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# ANALYSIS OF THE REASONABLENESS OF USING ELECTRIC DRIVES IN MOTOR VEHICLES

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## Summary

The EU transport policy is to implement a plan aimed at a significant reduction of the $CO_2$ emission, to be phased over the years 2020-2030-2050. Therefore, restrictions are to be gradually imposed on the use of vehicles with internal combustion (IC) engines, to eliminate such vehicles from urban traffic by 2050. Instead, the vehicles with alternative, low-emission drive systems will be promoted.

At present, very high prices of electrochemical traction batteries have a significant share in the vehicle purchase price and electric vehicles are much more expensive than vehicles with conventional drive systems. The high purchase prices are compensated by low electric energy costs in comparison with the costs of hydrocarbon fuels.

The present-day battery technologies should be considered an interim stage and should not be treated as a target, because they may turn out within a few years to be cost-consuming and obsolete solutions. On the other hand, electric traction motors have been built, developed, and used for many years and the risk of their failure is lower than the risk of a battery failure. The battery recharging process always involves the necessity of providing adequate infrastructure of a power supply network.

Electric vehicles, especially their batteries and battery charging systems, are still at the development stage, without a crystallized vision of target solutions. Another problem is the lack of infrastructure and standardization. In spite of this, electrical drives (including those with hydrogen fuelling), as being characterized by zero emissions, may be expected to become in the long term a target and predominating solution.

**Keywords:** electric vehicles, batteries, battery charging, charging infrastructure, electric drives

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# 1. Introduction

At present, road transport is accountable for 24 % of the total $CO_2$ emission in the 27 European Union countries. The EU transport policy is to implement a plan aimed at a significant reduction of the $CO_2$ emission, to be phased over the years 2020-2030-2050, so that the present emission of 1 200 million tons of $CO_2$ would be reduced to 1 000 million tons by 2030 and would reach a level of 400 million tons by 2050 [1].

The plan of achieving this goal has been divided into a package of particularized measures, with some of the most important of them having been presented below.

Table 1. Goals of the EU transport policy, related to a reduction of the $CO_2$ emission phased over the years 2020-2030-2050

| Goal | To be achieved by | Source document |
|---|---|---|
| Reduction of the greenhouse gas (GHG) emissions from the transport sector<br>- by 20 % below the 2008 level<br>- by 60 % below the 1990 level | 2030<br>2050 | EU strategies described in documents:<br>- EC Energy 2020. COM(2010) 639 final<br>- EC White Paper Roadmap to a single European transport area COM(2011) 144 final<br>- EU Road Map for moving to a competitive low carbon economy COM(2011) 112 final |
| Permissible $CO_2$ emission limits for newly registered passenger cars:<br>- 130 g $CO_2$/km<br>- 95 g $CO_2$/km | 2012-2015<br>2020 | EC Regulation 443/2009 for passenger cars |
| 20 % improvement in the efficiency of fuel consumption by the transport sector | 2020 | EC Energy 2020. COM(2010) 639 final |
| 10 % target for the share of energy from renewable sources in transport | 2020 | Directive 2009/28/EC on the use of energy from renewable sources (RES) |
| Use of vehicles with IC engines<br>- to be halved<br>- to be phased out | 2030<br>2050 | EC White Paper Roadmap to a single European transport area COM(2011) 144 final |

The documents mentioned above unequivocally show the direction of the future administrative measures, according to which restrictions are to be gradually imposed on the use of vehicles with internal combustion (IC) engines, to phase out such vehicles from urban traffic by 2050.

On the other hand, the vehicles with alternative, low-emission drive systems will be promoted (e.g. by exemption from the restrictions focused on conventionally propelled vehicles), to demonstrate the attaining of conformity with individual targets, guidelines, statistical goals, or superior authorities' requirements.

The low pollutant emissions from transport facilities may be initially achieved by the use of alternative fuels (CNG, LNG). The next stage will be the introduction of hybrid drive systems, which are an interim solution between drive systems with IC engines and electric drives. As a long-term target solution, electric and hydrogen-powered drives are considered. It should be remembered, however, that the generation of the electric energy used for charging the electric vehicle might also be connected with the emission of carbon dioxide. At present, the ecological benefit gained from the use of electric drives is related to the "export" of pollutant emissions outside urban areas and to the somewhat higher (by several percent) efficiency of stationary combustion of fuels at power plants, often combined into heat and power cogeneration facilities. As a long-term target, electric energy will be obtained from renewable energy sources (RES); thus, both electric vehicles and vehicles powered with hydrogen (generated by electrolysis of water) will be completely free of $CO_2$ emission.

