Holistic Approach in Developing Propulsion System for Urban Electric Vehicles

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Abstract - In order to develop an outstanding electric vehicle (EV) we have to use all the advantages which are offered by the transition to electric propulsion system.

Our concept involves direct drive (DD) propulsion system with four high specific torque inwheel electric motors, improved aerodynamics of a vehicle, weight reduction and optimized hybrid power sources involving a low power high energy primary source and a high power lower energy secondary source.

Optimization of propulsion system parameters has been performed in order to obtain satisfying driving and economic performance for a standard city driving cycle.

I. INTRODUCTION

We have analyzed different solutions for an electric vehicle propulsion system and found that with currently available technology we can build an electric vehicle suitable only for transportation within urban areas that will also be commercially successful. There is a great difference between performance demands between urban and extra-urban vehicles, and as a consequence the required characteristics differ greatly. The main advantages of urban vehicles are considerably lower energy consumption, lower peak power and simpler achievement of safety. Further to that, pollution problems and high traffic are additional reasons to concentrate on urban vehicles.

Even to construct such an urban vehicle, we have to use all the possibilities that are offered by transition to an electric propulsion system. The idea of replacing the internal combustion engine (ICE) with a central electric motor is not adequate even with a combination of the most advanced fuel cell (FC) systems and lithium based batteries. Price and range issues are too problematic at the moment. We can see that this approach is not working well from the fact that there are presently only a few electric or hybrid electric vehicles for urban areas commercially available.

The aim of this article is to show that it is possible to produce an economically interesting zero emission electric vehicle for urban areas using only today's technology. We have used the concept of the direct drive (DD) propulsion system and two optimized power sources to achieve the best results for the urban driving cycle.

Especially new inwheel motors designed for DD propulsion system represent important step in development of electric vehicles. We have used this concept with 4 inwheel electric motors placed directly inside wheels with no transmission or gears. Each of them is separately controlled.

Main benefits of DD propulsion system are: improved efficiency, reduced weight, better aerodynamics, additional driving capabilities (side driving, turning on a spot) and lower price. Most likely also new design solutions will be found due to reduced space and freedom in placement of propulsion system components. Characteristics of these inwheel electric motors will be analyzed in detail together with power sources requirements.

II. REQUIRED PERFORMANCES AND DATA USED

The most important urban vehicle's performances that are required for satisfying the average driver's needs are: a range over 300 km, top speed over 100 km/h and good acceleration, comparable with ICE vehicles used today (around 6 seconds from 0 to 60 km/s).

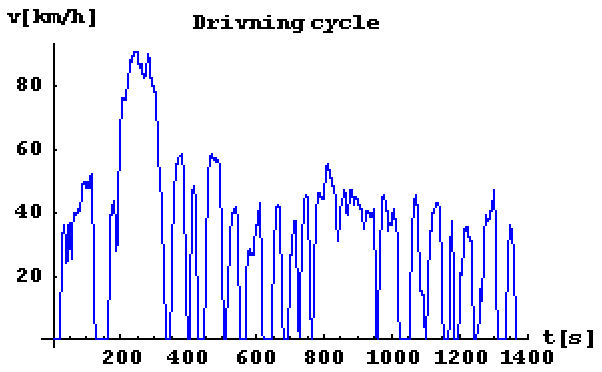
Technical parameters of the vehicle we are using in our calculations are based on several similar small vehicles, taking into account the reduced mass due to the lack of transmission mechanism and power source optimization.

Fig.1 PARAMETERS OF A VEHICLE

Frontal area	2.2 m²
Total mass (with 2 people)	650 kg
Air drag coefficient	0.35
Friction coefficient	0.015
Efficiency of electric motor and power electronics	Fig.7
Number of inwheel electric motors	4
Outer radius of a wheel	0.25 m

The procedure of calculating vehicle parameters strongly depends on the driving cycle used. Main calculation has been performed using the Urban Dynamometer Driving Schedule.

