with a power rail

Another way of the dynamic conduction charging for electric vehicles is via a power rail, placed in a shallow groove in the road or in a protective belt attached to the road. The vehicle is equipped with a current collector with a movable arm mounted on the chassis, the supplied current recharges the electric vehicle battery or powers the electric motor. The company Innorail, taken over by Alstom in 2004, is a pioneer in the development of conduction charging solutions via rails in accessible urban areas. Its own technology of conduction charging APS (Alimentation électrique par le sol) was developed to power the trams on lines in densely populated urban centres to avoid the installation of overhead catenary wires. The technology was first used on a network of new tram lines in central Bordeaux, launched in 2003, followed by the implementation of APS on tram lines in Reims, Angers, Orléans, Tours, Dubai, Rio de Janeiro, and Sydney. The power rail of the APS system for trams consists of a series of 8 m long rail segments conducting electrical current, separated by 3 m long rail insulation segments. According to the coded radio communication between the vehicle and the APS system, the power supply of the conductive segment on which the vehicle stands or passes is switched, the vehicle is supplied from the rail via two current collectors on each chassis. (Taufiq, 2007, Guerrieri, 2019)

Based on APS technology, Alstom, in cooperation with Volvo company, is developing a dynamic charging system for road vehicles. The length of the conductive rail segments in the road is assumed to be a priori the same as for the rail in the tramway, although the conductive segment will typically be longer than the powered road vehicle. The system with the power rail in the road switches on the power supply to the conductive segment only when the vehicle passes at a certain minimum speed from which the expected minimum length of the danger zone in front of and behind the vehicle results; entering it poses a danger for pedestrians or animals, this zone will be longer than the length of the power rail conductive segment. The power rail conductive segments are placed 15 mm above the road surface, this placement is sufficient for the outflow of water through the rail in heavy rain. In the event of flooding of the rail with water during extreme rain, a protective mechanism is activated, which interrupts the supply of electricity to the conductive segment flooded with water. (Sul, 2018) The Alstom conductive rail system is being tested at Volvo's test site in Sweden.

The Swedish company Elways, founded in 2009, is developing its own system of dynamic charging via the power rail in the road. The Elways charging system is not based on technology applied in another transport system. Contrary to the APS system, the conductor of the power rail is placed in a groove below the road surface, access to the conductor by a current collector on the vehicle is through a narrow gap in the carriageway, the collector draws current only at specific pressure on the conductor. Following the example of the APS system, the safety of life in contact with the supply conductor is guaranteed by the fact that the conductor is divided into partial conductive segments and the voltage in the conductive segment is switched when a current collector is detected in the segment. (Sul, 2018) The challenge in the development of Elways technology is also to ensure the operability of the charging system in bad weather. The groove of the rail in the road and the placement of the supply conductor in the groove are designed to ensure the outflow of rainwater from the road. In case of heavy snowfall, the use of a special plough to remove snow from the power rail is assumed, and in conditions with frequent freezing air temperatures, it is proposed to equip the power rail with electric heating. For testing purposes, the Elways conduction charging system was set up in Sweden, on road 893 in a 2 km section between the Stockholm-Arlanda airport freight terminal and the logistics centre in Rosersberg, 30 km north of Stockholm. In the test system, the charging of trucks and cars is examined, the tests proved the reliability of the technology for charging a truck weighing 18 t with an output of 200 kW at a speed of 60 km/h. (Elways, n.d.)

Figure 3: Elways technology conduction charging system

Source: elways.se

Another dynamic charging system developed by the Swedish company Elonroad is similar to Elways technology. The system of Elonroad is an original solution for a non-intrusive conduction line mounted in the protective belt fixed on the road. The belt with the power rail is 30 cm wide and 5 cm high, the edges of the belt are inclined at an angle of 10° to allow passage of road vehicles. (Elonroad, n.d.) The power rail consists of 1 m long conductive segments supplied with 650 V (Sul, 2018). The advantage of Elonroad technology is the possibility of quick installation of the conduction line on the road. The Elonroad dynamic charging test system was set up in 2019 in the centre of Lund, Sweden on a 1 km long road. The operational phase of the project is planned for 2022. The system primarily tests the operation of a Solaris bus being charged with an output of 150 kW. According to the source on the hydro.com portal (Hydro, 2020), Elonroad technology enables vehicle charging with an output of up to 300 kW at an efficiency of 97%. The partners of the electric road project are Lund University of Technology and the Swedish National Road and Transport Research Institute. The project in the city of Lund is specific for placing an electric road in the inner city.

