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IMPEDIMENTS AND OPPORTUNITIES FOR RAPID ELECTRIFICATION OF ROAD TRANSPORT

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Abstract
Depleted resources of hydrocarbon fuels and environmental problems that arise from the mass application of internal combustion engines offer a chance for rapid development of electrified transport. The barriers currently limiting the mass introduction of electric cars to the general public are mainly due to constraints related to the search for a suitable electrical source for the vehicle and absence of the infrastructure to support electrified transport. With a sufficiently large financial outlay and increased involvement of the scientific and research communities, the quick resolution of these problems is undoubtedly possible.

Introduction
The development of electric car transport began in the first half of the 19th century and after a period of oblivion is back again. Not everyone knows that the pioneering vehicles that can be called cars were electric vehicles. Although the first car shall be deemed the design of the American Thomas Davenport of 1834, in Europe between 1832 and 1839, a Scottish businessman Robert Anderson invented the first crude electric carriage, and perhaps he is entitled to priority, [2]. The invention of the lead-acid batteries by Gaston Plante in 1865, their improvement by Camille Faure in 1881 and the development of better electric motors opened the way for the advancement of electric vehicles. Until the First World War, before the widespread polluting internal combustion (IC) engines, electric vehicles had beaten many speed and distance records. One of the most notable events of those times was the first time that a road vehicle crossed the barrier speed of 100 km/h with driver Camille Jenatzy on 29 April 1899, [2]. The electric vehicle, La Jamais Contente, powered by two electric motors with a total output of 100hp reached a maximum speed of 105.88 km/h. The threat of depletion of the profitable resources of hydrocarbon fuels used as a primary energy source for IC engines as well as the multi-level environmental and health hazards-generally threatening human existence-has necessitated the search for a way out of this impasse. The quick search for another resource that could be used for transport and that would also protect users from the serious health risks posed by IC engines became an imperative at the beginning of the XXI century. It is believed that the electric motor could be one such solution. The electric motor is environmentally friendly, is three times more efficient than the IC engine and perfectly meets the conditions required in drive vehicles, namely engine produced torque and power change as a function of speed. What is more, the electrical energy necessary for its operation could be acquired from sustainable energy sources.

Threats posed by modern road transport
The twentieth century and the beginning of twenty-first century are characterized by a continued increase in car production; it is forecast that in 2020 over 100 million units will be manufactured per year. Until now these have mainly been vehicles with combustion engines, which rely on petroleum-based fuels as their energy source. Consequently, this has resulted in a strong demand for and annual increase in oil extraction-the primary source of petroleum based fuels–and has significantly contributed to the rapid exhaustion of this resource. World oil reserves in 2013 were estimated at around 1688 billion barrels (230 billion tons). In 1986, the extraction of oil was about 60 million barrels per day in 1996, about 70 million barrels per day, 80 million barrels per day in 2004 and about 87 million barrels per day in 2013, [3]. These data show a clear conclusion that with such a large excavation in the second half of this century we may quickly run out of our primary energy source for cars with IC engines.

Long-term burning of large amounts of fuels has negatively affected the equilibrium of the ecosystem in which we live. Threats exist in many areas. Aside from the problems of degradation and pollution of the environment at the stage of extraction, transportation and processing of liquid and gaseous hydrocarbon fossil fuels and noise emitted by the vehicles, the biggest health problem is related to the poisoning of our atmosphere from the release of toxic combustion products from the tailpipes of all means of land, water and air transport. These include mainly: oxides of nitrogen, carbon, sulfur, unburned hydrocarbons, and until only recently, lead compounds widely used in fuel production. Much published research shows that these compounds threaten the health and even the life of man, [13]. These substances not only pollute the air we breathe, but also result in the so-called effect of acid rain, which endangers flora and fauna on a global scale.

Another serious problem is the rapidly growing greenhouse effect caused by increased concentration of carbon dioxide in the upper atmosphere. This phenomenon is dangerous, because the environment is not keeping pace with such rapid changes. Shares of carbon dioxide in the production of the greenhouse effect are estimated at 50% where the vehicles from the year 1980 emit over 30% of the substance. For this reason, attempts being made to reduce this problem include introducing standards limiting the allowable emissions of CO_2 to the minimum level, [17]. Reducing toxic exhaust emissions can be achieved mainly by decreasing the amount of burned fuel, and it should be noted that the modern internal combustion-engine car is still surprisingly ineffective, which significantly reduces this possibility. The efficiency of the thermal engine is between a 20–35%. Losses associated with inter alia the transmission of energy and incorrect driving techniques result in no more than 13% of the energy from the motor to be provided to the wheels. Therefore, given that the weight of the driver, the passenger and the baggage is less than 10% of the weight of the vehicle, to perform the useful task of moving, less than 1% of the energy contained in the fuel is consumed, [5].