Fig.2 VELOCITY VERSUS TIME FOR URBAN DYNAMOMETER DRIVING SCHEDULE

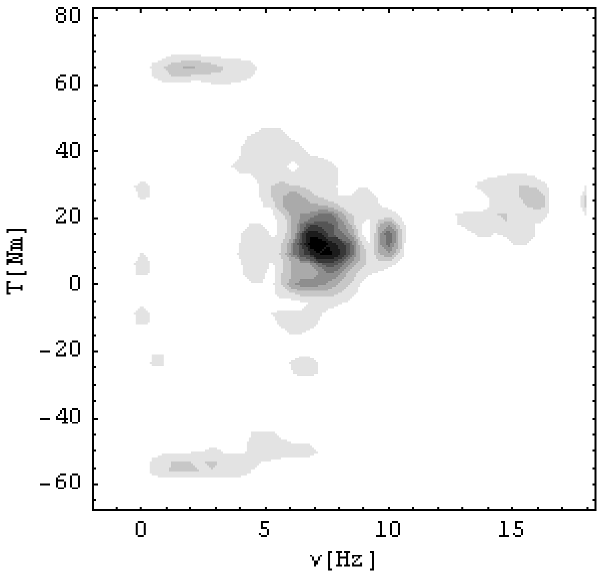


During these 1369 seconds of driving cycle, 12 kilometers are driven with an average speed of 31.5 km/h.

III. ELECTRIC MOTOR TORQUE AND FREQUENCY

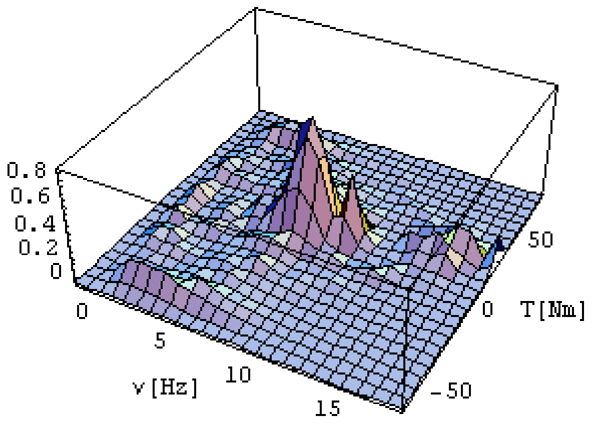
Using the vehicle and driving cycle data we can calculate a diagram showing torque and mechanical frequency demand. In this torque and frequency demand diagram it can be found what part of the driving time an electric motor spends at different torques and frequencies (Fig.3 and Fig.4). By calculating such a diagram, the torque and the frequency range which has to be achievable with an electric motor can be determined.

Fig.3 TORQUE AND FREQUENCY DEMAND (CONTOUR PLOT)



Dark color represents the area where the electric motor spends most of the time. White areas are less occupied. We did not take into account time spent at a stand still.

Fig.4 TORQUE AND FREQUENCY DEMAND (3D PLOT)



In Fig.3 and Fig.4 we can see how much time is an electric motor working at different conditions (torque and frequency).

From these data we can deduced that most of the time the electric motor is in regime at 15 Nm of torque and at mechanical frequency of 7 Hz. The peak torque and the peak frequency needed can also be established.

The peak frequency depends only on the top speed in the driving cycle and on the wheel diameter. It is found to be 16.3 Hz, or 978 RPM, which is far less then in electric motors used in combinations with gears.

The peak torque was determined from three different conditions. Firstly from the torque and frequency demand diagram in a standard driving cycle shows a peak torque of 69.7 Nm. However, this torque may not be sufficient for some special driving conditions where higher force or acceleration is required. Secondly, the peak torque needed can be calculated from acceleration requirements (0 to 60 km/h in 6 seconds). It is found to be 121 Nm. The third way of the peak torque determination is the hill climbing ability. In order to climb 35% slope, the peak torque needed is 134 Nm, which is the highest and is therefore taken for required value of peak torque.

