Why efficiency matters

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DeepDrive is developing fully flat, modular and plug & play skateboard platforms for electric vehicles (EV). One key technology of this platform is our ultra-efficient, compact and lightweight in-wheel motor, reducing energy consumption by up to 20% compared to state-of-the-art EVs. This translates into a total cost of ownership (TCO) reduction of more than 4.000€ over vehicle lifetime[1], allows large savings in battery capacity and consequently significantly reduces the CO_2-footprint of EVs. However, many times, we've been asked how this reduction can be possible, when today's EV drive units already achieve peak efficiencies of more than 93%.

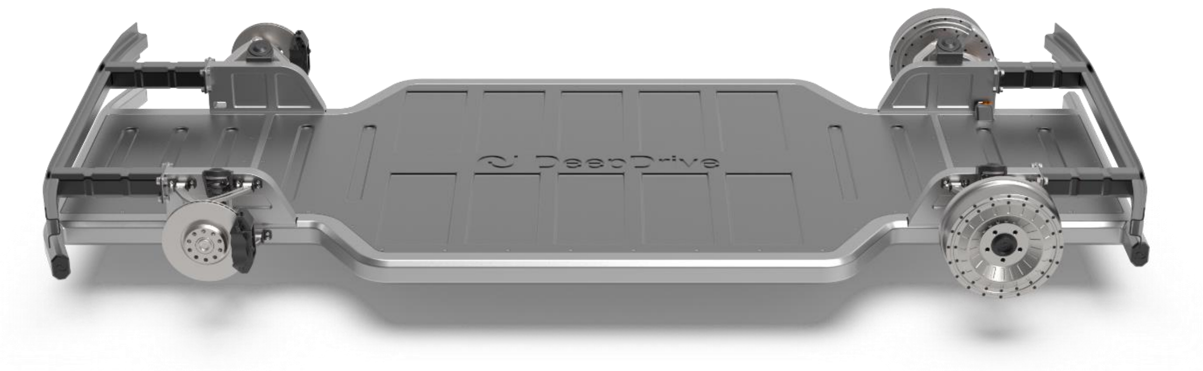

Figure 1: Flat and modular EV platform with in-wheel motors at rear axle

To answer this question, a closer look in energy consumption of state-of-the art powertrains and their operating conditions is necessary. These central drive units, in this paper referred to as *eAxle*, nowadays look very similar in all electric vehicles: They use a permanent magnet excited electric machine (PSM), often with hairpin winding in the stator and buried NdFeB-based magnets in the rotor. The inverter uses IGBTs or sometimes SiC-MOSFETS in a two-level B6 configuration. The transmission usually uses a two-stage spur-gearbox with a fixed gear-ratio in a range from 9:1 up to 13:1, leading to a maximum rotating speed of the motor from 14.000 rpm up to 19.000 rpm and an output torque at the wheels from 2.500 to 4.000 Nm. The power of such an eAxle varies from 150 to 250 kW and it has a weight between 80 kg and 100 kg. Figure 2 shows a representative eAxle from the VW MEB EV platform.

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[1] Savings in battery capacity and energy consumption. Assumptions: 300,000 km lifetime; 0.30 €/kWh electricity cost; 120€/kWh battery cost

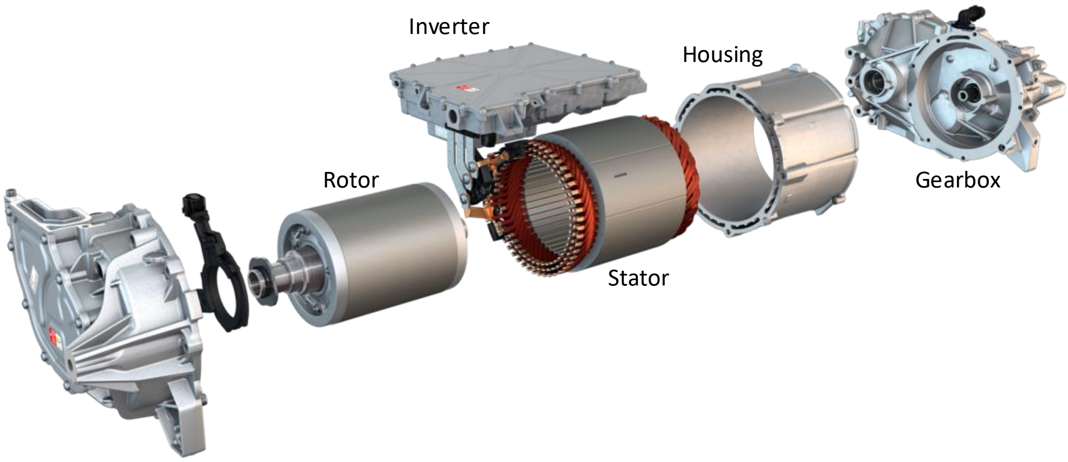

Figure 2: Components of an eAxle (Illustrative purpose, source: VW press release[2])