## 2. Total Cost of Ownership (TCO) of a motor vehicle

The total cost of ownership of a motor vehicle consists of:

- purchase price;
- operation cost, i.e.
  - fuel cost;
  - servicing and repair cost;
  - other costs (insurance, taxes, etc.).

At present, the prices of electrochemical traction batteries are very high (approximately 500-1 000 USD/kWh); therefore, they have a significant share in the vehicle purchase price and electric vehicles are much more expensive than vehicles with conventional drive systems.

The high purchase prices are compensated by low electric energy costs in comparison with the costs of hydrocarbon fuels, which may cause the use of electric drives to seem cost-effective.

The electrochemical batteries are now the least stable and simultaneously the most expensive component of an electric vehicle. During operation, the batteries undergo gradual degradation, manifesting itself in increasing internal resistance and in a loss of their electric capacity. The battery degradation process is natural and unavoidable. The loss of effective electric capacity shows itself in a gradually decreasing vehicle's range and a growing need of servicing the battery, i.e. replacement of individual cells or even complete modules (cell sets) within the battery. The electrochemical batteries are composed of a big number of individual cells primarily connected with each other in series and then in parallel. Due to such a configuration, the quality of a complete set of cells is limited by the condition of the cell that has become most degraded (as it is in the case of a chain, whose strength is such as the strength of the weakest link). The replacement of a single cell will improve the parameters of the complete set only to the level of the next most worn cell. In consequence, it may be expected that for the technical condition of the battery and the resulting vehicle's range to be significantly improved, a considerable number of the battery cells will have to be replaced, which will translate into high battery and vehicle servicing costs.

There are publications, e.g. [2, 3], which show that in spite of lower costs of electric energy compared with hydrocarbon fuels, the Total Cost of Ownership (TCO) of an electric vehicle may exceed that of a conventionally powered vehicle due to the battery degradation and the resulting costs of depreciation, servicing, or replacement of the battery.

This leads to a conclusion that from the point of view of the owner of an electric vehicle, it would be advisable to seek protection from the costs related to the depreciation or possible replacement of the battery by mechanisms such as leasing, insurance, or long-term guarantees that specific battery characteristics would not drop below predefined limits so that adequate vehicle driving range in specific conditions would be maintained.

## 3. Technologies of electrochemical traction batteries

At present, the technologies specified in the table below are most frequently employed to manufacture the electrochemical batteries used in electric vehicles.

Table 2. Energy characteristics of lithium batteries of the most popular types

| | **LiMn** | **LTO** | **LiFePO4** |
|---|---|---|---|
| Energy density by mass | 120-140 Wh/kg | 80-90 Wh/kg | 90-110 Wh/kg |
| Energy density by volume | ≈220 Wh/dm$^3$ | ≈165 Wh/dm$^3$ | ≈220 Wh/dm$^3$ |
| Nominal voltage of a single cell | 3.8 V | 2.3 V | 3.3 V |

Battery manufacturers tend towards raising the energy density (both by mass and by volume) of their products so that as much energy as possible could be stored in a unit of battery mass and volume, thanks to which the vehicle's range would be extended. However, a growth in the energy density not always goes hand in hand with the durability of a battery, because it is often a result of a compromise between the battery endurance and durability. High energy density values should always be confronted with the battery durability values specified by the manufacturer. It is always advisable to consider the strategy of choosing a battery with lower energy density if the battery shows higher power density and resistance to degradation. An example may be the technology of lithium–titanate (LTO) batteries (LTO stands for Lithium Titanium Oxide).

In the field of electrochemical batteries, special terminology is used:

"State of Charge" (SOC), specified in relative units (e.g. [%]), defines the level of the available energy accumulated in the battery. Since the battery capacity declines with time, a new battery and a used one, charged in both cases to SOC = 100 % and compared with each other, offer two different vehicle driving ranges. The SOC value informs whether, and to what extent, a battery is charged.

The SOC parameter is connected with defining the voltage characteristic curve of a battery. The shape of this curve (representing the battery voltage as a function of SOC) depends on, *inter alia*, the battery technology. Steeper decline in the voltage with a progress in the battery discharge process does not have to mean worse quality of the battery, providing that the shape of the characteristic curve be maintained with time. An issue of greater importance is the distance between curves plotted for various values of the battery current, as this distance represents the level of internal resistance of the battery. These characteristics directly lead to a conclusion that when a battery is loaded with a higher current, it will sooner reach the flat battery voltage level, which will result in shortening the driving range. Hence, if a longer driving range has to be achieved, the vehicle should not be subjected to higher current loads. This directly leads to the necessity of increasing the battery capacity.