To change such an unfavorable situation in 1993 the United States established the Consortium for next-generation vehicles, named the Partnership for a New Generation of Vehicles (PNGV), which included the three largest American carmaker companies: Ford, General Motors, Chrysler-and the US government which participated in 50% of the incurred costs of the project. Within this consortium's ambitious task of erecting to construct, within 10 years, a "supercar" that consumes 3 liters of fuel per 100 kilometers, while maintaining low emissions and the same levels of safety, comfort and price comparable to the average American mid-size car, [18]. After six years and expending more than 2 billion dollars, it turned out that the creation of such an economical and ecological vehicle is impossible, since physical laws, mainly those of thermodynamics, proved be too difficult to overcome.

Opportunities and barriers to the widespread introduction of the electric car

Fortunately, not everything has been lost, because Japan, which carefully analysed the reports of the American consortium, introduced to the market the compact, hybrid electric-petrol sedan of the first generation Toyota Prius in 1997, burning from 3.6 to 4.7 litres of fuel per 100 km, which was significantly approximated to the ambitious targets set by the PNGV. In terms of construction it was based on the Toyota Yaris sedan, one version of the Echo model, which was designed, among others, for the American market. The vehicle with an IC engine of 1.5 liter capacity has a maximum output of 58 hp, whereas the maximum output for an electric motor is only 40hp. The source of electricity came from NiMH batteries with an energy of 1728 Wh, weighing 57 kg, producing a voltage of 288 V. This solution, despite the fairly high price-two drives in one vehicle, the high price of batteries, computerized control system-turned out to be a success, and until now has sold about 3.2 million vehicles in the world in three generations, [16]. In 2015, the company announced the launch of a fourth generation model of this type, the Plug in Hybrid Vehicle (PHV) with even lower fuel consumption, mass and price.

However, hybrid vehicles are not entirely satisfactory solutions, since they still rely on uneconomical and non-ecological combustion engines, of which the total energy efficiency-including the full cycle of production, distribution and utilization of energy in the vehicle-is more than 4 times lower than electric motors. Therefore proponents of IC engines often criticize the electric car for being uneconomical, despite its use of electrical energy. If we calculate costs honestly the ratio of energy obtained to the money spent on its acquisition, it turns out that the cheapest for one GJ of energy invested in producing fuel and thus the furthest, in the US we can ride an electric car, for as many as 10460 km in a car powered by traditional petrol 5800km, powered by a gasoline from bituminous sands–1770 km and by shale petrol–1450 km, [8]. Distance travelled was calculated taking into account the energy required to produce and broadcast for each the fuel and energy density. Comparing only these two aspects it should be noted that electrically propelled cars are much more advantageous. Despite numerous barriers and strong resistance imposed by powerful gas-engine lobbyists, work on the introduction of electric cars resumed after the Second World War, but only model EV1 of the American company General Motors was mass-produced between 1996–1999. In this period, among the group of major electric car manufacturers, Japanese companies that introduced the Honda EV Plus and Toyota RAV–4 EV to the market should be included. In the next ten years, to more interesting solutions, we may also include the Ford Think. However, the greatest success has been the launch by Mitsubishi of the iMiEV model in 2009, which until 2013 sold more than 30 thousand copies. The iMiEV car is very economical, since it consumes only a little over 12kWh per 100 kilometers, which translates into a reduction in the cost of driving from 3 to 9 times its combustion counterpart. The vehicle can travel up to 160 km on a single charge and energy can be supplemented in three different ways. The maximum speed is 130 km/h. The high torque of 180Nm, achievable at low engine speeds, implies that the vehicle has a good acceleration. Charging time to the 80% of rated capacity takes around 30 minutes with a system of rapid charging (200 V, 50 kW and 250 A). The energy stored in the batteries is 16 kWh. The biggest marketing success achieved in recent years, goes to electric compact from C-class car Nissan LEAF (Leading, Environmentally friendly, Affordable, Family car), which received the title of World Car of the Year 2011 and reached a sales results of 100 thousand models–more than all the other competitors sold in the same period of time. Noteworthy is the product with interesting traction characteristics produced by the American company Tesla Motors. They began sales of the Tesla Roadster in 2003 and from 2012 introduced the luxury limousine Tesla S, powered by an electric motor with 302 to 416hp which can reach 100 km/h in 3.7 seconds, averaging a range of 340 km (with a maximum range of 500 km in the versions with lithium-ion batteries, (Fig. 1) and with an energy cost less than $2 per 100 km.

