ELECTRIC TRACTION FOR AUTOMOBILES – COMPARISON OF DIFFERENT WHEEL-HUB DRIVES

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Abstract

In this paper, a comparison concerning electric traction drives for passenger cars is given. Electric traction drives presently available on the market are analyzed and future developments are described. Two main classes of such drives are presented: centre drives (like presently known from hybrid cars) and wheel-hub drives (which are still in the research and development phase). The wheel-hub drives are investigated in detail. Two different concepts are regarded: High-speed drive with gear-box and low-speed direct drive. The advantages and disadvantages of both concepts are shown, resulting in the fact that most probably the low-speed direct drive performs better.

Keywords: Electric traction drive, wheel-hub drive, low-speed direct drive, permanent magnet motor

1. Introduction

The present discussion on the CO_2 emissions of passenger cars gives a new stimulus to electric traction drives. At least for city travel the fuel consumption and consequently the CO_2 emissions can be reduced by applying a concept containing electric traction.

Automobiles with electric traction – such as battery, hybrid, or fuel cell vehicles – need additional space for the energy storage, if an acceptable operational range of the vehicle is required. This comes from the fact that the energy density of batteries or hydrogen storage tanks is much lower than that of conventional fuel tanks. Therefore, integrating the electric motor into the wheel-hub offers additional space under the hood, which may be used for additional energy storage.

In general, there are two different possibilities of realizing an electric wheel-hub drive: low-speed direct drive or high-speed drive incorporating an additional gear-box. In this paper, these two alternatives are compared concerning weight, volume, and complexity for a typical mid-class passenger car. For this application, weight is one of the most important parameters, because the unsprung mass is increased with (at least in principle) negative effects on the driving performance of the car.

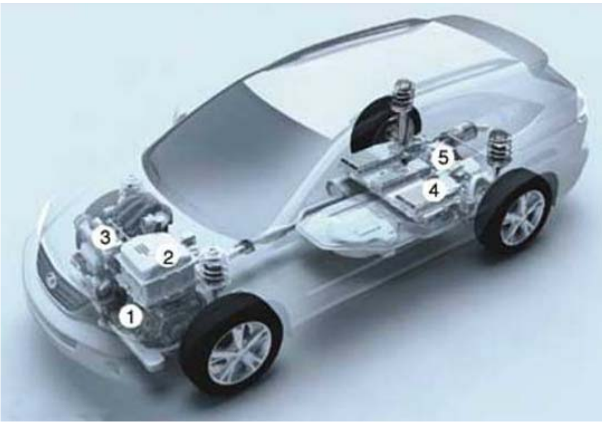
Starting with the requirements to such an electric traction drive, both alternatives (low-speed direct drive and high-speed drive incorporating an additional gear-box) are investigated in detail. The most important influencing factors will be emphasized and analyzed. Electromagnetic and thermal optimizations using finite element method (FEM) calculations lead to electric motor designs for both alternatives, that can be realized with today's technology. Finally, upcoming technical and economic trends are judged concerning the impact on electric wheel-hub drives.

2. Present Electric Traction Drives

2.1 Centre Drives

The electric traction drives presently available on the market are realized as centre drives under the hood of the vehicle. The different specialities will be outlined in this chapter. In addition, many companies are researching wheel-hub drives, which can be classified into high-speed drives with gear-box and direct drives. A survey of these possibilities will be given in the next chapter.

That hybrid car system best known to the public undoubtfully is the Toyota / Lexus system. The system set-up can be seen in fig. 1, which is taken from the Lexus homepage. The electric motors used for this application (123kW at the front axis and additional 50kW at the rear axis) are permanent magnet motors with buried magnets.



<u>Lexus Hybrid Synergy Drive:</u>
1 generator / front electric motor
2 power electronics (inverter)
3 V6 combustion engine
4 battery
5 rear electric motor

Figure 1: System set-up of the Lexus RX400h hybrid car [1].

A second hybrid system presently commercially available on the market is the Honda Civic IMA system, see the following fig. 2. This system is designed for a power of about 15kW.

Figure 2: Honda Civic IMA system, electric motor shown in the front [2].