"State of Health" (SOH) defines the battery wear level. In result of battery operation, its effective capacity declines and its internal resistance increases (example: [4]), which results in a reduction in the electric vehicle driving range. The battery wear is a natural and unavoidable process; anyway, the degree of battery wear should be periodically examined for the whole battery service life to check whether the battery wear process runs in accordance with manufacturer's declarations and whether it does not go with an excessive rate. The technical condition of a battery may be examined by carrying out specialist tests, e.g. impedance spectroscopy [5], at specialized laboratories or on an ad hoc basis (in a simpler way but with a wider margin of error) by checking the range of vehicle driving in specific and repeatable conditions (the same route, load, traffic intensity, ambient temperature, etc.).

One of the factors that have an impact on accelerated battery degradation is the value of the battery charging current. The "fast charging" technologies require the applying of high charging current values, which result in the emission of a large amount of heat, proportional to the product of the square of the current and internal resistance of the battery. This heat, even if removed, accelerates the battery degradation processes. The fast charging technologies may only be effective and used for a long time in the case of batteries with very low internal resistance values (e.g. LTO batteries) or battery-supercapacitor combinations.

"Battery capacity" defines the amount of electric charge the battery can accumulate. The battery capacity may be increased by connecting individual cells in parallel. The connecting of cells in series will not increase the battery capacity; only the voltage of such a battery of cells will be raised. The battery capacity gradually declines with battery operation time, which has been explained above. It is important that the battery capacity should be regularly verified and checked for conformity with manufacturer's specifications. The battery capacity is directly related to the vehicle driving range. The battery capacity depends on temperature; in general, it increases with growing temperature to reach a maximum and to decline when the temperature growth is continued. An excessive temperature not only causes a drop in the battery capacity but also results in battery degradation and shortens its service life [6]. Any systems that stabilize the temperature of an electrochemical battery (battery heating, ventilation, and cooling systems), apart from improving the safety of battery operation, extend the battery service life. The providing of a vehicle with a battery temperature stabilization system constitutes a considerable improvement and already begins to become standard. On the other hand, when a battery is not provided with such a system and when it is operated at low temperatures (e.g. during winter), it is exposed to the risk of a significant reduction in battery capacity and of an increase in the internal resistance of the battery, which may even result in total immobilization of the vehicle.

"Battery Management System" (BMS) – The electrochemical battery is a vehicle component that is expensive and susceptible to improper operation. To extend the battery service life, an appropriate battery management system (often referred to as "BMS") should be applied. Such a system should e.g.:

- monitor the condition of individual battery cells;
- prevent the exceeding of current, voltage, and temperature limits;
- enable battery operation after switching over into the Limp Home Mode;
- disconnect the battery in case of a dangerous situation;
- equalize the voltages and charges between individual battery cells;
- determine the SOC value;
- determine the SOH value;
- display messages and information about battery operation parameters on driver's instrument panel;
- predict the vehicle driving range remaining available;
- manage the battery charging process, inclusive of appropriate shaping of the profile of the battery charging current;
- provide a possibility of pre-charging the battery in order to test the battery condition and to prevent the applying of full-power charging current to the battery if it is defective;
- provide a possibility of recharging individual cells;
- record the history of battery operation errors, e.g. exceedances of limits, in order to identify defective cells;
- enable the switching over of the system into the Limp Home Mode, i.e. make it possible for the vehicle to reach a recharging station with turning off the unnecessary loads (air-conditioning, audio, display, etc.).

Obviously, the more functions of this kind are supported by the BMS, the better. Anyway, the lack of such a system in an electric vehicle is inacceptable.

## 4. Development prospects of the technologies of electrochemical batteries

At present, the biggest problem related to the operation of electric vehicles consists in high battery prices (approximately 500-1 000 USD/kWh) and limited energy storage capacity of the batteries. At the same time, the growing scale of production of electric vehicles as well as the development of new battery technologies makes it realistic that within a time horizon of 2010, the battery cost may be significantly cut down, i.e. reduced by about 60 %, to a level of approximately 270-330 USD/kWh [7, 8].

Simultaneously, the development of new battery technologies, such as Zn-air, Li-S, or Li-air will make it possible to raise the energy density of cells to a level of 300-900 Wh/kg [9].