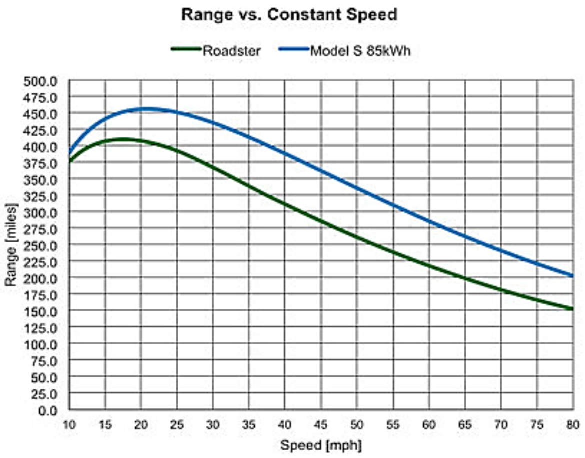

Fig.1 The range of Tesla S with the 85k Wh battery (top graph) and Tesla Roadster (lower graph) vs. constant speed, using the 2-cycle EPA test procedure, [7]

An interesting concept of an electric car was created by prof. Hiroshi Shimizu from the Japanese company SIM-Drive, [15].

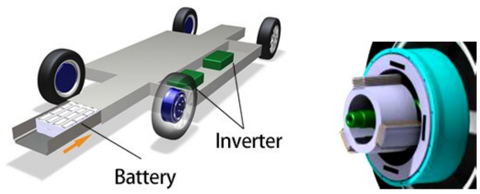

Fig.2 Concept of SIM-Drive, 4-wheel 4-drive, [15]

Incorporated into this concept by SIM-Drive (Fig. 2) are all of the necessary components for drive mounted in a rugged frame structure located under the vehicle floor and inside of the wheels (electrical motors). By eliminating many unnecessary components, the vehicle becomes lighter, inside the body is about 40 cm higher and ensures much more space relative to traditional solutions with the cubic capacity in the class B segment the interior volume of the E-type segment. Its low center of gravity and compact design increases driving comfort and safety in the event of a collision. This model provides a range of 351 km on a single charge and a top speed of 100 km/h in 5.4 seconds, which is the result achieved by the middle class sports vehicles. The greatest impetus to growth in the production and sales of electric cars was recently exhibited by China, as exemplified by products of BYD, and therefore the global automotive market is closely monitoring this process. In the opinion of the CEO of Renaults-Nissan, Carlos Ghosn, investments in the automotive industry will soon be driven mainly by plans to introduce more than two million cars with electric drive on the Chinese market by the end of 2020, [6].