2.2 Wheel-Hub Drives

2.2.1 High-Speed Drives with Gear-Box

Presently, there is no electric wheel-hub drive for passenger cars in series production. But there are several announcements of different companies concerning electric wheel-hub drives for passenger vehicles. Most of these companies are either tire companies or car companies. Most announcements deal with high-speed drives comprising an additional gear-box inside the wheel-hub. Some example companies are Michelin, Toyota (e.g. Toyota “Fine X” vehicle, four times 20kW electric motors) and the Eliica research car from the Keio University in Japan (see fig. 3, eight times 60kW electric motors).

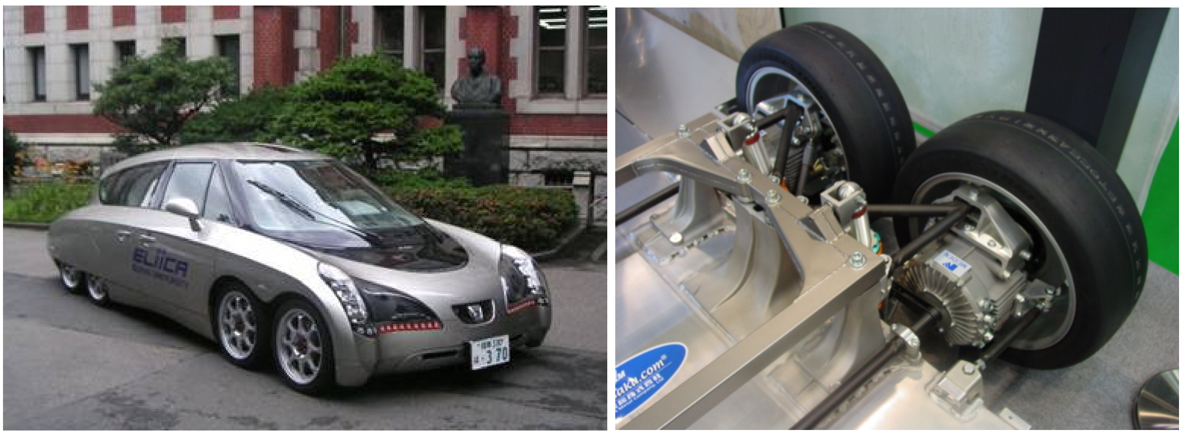


Figure 3: Eliica research car from the Keio University in Japan [3].

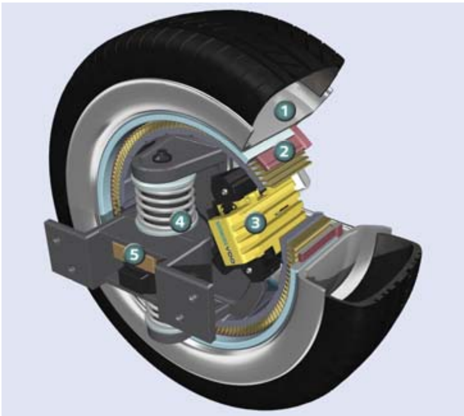
A passenger car that uses two different kinds of electric drives is the Honda FCX, which is announced as a fuel cell car going into (small) series production in very near future. This car contains a centre drive (80kW) for the front wheels and two wheel-hub drives, one for each rear wheel (two times 25kW).

Figure 4: Honda FCX [4].

The Toyota Fine X and the Honda FCX are both fuel cell cars (Toyota Fine X with 80kW fuel cell stack, Honda FCX with 100kW fuel cell stack). The Eliica research car is a purely battery driven electric car.

2.2.2 Low-Speed Direct Drives

Even direct drives are announced from several companies, e.g. Bridgestone, Siemens VDO (see fig. 5) and Mitsubishi (see fig.6).



(1) wheel rim
(2) electric wheel-hub motor
(3) electronic wedge brake
(4) active damping
(5) electronic steering

Figure 5: Siemens VDO „eCorner“ system [5]

Figure 6: Mitsubishi Lancer MIEV [6].