These data show that the present-day battery technologies should be considered an interim stage and should not be treated as a target, because they may turn out within a few years to be cost-consuming and obsolete solutions.

## 5. Battery charging technologies

Electrochemical batteries must be recharged, which may be done in the following ways:

- Battery swapping;
- Slow recharging;
- Fast recharging;
- Induction recharging.

The advantages and disadvantages of individual methods will be described below. The battery recharging process always involves the necessity of providing adequate infrastructure of a power supply network.

The battery swapping consists in a fast removal of a discharged battery from the vehicle and replacing it with a fully charged one. Such a system is used e.g. for passenger vehicles by a company named Better Place. Another example is the fleet of electric buses operated in Beijing.

Advantages:

- The batteries are recharged in stationary conditions, outside of the vehicle, thanks to which the vehicle mass may be reduced and the space available in the vehicle may be increased.
- Thanks to stationary slow charging of the battery at an appropriate current and temperature, the process of battery recharging and of keeping it in a good condition for a long time may be precisely managed.
- The battery swap and recharging stations are stationary energy stores, operating in the "smart grid" system.
- The short battery swap time is comparable with the hydrocarbon fuel refilling time.
- The possibility of frequent battery swap enables a reduction of the battery capacity and a growth in the transportation capabilities of the vehicle.

Disadvantages:

- High cost of the infrastructure.
- Necessity of driving the vehicle to a battery swap station and the resulting limited vehicle driving range.

The slow recharging consists in connecting the vehicle battery to the public power grid.

Advantages:

- Minimum cost of the infrastructure and possibility of using the existing terminals.
- High flexibility of the selection and change of the recharging point.
- Prolonged charging with a low current has a favourable impact on the battery service life.
- High capacity of the battery ensures a relatively long vehicle driving range.

Disadvantages:

- Necessity of the on-board installation of a battery charger.
- High capacity of the battery has an impact on a reduction in the free space available in the vehicle.
- Prolonged battery charging time results in a long time of vehicle unavailability.

The <u>fast recharging</u> consists in connecting the vehicle battery to a charger of high power rating.

Advantages:

- Possibility of using a low-capacity battery, thanks to which some additional free space can be found in the vehicle.
- Short battery charging time reduces the time of vehicle unavailability to a minimum.

Disadvantages:

- Necessity of the construction of expensive infrastructure along vehicle driving routes and of the making of high-power electric service lines (with a capacity of the order of several hundred kW).
- Limited possibility of standardization due to a large number of solutions developed by various manufacturers.
- Low flexibility of choosing and changing the vehicle driving route.
- The battery charging with a heavy current requires the use of special connectors and increases the risk of damage.
- The high value of the charging current accelerates the battery degradation process.
- The technology is at the development stage, there is a lack of standardization.

The <u>induction recharging</u> is similar to the fast recharging, with the difference lying in the fact that the energy is transmitted by a magnetic flux, as it is in a transformer. The advantages and disadvantages of this method are similar to those of the fast recharging.

Additionally, the following disadvantages of this method may be pointed out:

- Necessity of minimizing the distance between the windings placed in the road surface and in the vehicle, which may cause problems in the case of roads of poor quality and in winter conditions.

- Necessity of precise positioning of a vehicle in relation to the winding placed in the road surface.
- High energy losses in the air due to dissipation of the magnetic flux.
- Incomplete knowledge of the impact of strong magnetic flux on vehicle occupants and equipment.
- The technology is at the development stage; there is a lack of standardization.

## 6. Other components of electric vehicles

The electrochemical battery and the battery charging system are now the most expensive and sensitive components of an electric vehicle; therefore, they require special care during operation.

Another important vehicle component is a traction motor (or a system of traction motors). The electric traction motors have been built, developed, and used for many years and the risk of their failure is lower than the risk of a battery failure, but the possibility should be kept in mind that such a risk may also occur in certain conditions. The risk is lowest in the case of asynchronous AC induction motors thanks to their simple construction. A higher risk may be encountered when synchronous motors with permanent magnets are used. Permanent magnets are very sensitive to overheating and they permanently lose their magnetic properties when their temperature reaches a specific temperature level (the Curie point). Therefore, it is important that motors of this type should be provided with a temperature monitoring system and a cooling system (preferably based on liquid cooling). Another risk arises from the possibility that the magnets might get unstuck, because gluing is practically the only available method of fixing the magnets in a motor. At present, the conventional DC motors are not used for vehicle propulsion purposes.