The loss mechanisms of these drive systems are well understood and validated, which allows an accurate prediction of the efficiency and therefore the energy consumption and range of electric vehicles using these systems. For a detailed comparison with our in-wheel motor, a generic reference eAxle has been defined in this paper and calculated with state-of-the-art calculation methods. Figure 3 shows the specifications and the resulting efficiency map of this reference eAxle, reaching ~94% peak efficiency. The calculated losses include all relevant mechanisms, including switching-induced losses in iron and magnets, reverse recovery losses in the inverter, AC-losses in the windings, splashing losses in the gearbox and all other friction losses.

Reference eAxle specifications	
Motor-type	PSM, V-magnets
Lamination thickness	0.27 mm
Winding	Hairpin
Inverter	IGBT, 650V
Nom. DC-voltage	340 V
Max. current	500 Arms
Peak power	180 kW
PWM frequency	10 kHz, SVPWM
Gear ratio	11:1
Nom. temperature	80°C

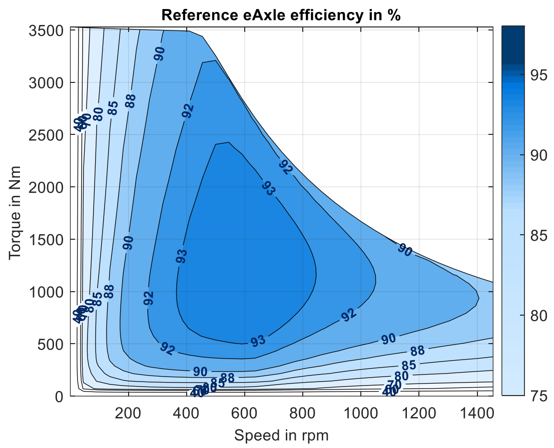

Figure 3: Specifications of generic reference eAxle and resulting efficiency map based on own calculation

Based on these loss-maps as a function of speed and torque, the energy consumption of an EV can be calculated. In Europe, the WLTP cycle (WLTC) is used for comparison and certification. For the reference eAxle and a generic C-segment EV[3], this calculation

[2] https://www.volkswagen-newsroom.com/en/press-releases/in-brief-more-than-200-horses-in-a-sports-bag-the-electric-drive-in-the-volkswagen-id3-5541
[3] m=1800 kg, cwA=0.55 m², μ_{roll}=0.011

results in cycle losses of 3.0 kWh/100km and a total energy consumption W_{el} of 13.3 kWh/100km excl. any auxiliary consumers. From this numbers, a cycle efficiency

$$\eta_{\mathrm{Cycle}} = \frac{W_{\mathrm{mech}}}{W_{\mathrm{el}}}$$

can be calculated using the mechanical energy W_{mech} used in the cycle. Thus, the resulting cycle efficiency for the reference eAxle in WLTC is just 77%.

The reason for the deviation from peak efficiency to cycle efficiency becomes visible in Figure 4. It shows the speed profile of a WLTC and the corresponding torque-speed values in the efficiency map of the reference eAxle[4]. The load points concentrate on the low torque area with efficiencies far below 90% and barely reach the area of peak efficiency. Moreover, the kinetic energy is transferred multiple times through the eAxle during braking and accelerating, which reduces the resulting cycle efficiency further.