3. Comparison of Different Wheel-Hub Drive Alternatives

3.1 System Analysis

Analyzing typical mid-size passenger cars, one can conclude that at the wheels about 45kW power and about 1800Nm torque at low speed is sufficient, see the following fig. 7. For this analysis, the following parameters have been assumed:

- maximum torque of the combustion engine: 300Nm
- ratio of the first gear: 12.74
- efficiency of the current automotive gear-box: 95%
- two-wheel-drive

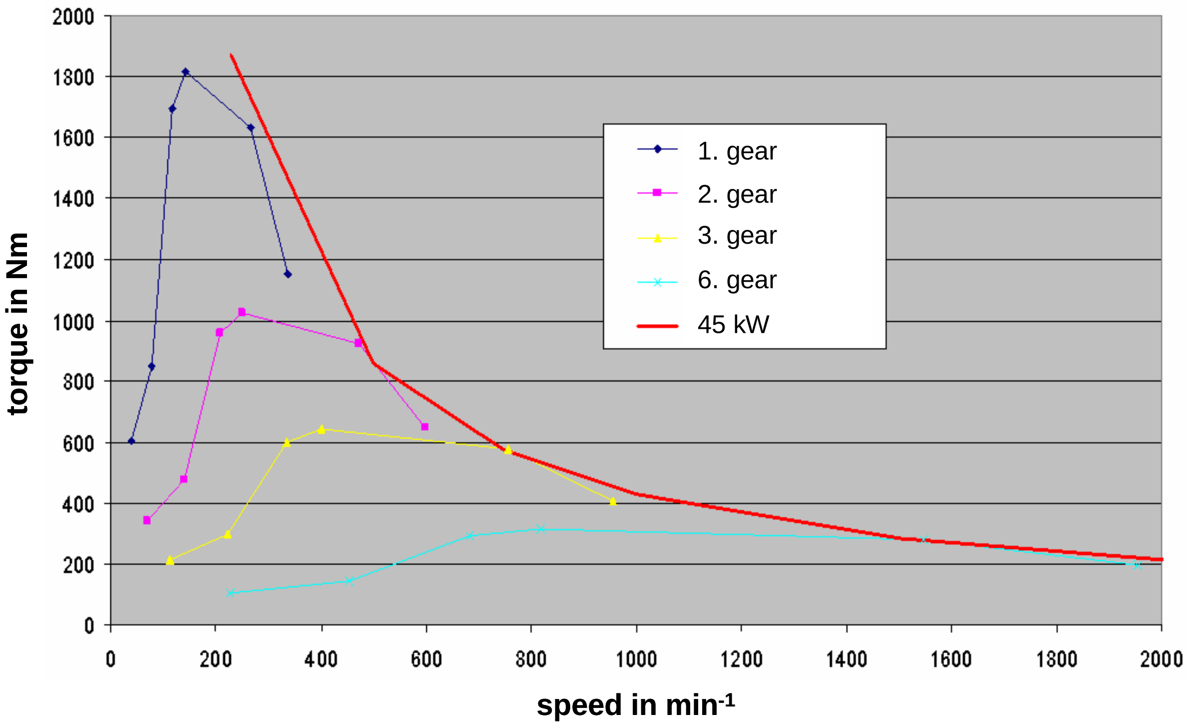


Figure 7: Torque-speed-characteristic at the wheels of a typical mid-size passenger car.

Several design calculations concerning the electric drives have been performed at the Institute of Electrical Drives (EAA) at the University of Federal Defense Munich, Germany. It turned out, that an air-cooled high-speed drive by far is not feasible. For this alternative a forced water-cooling has been assumed in the following, having the following characteristics:

- temperature of the cooling fluid: 65°C
- convection coefficient between electric motor and cooling fluid: 6000 W/(m^{2}K)

In contrary, the low-speed direct drive is suitable to be cooled by forced air. The respective data are:

- air temperature: 35°C
- convection coefficient between electric motor and cooling air: 190 W/(m^{2}K)

3.2 High-Speed Drive with Gear-Box

For the alternative with high-speed drive, the gear box has to be defined.[1] It turned out that a planetary gear-box will be most promising, because of its low weight (0.2 to 1.0 kg/kW) and relatively high gear ratio (3 to 35). Analysing existing planetary gear-sets it can be concluded that for a torque of 1800Nm a ring gear diameter of about 170mm is required, resulting in a specific weight of 0.1kg/Nm. This holds true for industrial gear-sets with 100% duty cycle. Although the duty cycle in automotive applications is the same a more lightweight construction can be assumed because of anticipated optimization potentials. For the following calculations, a specific weight of 0.05kg/Nm will be regarded. To calculate the torque at the wheels, a 98.5% efficiency of the gear-box is assumed in the following.