IV. EFFICIENCY OF ELECTRIC MOTOR AND POWER ELECTRONICS

In order to develop the appropriate electric motor for DD application, its efficiency has to be optimized according to working conditions in the predicted driving cycle. Multiplying torque and frequency with power at each point of the diagram, a new diagram is obtained, showing the amount of energy released at any specific torque and frequency during driving cycle. The best overall efficiency will be obtained when the electric motor and power electronic efficiencies are optimized at those points where most of the energy is released. This diagram (Fig.5 and Fig.6 - Energy flow distribution) is useful for optimization of electric motors and power electronics for special applications.

Fig.5 ENERGY FLOW DISTRIBUTION (CONTOUR PLOT)

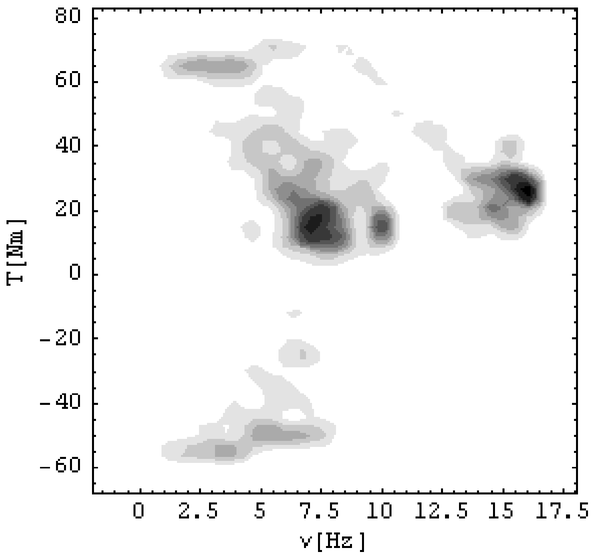
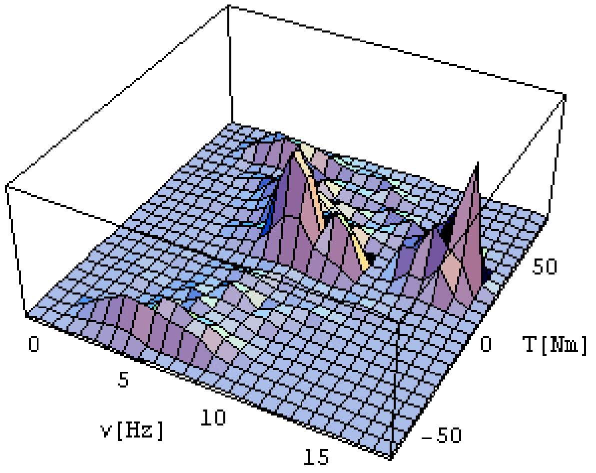


Fig.6 ENERGY FLOW DISTRIBUTION (3D PLOT)



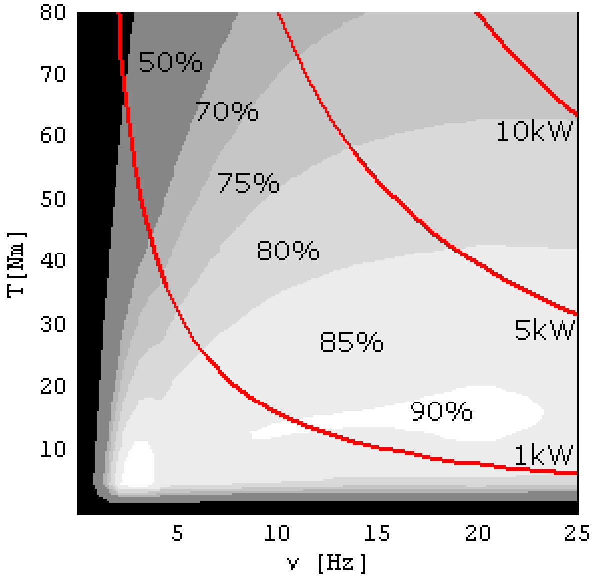
Absolute values of energy are used, thus in case of energy recuperation at regenerative breaking the energy shown is positive. The more important values have moved from the middle of the diagram (in Fig.3 and Fig.4) to values with higher powers (higher torques and frequencies). Approximately 40% of released energy is in the middle area of the diagram, 21% at high speeds, 9% at low speeds and 16% at regenerative braking area.