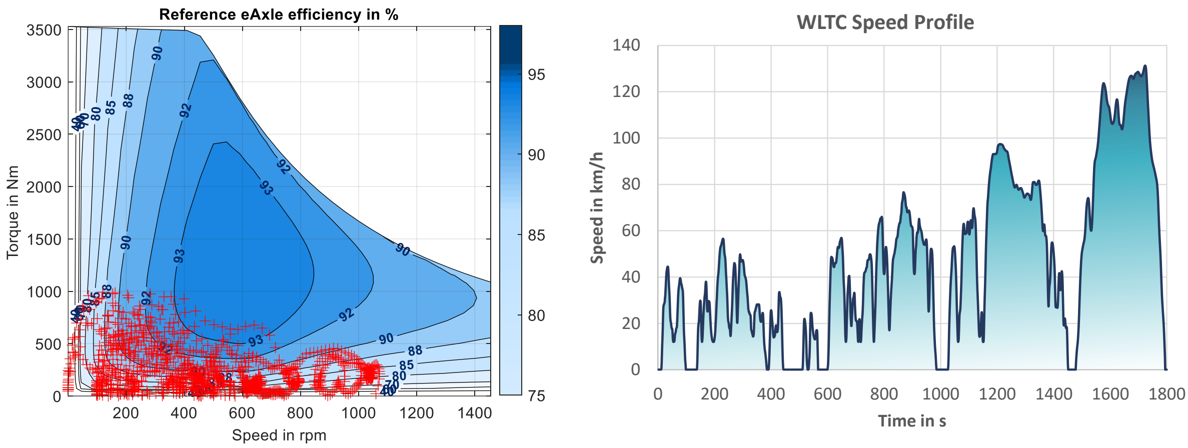

Figure 4: WLTC speed profile and resulting torque-speed points for a reference C-segment EV[3] in the operating area of an eAxle

For the sake of completeness, it must be mentioned that the efficiency of today's eAxles may be increased by some measures, e.g., using a SiC-inverter instead of IGBT, enlarging the electric machine, reducing lamination thickness or lowering the gearbox ratio. However, it all comes at the expense of additional cost and weight without big chances of increasing the cycle efficiency to values >80%.

The problem of cold eAxles

In real world driving scenarios, an additional problem arises. All values given by now refer to an operating condition with *nominal* temperature, which is usually defined between 60°C to 80°C. In real use-cases, the eAxle often does not reach this temperature level. When it comes to lower temperatures, the cycle efficiency reduces significantly because of two important effects. On the transmission side, the viscosity of the oil rises, leading to much higher splashing losses. Thus, for a temperature of 10°C, the cycle losses of the gearbox nearly double compared to operation with 80°C. On the e-machine side, a lower temperature of the magnets leads to increased iron losses and higher field weakening

[4] For sake of simplicity, all generator operating points are mirrored to the motor operating area in this figure.

current. Consequently, the cycle losses rise to 3.8 kWh/100km at 10°C for the reference eAxle, reducing the cycle efficiency to 73%.

The DeepDrive technology

The DeepDrive in-wheel motors are a direct-drive concept omitting the gearbox and consequently all gearbox losses. Moreover, the new motor technology creates very low iron losses and high specific torque density of more than 80 Nm/kg related to the active parts[5]. The high necessary torque of a direct drive comes at the expense of an increase in copper losses, but they have little influence on cycle losses. Also, a very effective cooling concept allows them to be dissipated very easily, enabling a continuous torque of more than 900 Nm per motor.

The integrated inverter uses SiC-MOSFETS in a new configuration reducing inverter switching losses as well as PWM-induced losses in the electric machine. This technology also contributes to the excellent efficiency in the partial load condition.