In addition, detailed electric machine designs have been elaborated (computed using the analytical software SPEED and in addition the FEM-software ANSYS 2D) to get all relevant data for a comparison Two examples are shown in the following figures 8 and 9.

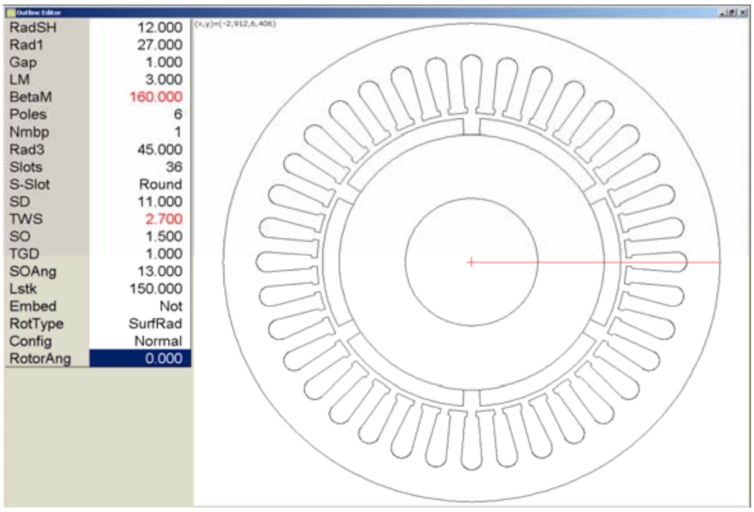


Figure 8: Geometry of a high-speed electric motor calculated using SPEED.

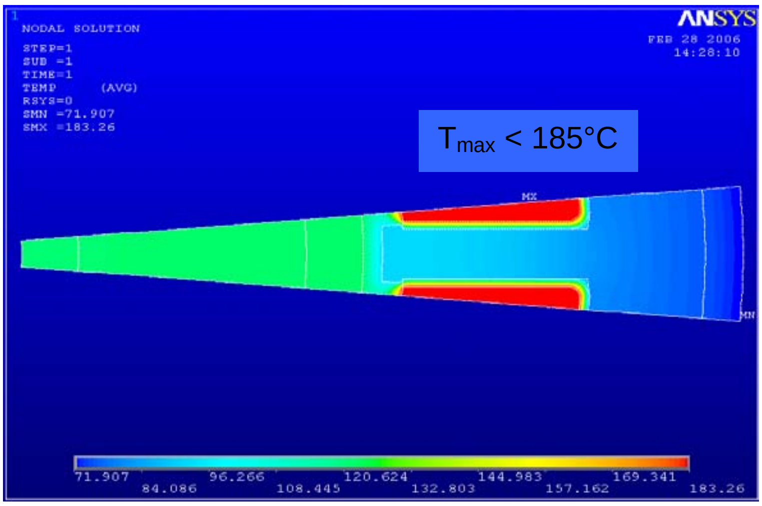


Figure 9: Temperature calculation of a high-speed electric motor calculated using ANSYS (long-term torque capability: 34Nm).

[1] The authors like to thank the fka, Aachen (Germany) for very helpful discussions concerning mechanical gears suitable for the automotive industry.

For both, high-speed drive and low-speed drive, a somewhat lower torque at the wheels than for the vehicle with combustion engine has been specified, because the electric drive delivers the maximum torque from zero speed on. This lower torque at zero speed results in the same acceleration performance of the vehicle like for the combustion engine version. The chosen data are:

- combustion engine: two-wheel-drive with 1800Nm each
- high-speed electric traction drive: four-wheel drive with 34Nm (electric motor) each
- low-speed electric traction drive: four-wheel drive with 350Nm each

3.3 Low-Speed Direct Drive

For the low-speed direct drive an outside rotor version has been chosen, because then the rotor can be mounted directly into the wheel-hub of a vehicle. The geometry (see fig. 10) is designed to fit into a 19 inch tire. The respective temperature calculation can be found in fig. 11.