Despite many convincing arguments, electric vehicles are rather slowly entering the world markets. This is due to many factors. First of all, it is very time consuming. According to estimates by the Laboratory for Energy and the Environment at MIT, the total time needed to introduce, for example, hybrid vehicles with petrol and electric engines is 35 years at the moment they are entering the phase of mass production, [5]. Success is not only based on technical and economic factors that extend or shorten the time required to implement new solutions, but also on a properly educated personnel. American and European universities of technology are quickly starting to introduce automotive electrical engineering into their programs of study, due to the lack of specialists in the area of automotive industry and automotive manufacturing, [4]. To accelerate the electrification of road transport increased funding is also required. The European Union, within of frame of the so-called Barroso plan, invested approximately 1.0 billion euros in the years 2010–2013 on the implementation of the Green Car. In ongoing research projects it is assumed that new-generation urban electric vehicles should reach speeds of at least 110 km/h with a full load, have a range of at least 160 km and only require 15 minutes of charging for at least 50 km of driving. Another major constraint in rapidly implementation of electric road vehicles is the lack of a suitable electrical power source. This problem is mainly due insufficient investments in R & D in the energy sector, which not only do not increase, but since 1980 has been steadily decreasing and for this reason global progress in this field has been hampered, [10]. Despite this unfavorable economic situation the electric vehicle has made surprisingly good progress. According to Volkswagen AG in the latest electric car E-Golf a new type of lithium aircraft battery will be used with a capacity of 80Ah and specific energy of 1000 Wh/kg (modern lithium-ion batteries have specific energy of 150-250 Wh/kg), [14]. A significant constraint when it comes to the use of electrochemical energy sources for vehicles is the long charging time for its batteries, although it should be noted that in recent years this has been greatly reduced. Present day rechargeable lithium-ion batteries can be recharged to 80% of their capacity over a period of 15 to 60 minutes, by being provided with a higher charging current, which can cause quicker degradation of the existing batteries. In order to eliminate the time wasted due to battery charging, Tesla engineers have proposed a system whereby driving under electrical power is possible after only about 90 seconds. The company offers special "battery swap stations" which will allow the rapid exchange of batteries in up to 95 seconds, [11]. Just enter your car on the appropriate platform and turn the drive off. The system installed at the station will quickly and automatically replace the uncharged batteries with fully charged ones. However, this means the need to create from scratch a new infrastructure in the form of a new generation station network of density similar to an existing network of gas stations. The most convincing arguments for the widespread introduction of electric vehicles are the application of electric propulsion motors. They fulfill in these vehicles a triple role: processing with an efficiency of 90% which is over three times more than that of heat engines. Converting electrical energy into mechanical energy used to propel the vehicle makes it possible to stop the vehicle with the possibility of converting braking energy into electric energy accumulated in batteries and super capacitors. This is not feasible in vehicles with combustion engines in which energy is irretrievably lost and in the generator mode converts kinetic mechanical energy into electricity. For example, when driving down-hill, decelerating, or while braking. Thanks to these advantages, electric cars are extremely economical in their consumption of energy needed to run them and much cheaper to operate.

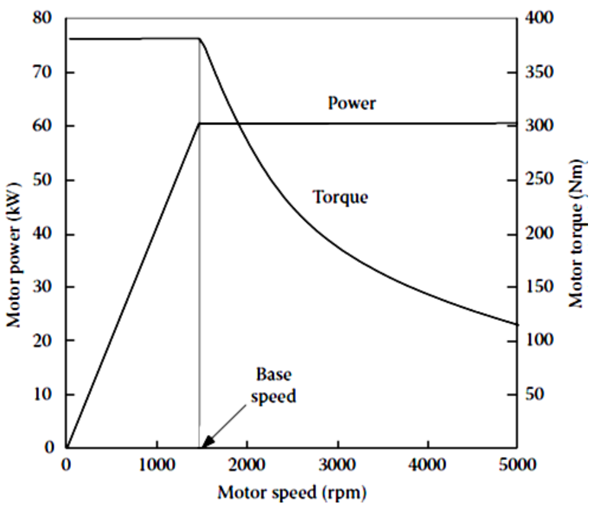

Fig.3 Characteristics of changes in torque and power of an electric motor with 60 kW, which is used in electric vehicle drive, [12]

Unlike industrial applications, motors used in electric cars must meet several different requirements. These motors must handle frequent starting and stopping, must allow for quick acceleration and deceleration, and be characterized by a high torque at start-up, low speeds and when driving uphill. In addition, motors must have a wide range of rotational speed and have sufficient and consistent speed as a function of power. Figure 3 shows the variation in characteristics of power and torque as a function of engine speed in a 60 kW engine, used to power electric vehicles. By obtaining maximum torque practically at the start, electric cars can in fact give up the gearbox. In the case of the application of motors in the drive wheels of the vehicle differentials and interfacing with the shaft electric motors also becomes superfluous. A fixed value of power over a wide range of rotational speed changes has a big impact on improving the dynamics of the electrically powered vehicle, without the need to downshift, often crucial in such a situation involving vehicles with internal combustion engines.