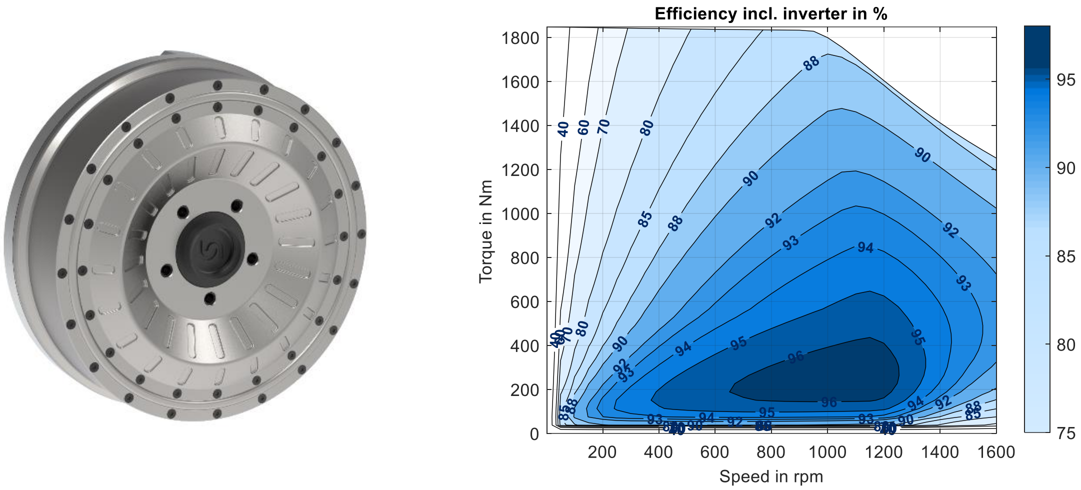

Figure 5: DeepDrive in-wheel motor and efficiency map

Figure 5 shows a picture of the DeepDrive in-wheel motor and an efficiency map including all relevant loss components for a DC-link voltage of 340 Vdc and a nominal temperature of 80°C. The predicted values and calculation methods have already been validated using a diameter-scaled prototype on a test bench[6], proving the very small iron losses, the overall efficiency and the torque density. It is visible that the peak efficiency of the complete system is above 96%. Moreover, the area of best efficiency concentrates on the low torque region, leading to an excellent cycle efficiency of 89% with nominal temperature. In contrast to conventional eAxles, cycle efficiency of the DeepDrive in-wheel motors rises to 90% at lower temperatures, because the copper losses reduce with lower temperatures. This means, the losses in the powertrain reduce by 1.7 kWh or 55% at nominal temperature (Figure 6) and even 2.5 kWh or 65% in low temperature operation.

[5] copper, iron and magnets
[6] https://www.electrive.net/2021/08/27/deepdrive-zeigt-radnabenmotor-auf-der-iaa/

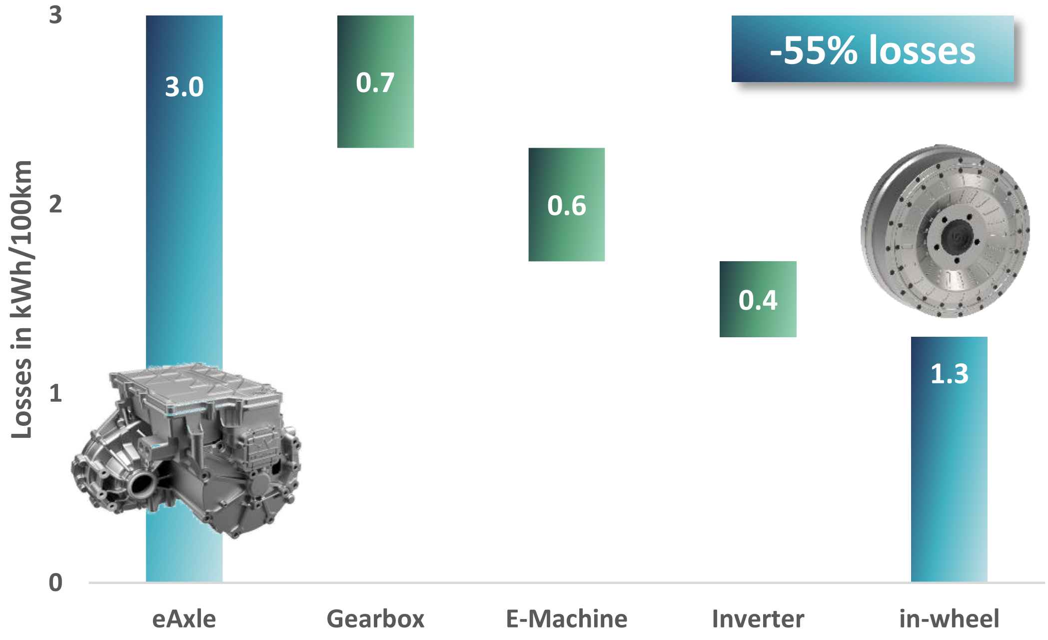

Figure 6: Loss reduction of the DeepDrive in-wheel motor compared to the generic eAxle at nominal temperature (60°C). For low temperature (10°C) operation, the loss reduction rises to 2.5 kWh or 65%. The inserted picture of the eAxle (Source: BorgWarner[7]) is just for illustrative purpose.