From this calculation it can be seen that the efficiency of the propulsion system has to be high in a wide area of torques and frequencies.

V. POWER DEMAND DURING DRIVING CYCLE

Efficiency of the electric motor and power electronics are shown in Fig.7 we have used data predicted by calculations of our prototype inwheel electric motor.

Fig.7 EFFICIENCY OF INWHEEL ELECTRIC MOTOR AND POWER ELECTRONICS

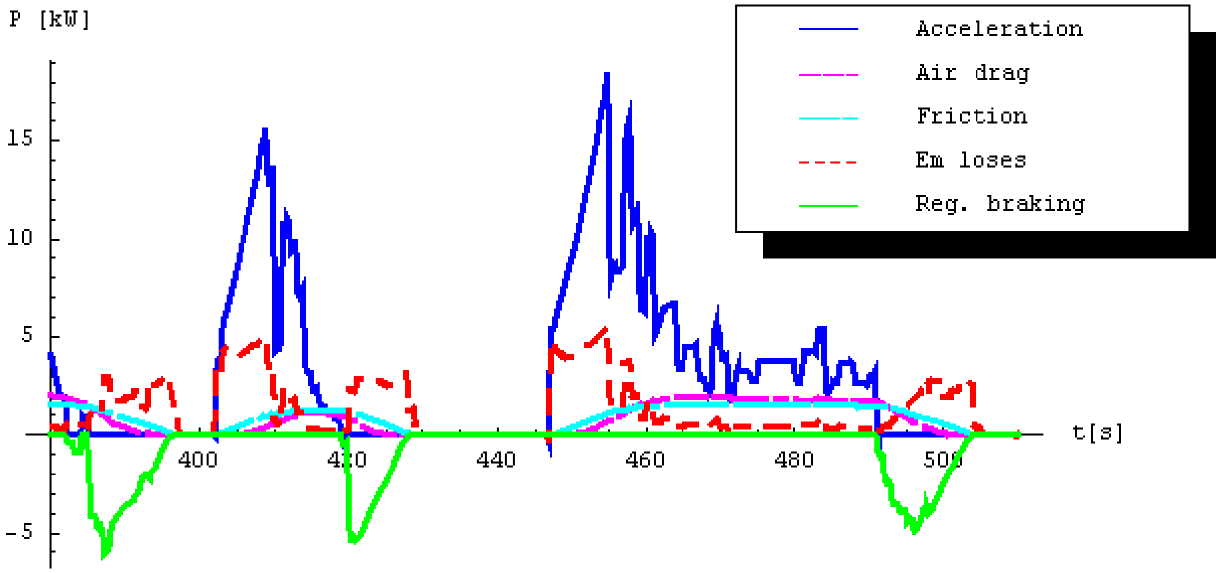


The highest efficiency is in two white areas where it is slightly over 90%. In following areas the efficiency is 5% lower until we reach 70%. Under that efficiency only efficiency over and less than 50% are shown. Three dark lines connect points with same power (1 kW, 5 kW and 10 kW). The reason for two peaks of efficiency is nature of losses which occur in copper (ohmic) and in iron (hysteresis and Eddy current).

During the driving cycle, the power needed to accelerate the vehicle has been calculated together with the power spent for compensating the air drag and friction as well as the power restored during braking.

In Fig.8 the total power required in a typical segment of the standard driving cycle is shown together with the power needed to compensate the air drag, friction forces and losses in electric motor and power electronics. The negative curve is the power which is regenerated by the braking system, for which we assumed that the battery recharging efficiency is 80%. The electric motor and power electronics efficiencies were also taken into account.