Renewable energy sources are an essential condition for the widespread introduction of eco-road electrically driven vehicles

Electric cars with applicable energy storage in the form of electrochemical batteries which–will be sourced from eco-sources—are as green as the energy required for charging their electric power. Currently the source of electric power is not green, because it is produced using mostly non-ecological fossil fuels that are characterized by relatively low efficiency thermal plants. Also the loss that occurs in the consecutive chain links of energy transmission and processing is very high, exceeding 90%. Already at the beginning of the chain, in the thermal power plant, the loss amounts to 70%, which means that the energy available to the user situated at end of the chain amounts to only 9.5 units out of 100 units included in the fuel used for its production in the power plant, [1]. Scientists have long been trying to find an answer to the question: how can low efficiency and non-ecological electrical power plants utilizing fossil fuels be replaced with efficient ecological sources of energy. In 2009, researchers at Stanford University published a ranking of reliable energy systems, taking into account their impact on global warming and other factors relating to the environment, such as pollution, environmental degradation, water consumption and management of natural resources. It follows that the best solution would be the application of methods that acquire energy using wind, solar, tidal, ocean currents, and rivers as soon as possible, which generally speaking, would mean that all the energy in the world would derive from renewable energy produced by wind, water and the sun–in short, the WWS system. According to data from the Energy Information Administration (USA), the theoretical level of electricity consumption in the world requires sources with a total power capacity of 12.5 TW. By 2030, it is estimated that the demand for power will rise to 16.9 TW, which would necessitate the construction of thousands of new coal fired power plants at a cost of approximately 10 trillion US dollars. However, if we apply only the renewable sources of WWS, this demand will decrease to 11.5 TW, mainly by eliminating low efficiency energy based on heat, [9]. Detailed studies show that with current knowledge and existing technological possibilities, practically 40–85 TW and potentially 1700 TW of wind energy can be used, while in the present only 0.02 TW is used; 580 TW and potentially 6500 TW of solar energy can be harvested, while in the present just 0.008 TW is used. To achieve this objective 3.8 million 5 MW wind turbines would needed which would provide 51% of the required energy. Another 40% could come from photovoltaic battery systems and concentrating solar power plants which would require the construction of eighty-nine thousand solar power plants with an average power of 300 MW. About 30% of photovoltaic cells could be placed on the roofs of houses and commercial buildings. The remaining 9% of energy could be produced by hydroelectric power stations of which 70%

already exist. The total cost of the investments related to the implementation of the WWS system in the span of 20 years would be approximately 100 trillion dollars. The estimates do not include significant investment in external factors, namely health problems, environmental damage and negative impact on the climate, which are brought about by the usage of fossil fuels related. The estimates show that by 2020 the price relations will change in favor of the WWS system, [9].

An often cited argument by proponents of coal power plants is the price of energy taking into account the cost of generation and transmitting over the network. Currently, in the US the price per kilowatt hour of wind, geothermal and hydroelectric energies are approximately 7 cents, roughly the same as conventional sources, while the price of energy from wave and solar sources is higher. However, the estimated calculations indicate that by 2020 the price relations will change in favor of WWS system. With a reasonable international policy, it is possible that in 10–15 years 25% of the world's energy could already be sought from WWS system, in 20–30 years almost a 100%, but more realistically it would be in 40–50 years and it would be a big success, because in around 50 years we may exhaust hydrocarbon fossil fuels with a price close to today's already high price, [9].

Conclusions

Depleted resources of liquid fossil fuels and environmental problems spawned the reconsideration of electric vehicles. This is not an easy and fast process since it is determined by a number of factors. It is undoubtedly a positive fact that electric motors used to drive electric vehicles are more than three times as efficient as internal combustion engines and have the characteristics of change in power and torque produced as a function of speed perfectly matching the requirements stemming from vehicle propulsion. An inhibiting factor still requiring a solution is the electrical energy source in vehicles and the possibility of rapid recharging. Great efforts are being made to overcome the problems associated with widespread use of fuel cells in vehicles, which would help solve this problem. Optimists say that within half a century it will be possible to overcome this limitation and produce the necessary electricity for charging using eco-friendly renewable WWS energy sources. Some obstacles of possibly implementing the WWS system are political in nature, not technical. Despite the many difficulties in sales, there have been many interesting solutions for electric vehicles, but their primary drawbacks remain their high price, unsatisfactory recharging parameters requiring electrochemical sources of electricity, and the constraining conditions of the range and dynamics of these vehicles. It is well known that in order to achieve any success, properly educated people, financial expenses and time are needed. Larger financial outlays offer an opportunity to introduce the subject to a larger number of people and to accelerate the process. Unfortunately, the published data show that since 1980 it is noted that in the most developed countries of the world, financial outlays are also rapidly declining in the area of scientific and energy research, indicating that time necessary to achieve success may be dangerously extended.

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