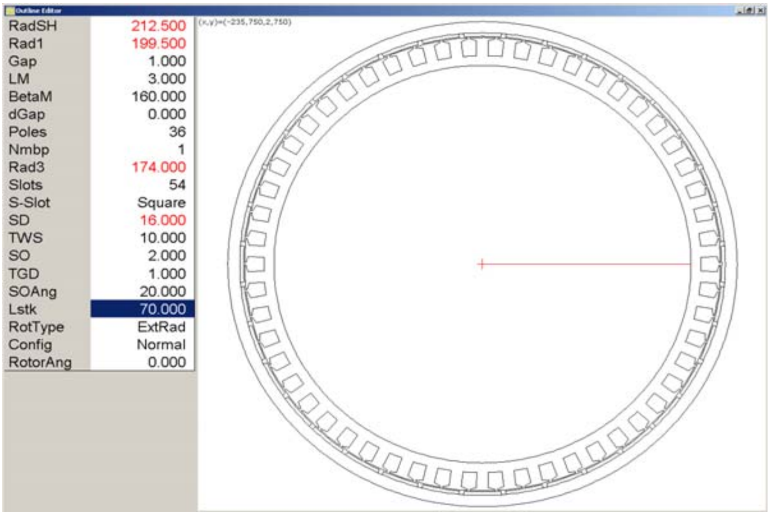


Figure 10: Geometry of a low-speed direct drive electric motor calculated using SPEED.

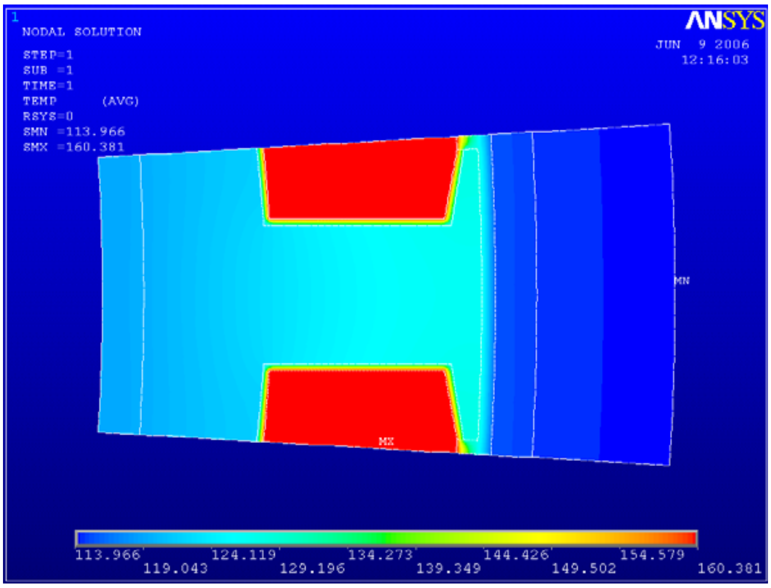


Figure 11: Temperature calculation of a low-speed direct drive electric motor calculated using ANSYS (long-term torque capability: 350Nm).

3.4 Comparison

Comparing both alternatives for wheel-hub drives (high-speed drive with additional gear-box and low-speed direct drive) shows the following characteristics:

- high-speed drive with additional gear-box
  - high-speed and low-torque electric motor leads to a small motor and therefore a small motor weight
  - the additionally required coupling and gear-box implicates additional losses and weight
  - water cooling is necessary
  - in total it is a complex mechanical construction
- low-speed direct drive
  - low-speed and high-torque electric motor means a high motor weight
  - forced air-cooling is sufficient
  - the construction is less complex than for the first alternative
  - the direct drive may be integrated into the wheel-hub
- for both alternatives
  - the temperature is critical because of the unavoidable mechanical brake

The unsprung mass is critical for the driving comfort and safety of automobiles. As both alternatives for wheel-hub drives increase this unsprung mass, it can be only decided on the basis of detailed designs, which alternative is advantageous. Therefore, at the Institute of Electrical Drives (EAA) of the University of Federal Defense Munich, Germany, such designs have been elaborated. On the basis of detailed electric machine designs (computed using the analytical software SPEED and in addition the FEM-software ANSYS 2D) and, for the high-speed drive, with an additional weight of 0.05kg/Nm for gear-box, coupling, and respective housing it turned out that the low-speed direct drive is advantegeous: it requires less overall weight for the same mechanical power at the wheels (please refer to the following fig. 12).