Impact on Energy consumption of EVs

For a final comparison of the energy consumption, the possible weight reduction has to be taken into account: In our EV-platform (Figure 7), the in-wheel motors replace the mechanical brake system at the rear axle, the conventional eAxle and the drive shafts which gives a weight reduction of ~70kg. Moreover, for a 500 km range EV, the battery capacity can be reduced by ~10 kWh for the same range, giving another 60 kg weight reduction[8]. This 130 kg total weight reduction reduces the vehicle's rolling resistance. Adding this to preliminary shown loss reduction, the total reduction of energy consumption by our DeepDrive in-wheel motors ends up with ~16% for nominal temperature and ~21% for low temperature operation. Moreover, the vacant space in the rear gives additional freedom of design to reduce the energy consumption of EVs. E.g., it might be used to increase aerodynamics of the vehicle, as recently shown by the EV start-up Lightyear in their highly efficient Lightyear One[9], also driven by in-wheel motors.

[7] https://www.borgwarner.com/newsroom/press-releases/2019/01/24/borgwarner-s-eaxle-idm-takes-electric-propulsion-to-a-new-level
[8] Assuming a 180Wh/kg energy density of the battery pack
[9] https://lightyear.one/

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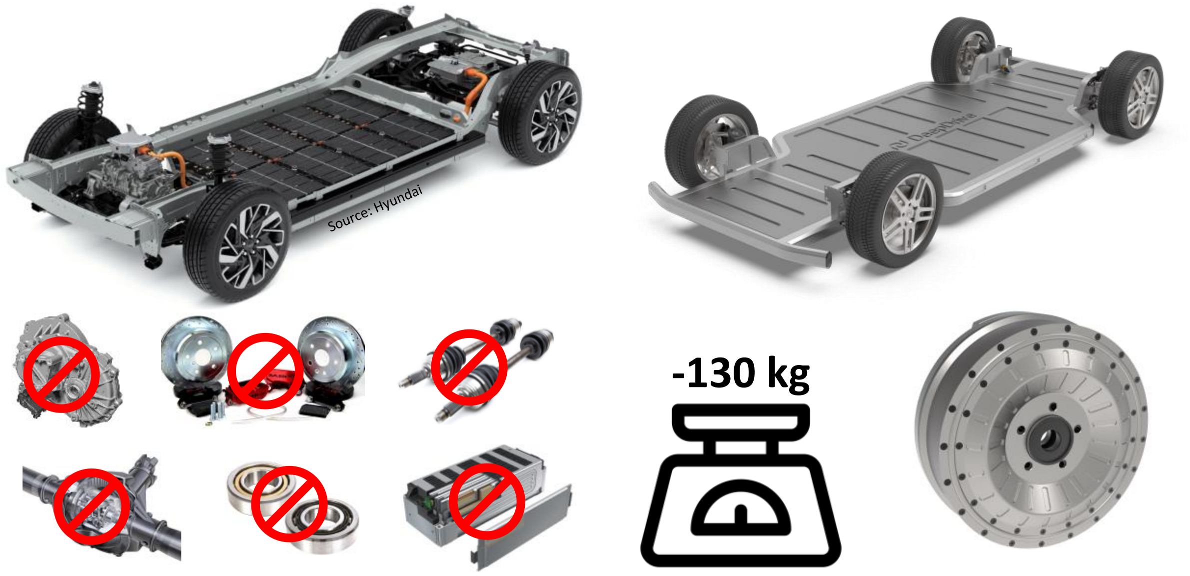

Figure 7: Removed components and weight savings in DeepDrive platform with in-wheel motors compared to conventional EV-platforms

Conclusion

The DeepDrive EV platform using our in-wheel motors reduces energy consumption of electric cars by up to 20%. This is possible, because today's eAxles still waste more than 25% of the electrical energy and utilise a lot of space and weight. In contrast, the DeepDrive in-wheel motors provide excellent efficiency, especially in low torque area and real-world driving situations, and reduce the overall weight of an electric car by ~130 kg. Moreover, the lightweight design and the possibility to replace the mechanical brake system at the rear axle solves the problem of unsprung masses, removing a major barrier for the application of in-wheel motors.

For our customers, this translates into the best-in-class TCO, an unmatchable freedom-of-design and high flexibility. The modular, plug & play concept helps to reduce time-to-market and allows large savings in development costs for new vehicles.

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