Fig.8 POWER DEMAND



In Fig.8 we show power for acceleration and different sources of power losses in a segment of driving cycle. Negative curve represents power which can be reused using regenerative braking system. Using such calculation over whole driving cycle, we have obtained required parameters of power sources.

Calculated quantities for an electric vehicle over whole standard driving cycle are presented in the following table:

Fig.9 POWER AND ENERGY REQUIREMENTS

length of driving cycle	12 km
total time of driving	1369 s
time of standing still	244 s
time of moving	1125 s
average power (all time)	3.0 kW
average power (moving time)*	3.7 kW
peak power	21.2 kW
energy required per 1 km	96 Wh
energy regenerated from braking system per 1 km	8 Wh
improvement of range with regenerative braking system	9%
energy lost for compensating air drag	34%
energy lost for compensating friction forces	32%
energy lost in electric motor and power electronics	34%

*we take into account only the time, when the vehicle is moving.

Results of power demands presented in Fig.9 show us, that even if the peak power is more then 20 kW, the average power is still only about 3kW. The total energy required for the range of 300 km is 28.8 kWh without a regenerative braking system or 26.4 kWh with such braking system.

VI. POWER SOURCE OPTIMIZATION

We can see, that achieving a range of 300 km is hardly possible using only battery. We would require over 200 kg of lithium battery (130 Wh/kg) which is too expensive, or over of 600 kg lead battery which is too heavy.

Based on the considerable difference between the peak power and the average power we are suggesting a hybrid power source system with two power sources, each being for a different purpose. The first can be a fuel cell or ICE generator with a power only slightly above the average power (3kW) and with an energy capacity of at least 26.4 kWh. The second can be a battery or ultracapacitor with peak power over 21.3 kW and an energy capacity of around 2 kWh (enough for 29 km without stopping).

The 3 kW fuel cell is not as expensive as fuel cells for higher power, and battery do not need to be very heavy and expensive either. Lithium battery weighting 20 kg would suffice. Assuming that one half of the distance traveled will be powered by the energy from battery and that battery last for 1000 full charge-discharge cycles, they would only have to be replaced after 59000 km driven. This is economically interesting information.

VII. CONCLUSION

With a DD propulsion system we obtain many advantages (reduced weight of vehicle, better efficiency, better design, lower price…) that make the construction of light urban area electric vehicle possible. The two main obstacles in achieving this goal were analyzed.

The first is the exact determination of the required torque and efficiencies of inwheel electric motors. The peak torque has to be around 130 Nm and the efficiency has to be good within a wide area of torque and frequency (Fig.5 and 6).

The second key obstacle is optimization of the power sources. A primary low power, high energy power source and secondary high power low energy capacity power source are needed. The primary energy source (FC or ICE engine) has to be able to produce around 3 to 4 kW of power and has to have an energy capacity over 26.4 kWh. The secondary power source (battery or ultracapacitor) has to produce a high power (at least 21.3 kW) but its energy capacity can be as low as 2kWh or even less.

An important conclusion is the fact that such hybrid vehicle can be produced using low power ICE engine and lead battery. It can be economically successful and ecologically superior to current ICE. On the other hand also FC system and lithium battery can make success due to low power FC required.

However we are aware that some additional technological reasons may to some extent change optimized parameters.

- FC peak efficiency is at around 25% of its peak power, so better overall efficiencies will be achieved when we use an FC of power around 12 kW. Also the durability would increase if FC does not work at its peak power.
- The battery cycle life is a limitation, as it may not be 1000 cycles in all conditions.
- Ultracapacitors have lower energy densities, thus a larger mass of them is needed in order to achieve suitable energy capacity of secondary power sources. They also work at a variable voltage so a DC – DC converter is required. Alternatively, the best combination might be the use of a combined secondary power source (battery and ultracapacitor).
- The system has to work also in driving conditions that may differ from the standard driving cycle.
- The dependence of battery efficiency on working conditions was not included in the simulation. It is, nevertheless, an important factor since a considerable amount of energy stored abroad the vehicle in the primary power source is lost while recharging the secondary power source.

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