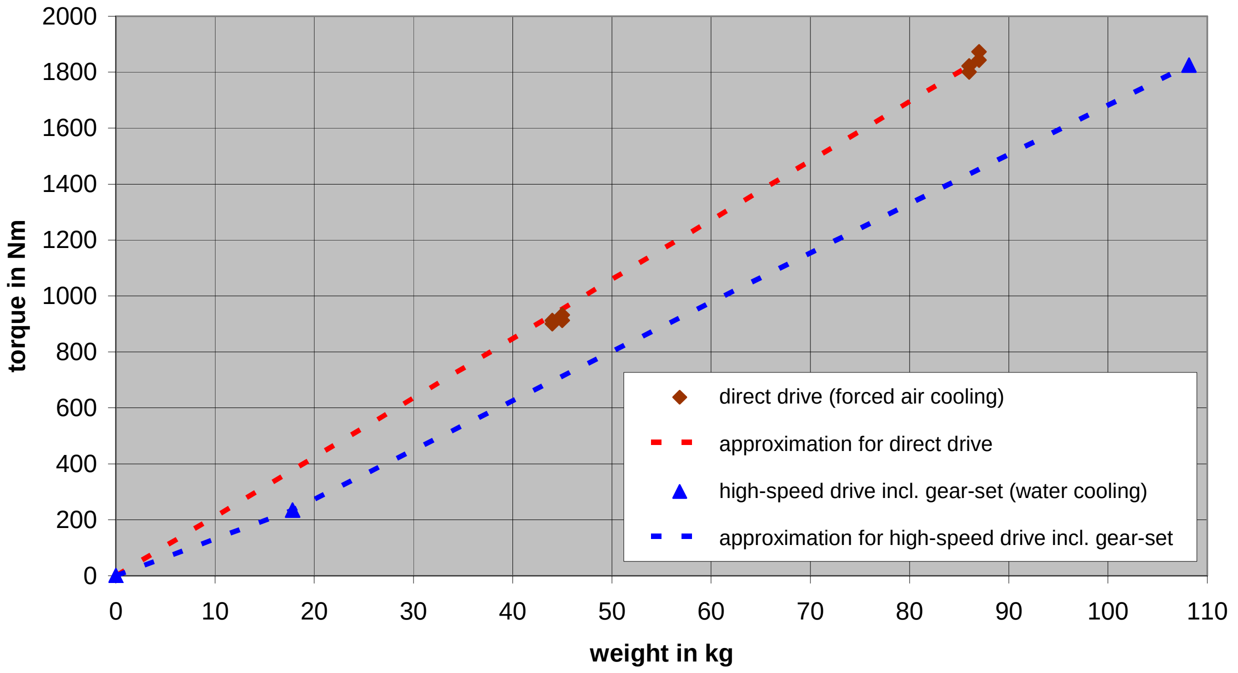


Figure 12: Torque versus weight characteristics of the different wheel-hub drive alternatives.

4. Conclusions

Electric traction drives for hybrid and fuel cell passenger cars can be divided into two major classes: centre drives and wheel-hub drives.

The centre drive is already commercially available, e.g. as full hybrid (Toyota / Lexus) or mild hybrid (Honda). Most of the other car manufacturers have announced similar hybrid systems (all equipped with centre drives).

There are many companies researching wheel-hub drives, but up to now no such drive can be purchased in a series production car. The main driving force to investigate wheel-hub drives is, that there is more space left under the hood for batteries (hybrid cars) or hydrogen storage tanks (fuel cell cars) to enhance the driving range of such vehicles.

The detailed analysis presented in this paper leads to the conclusion that the low-speed direct drive most probably is advantegeous concerning the additional unsprung mass. Nevertheless, there is still much to do: Beside the electromagnetic and thermal optimization of such wheel-hub drives (including electric machine, power electronics, and control), even the mechanical construction (including integration, mass reduction, and vehicle dynamics) is a major research and development topic.

5. References

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