Figure 4: Belt with a charging rail laid on the road – Elonroad technology

Source: elonroad.com, hydro.com

3. Wireless dynamic charging systems for electric vehicles

Wireless power transmission technologies have been studied since the beginning of the development of electrical engineering. Nikola Tesla made the first attempts at contactless electricity transmission at the end of the 19th century in Colorado Springs, USA. (Borts, 2016) There are basically two ways of wireless electric power transmission, inductive magnetic field transmission and capacitive electric field transmission. Due to the limitations of capacitive transmission technology, especially in low power and the need for a short distance between the capacitor coupling transmitter and receiver, only inductive energy transmission technology is used for recharging electric vehicles. The principle of inductive charging is based on the transfer of energy in the air gap between the primary and secondary coil, the primary coil (transmitter) generates a time-varying magnetic field, which induces voltage in the secondary coil (receiver). In the inductive charging system for electric vehicles, the transmitter is embedded in the road, the inductive coupling receiver is mounted on the vehicle, the voltage induced in the receiver supplies the vehicle with a current which drives the electric motor or is stored in the vehicle battery. To increase the transmission power, compensating circuits, consisting of capacitors, are integrated on both coils, compensating circuits serve to tune the resonant frequencies on both coils and increase the efficiency of inductive coupling. The functional principles of dynamic and static inductive charging do not differ in principle, however, dynamic charging of electric vehicles places greater demands on the robustness and performance of the charging system due to the size of the air gap of the inductive coupling.

Inductive charging technology for electric vehicles has been the subject of research in many countries around the world since 2000, with remarkable achievements at the beginning of development being made in South Korea. The cooperation between the KAIST (Korea advanced institute of science and technology) and the Korean railroad research institute since 2008 has resulted in several conceptual solutions for inductive charging systems for various types of vehicles, passenger cars, SUVs, buses charged at the air gap of 20 cm with an output of 14 - 27 kW. The charging efficiency was 71-83%. Bombardier, the rolling stock manufacturer, has been developing static inductive charging systems for trams and buses since 2010 and, based on this technology, tests the dynamic charging for road vehicles with an output of up to 200 kW at speeds of up to 70 km/h. (Sul, 2018)

In the field of practical testing of dynamic inductive charging in normal road traffic, the Israeli company Electreon is achieving a number of significant results. Electreon has set up a test electric road with its own inductive dynamic charging technology in Sweden, a 1-mile road section on the island of Gotland between the airport and the city of Visby, then in Karlsruhe, Germany, a 100-metre long road at the Rhine port, and also in Brascia, Italy, 1 km long electric road put into operation in December 2021. In established test systems, Electreon examines the charging of trucks weighing up to 40 tons, electric buses, and passenger electric vehicles. In the dynamic charging system in Sweden, charging with an output of 70 kW at a speed of up to 80 km/h is tested. (Coban, 2022; Electreon, n.d.) In 2022, Electreon won a tender to build the first induction road in the United States in Detroit. This is a 1-mile test induction road project designed to recharge various types of vehicles, the electric road operation is scheduled to begin in 2023. The project is supported by the Michigan Department of Transportation for $ 1.9 million. (Electreon, 2022; State of Michigan, 2022)

Figure 5: Induction coils of the Electreon system

Source: electrive.com

4. Summary

None of the diverse dynamic charging technologies for electric vehicles has yet been established on a wider scale in the world than in test systems on road sections shorter than 5 km. The charging system with the overhead catenary is so far the closest to the realization of a permanent electric road with a length of tens of kilometres. Derived from electric railway traction, this technology is considered reliable and easy to implement with high recharging power. Unlike overhead catenary systems, wireless and power rail contact technologies allow charging of lower vehicles, not just buses and trucks, to which a retractable pantograph can be attached. The disadvantages of wireless and contact technologies with a power rail are a priori lower charging power and the difficulty of installation on the roadway. A number of technical difficulties also remain to be solved for the mentioned technologies. For contact systems, ensuring the reliability of connecting the current collector to the power rail and the health protection during system operation, while keeping reasonable maintenance costs, are the subject of further development. For inductive systems, the efficiency of the vehicle charging technology is assessed, especially in the case of a large air gap between the transmitter and receiver of the inductive coupling. The common feature of dynamic charging systems is their high investment costs. In order to significantly replenish energy in the vehicle, the electric road must reach a length of tens of km, the establishment of such a long electric road involves investment costs in the order of tens of millions of euros which are profitable, compared to static charging devices, only on particularly heavily trafficked roads with the potential for dynamic charging of a large part of vehicles in the traffic flow.

Table 2: Overview of dynamic charging technologies for electric vehicles

	suitability for vehicles category	max. vehicle speed [km/h]	output [kW]
overhead catenary line	heavy truck	90	500
power rail *	passenger, freight	60	150-300
inductive charging *	passenger, SUV	110	70-200

Source: author
(- limited data, systems in development)*

Conclusion

The limits of existing batteries used in electric vehicles, especially unsatisfactory parameters of their capacity, weight, disproportionate prices, make it impossible to use long-distance heavy electric trucks efficiently. In addition to upgrading existing lithium-ion battery cells and using other types of batteries in vehicles (e.g. lithium-metal), the introduction of dynamic charging systems is another means of developing electromobility in freight transport; some conduction and wireless charging systems also make the use of standard personal electric vehicles more comfortable. The technologies of dynamic charging systems for electric vehicles are currently undergoing intensive development, the basic types of these technologies were presented in the paper. Selected dynamic charging systems, especially overhead catenary systems, have entered the phase of practical testing in normal road traffic, other technologies for charging road vehicles remain in the phase of solving conceptual designs.

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