Electric motors are powered from batteries through inverters, which convert direct current into polyphase alternating current with specific voltage profile (e.g. sinusoidal, trapezoidal, etc.) and parameters (frequency, amplitude, and phase shift). The inverter should be so advanced that it would make the regenerative braking possible as well. Moreover, a possibility of appropriate cooling of the inverter would be recommendable.

The motor location is another matter of great importance. The simplest solution, least susceptible to damage, is the conventional configuration where a single motor is combined with a differential gear. In such a case, however, the use of a low-floor vehicle body is hardly practicable.

As an alternative, tractive motors may be placed in wheel hubs. In such a configuration, the vehicle may be provided with a body of full-length low-floor design. On the other hand, certain disadvantages of a solution like this may be encountered, the possibility of which should be taken into account:

- growth in the unsprung mass;
- necessity of sealing the motor interior and protecting it from water and contamination;

- necessity of applying forced motor cooling, especially in the case of a motor with permanent magnets;
- necessity of separate controlling of the speeds of individual wheels (differentiation of wheel speeds) to reproduce the differential operation effect when negotiating turns.

The motor must be appropriately designed and made for the above disadvantages to be minimized.

A considerable impact on the efficiency of the electric vehicle propulsion system as a whole is exerted by the rated voltage of the battery and the traction motor. In general, the higher voltage the lower current is at the same power; in turn, the lower current means lower energy losses over the system resistances. Thus, the high-voltage solutions offer a chance for the attaining of higher efficiency values. On the other hand, excessive voltage increases the risk of electric shock in case of breakdown situations and raises the level of electromagnetic emissions from the inverter. The voltage levels considered as relatively safe are of the order of 500 V. A parameter that should also be taken into account is the declared energy consumption per 1 km. This parameter depends on many factors and may vary depending on driving conditions. Its values are affected, as it is in the case of a conventional vehicle, by e.g. the following factors:

- the driving cycle according to which the vehicle's range was estimated and the related maximum speed values, values and frequencies of accelerations and braking decelerations, and gradients negotiated;
- aerodynamic drag coefficient (cx) of the vehicle;
- vehicle mass and rolling resistance;
- possibility and efficiency of the recovery of braking energy;
- efficiency of the vehicle driving system;
- battery state and operating conditions (internal resistance of the battery).

The value of the energy consumption by a vehicle is more strongly affected by the driving conditions than by the current vehicle condition and quality. For a 12 m bus, the value of this parameter averages out at 1.2-1.4 kWh/km, as against 0.25-0.4 kWh/km for a passenger car. Obviously, these figures may be much higher in difficult conditions (e.g. at uphill or high-speed drives).

## 7. Recapitulation

Electric vehicles, especially their batteries and battery charging systems, are still at the development stage, without a crystallized vision of target solutions. This situation is made even harder by the lack of infrastructure and standardization. In spite of this, electrical drives (including those with hydrogen fuelling), as being characterized by zero emissions, may be expected to become in the long term a target and predominating solution. Nevertheless, a possibility should be taken into account that in terms of practical operation, electric vehicles will not be able to rival the conventional ones before around 2020.

In the initial period, it would not be advisable to choose complicated solutions that would involve big investments in the infrastructure, because it may happen that other systems would gain superiority with time. Investments in the infrastructure and in the more advanced solutions should be made gradually, based on the experience acquired with simpler solutions.

The plans of obtaining economic benefits from the use of electric vehicles thanks to lower costs of electric energy compared with hydrocarbon fuels should be approached with caution, the more so that many of the proposed prototype solutions may be burdened with high failure rates.

It may happen that the battery servicing, repair, or replacement costs will exceed the savings from the difference between the costs of electricity and engine fuels. Therefore, it is important that appropriate protective measures should be taken against such costs, in the form of a guarantee of maintaining a specific battery condition for a long time. The battery condition may be determined on an ad hoc basis by measuring the range of vehicle driving in specific and repeatable conditions (the same route, load, traffic intensity, ambient temperature, etc.) or at specialized laboratories.

I would be advisable for the owners of fleets of electric vehicles (e.g. buses) to have a number of diversified solutions (e.g. batteries of various capacity) at their disposal so that they would be able to select the better and worse solutions, based on the experience acquired during real fleet operation. The operator of a fleet of electric vehicles (e.g. buses), having gained experience from real operation of such vehicles, may become an owner of valuable know-how. The possessing of both a fleet and a base of knowledge may provide grounds to apply for the subsidizing of projects and solutions that would be more technologically advanced but more economically hazardous at the same time.

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