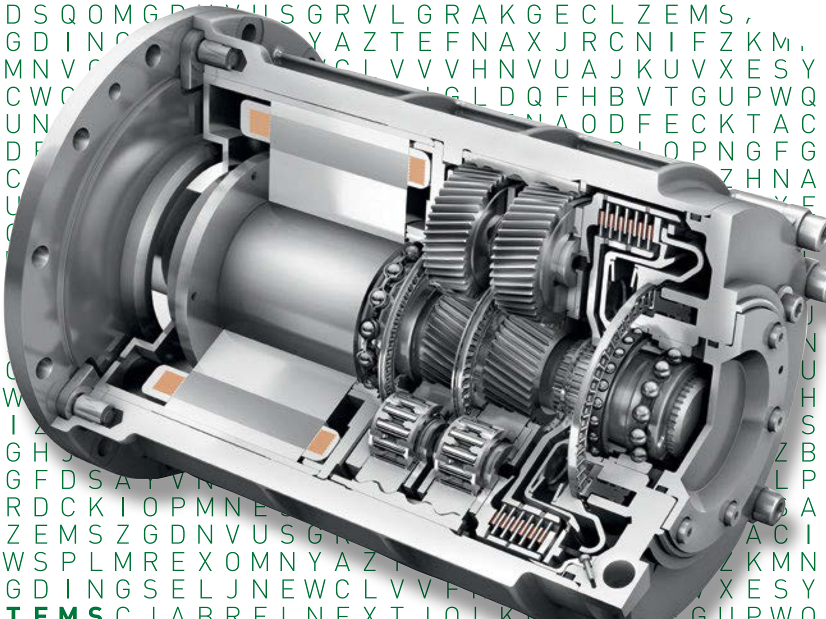
HYBRID

TORQUE VECTORING

AXLE SYSTEMS

MODULARITY

ELECTRICAL ENGINE



Who's Afraid of 48 V? Not the Mini Hybrid with Electric Axle!

Modular electric axle drive in a 48-volt on-board electric system

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Axle drives for hybrid vehicles

Development level of the eDifferential in a high-voltage design

In the entire automobile industry, there is a discernible trend towards hybrid vehicles in order to meet future CO_2 requirements. The test cycles used for determining CO_2 emissions favor vehicles with a long range of electric operation. Plug-in hybrid vehicles are increasingly appearing on the market, whose batteries can be charged using public or private power supply systems. The driving performance required from these vehicles requires relatively high levels of electric power with low space requirements.

At the Schaeffler Symposium 2010, Schaeffler presented a technical solution for these vehicles with the first generation of the so-called “active electric differential” [1]. This electric axle enables both an optimum use of space as an axle drive and also active torque distribution to the wheels so that very good values for driving dynamics are achieved as well.

Schaeffler has been consistently developing the electric axle drive ever since. The third generation currently being tested is matched to the topology of a plug-in hybrid vehicle with a front mounted engine and front-wheel drive. The drive unit (Figure 1) is still designed to be fitted coaxially in the rear axle and is characterized by the following features:

- Water-cooled electric motors in hybrid design (permanently excited synchronous motors with a high proportion of reluctance) are used. These meet automotive-specific requirements in contrast to the industrial motors used in the first generation.
- The transmission is still in planetary design and now has two ratio stages.

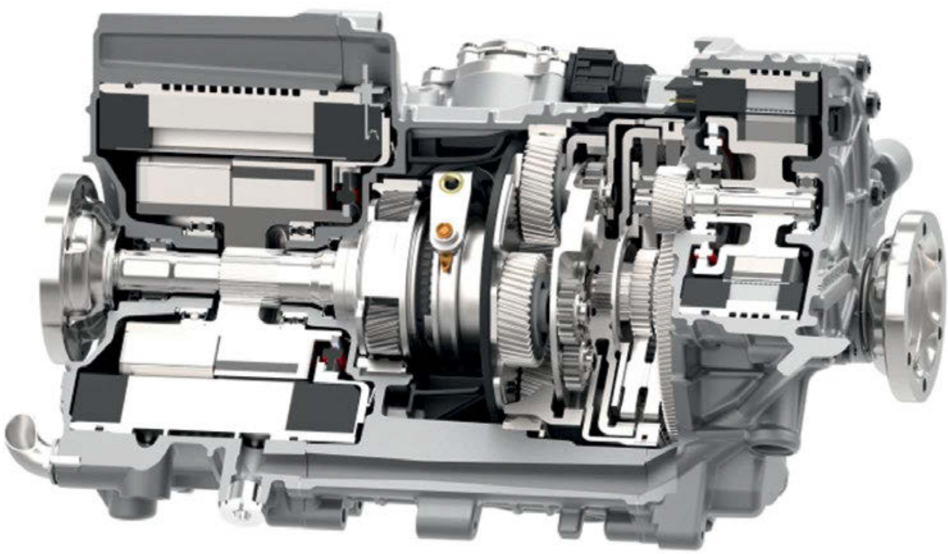

Figure 1 Section through the electric axle in a high-voltage design

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	Gen 1 (VEP)	Gen 2	Gen 3
Application	EV, E-AWD	HEV, E-RWD	HEV, E-RWD
Dimensions	300 x 562	230 x 550	230 x 525
Weight w/o power electronics	120 kg	89 kg	79 kg
DC Battery Voltage min / nom / max	350 / 400 / 450 V	270 / 320 / 360 V	264 / 323 / 361 V
Max. power	105 kW (< 10 s)	55 kW (< 30 s)	65 kW (< 60 s)
Continuous output	–	38 kW	45 kW
Max. torque	1,200 Nm	1,800 Nm	2,000 Nm (60 s)
Continuous torque	–	–	1,200 Nm
Max. speed (electr. motor)	8,900 rpm	13,000 rpm	14,000 rpm
Ratio	i = 7	i_1 = 12.3 ; i_2 = 4.2	i_1 = 12.3 ; i_2 = 4.2
V_{max} vehicle (electric)	< 150 km/h	< 250 km/h	>= 262 km/h
Max. torque vectoring torque	1,500 Nm	1,150 Nm	1,200 Nm (10 s)
Max. differential lock	–	–	1,600 Nm (5 s)

Figure 2 Technical data for three generations of high-voltage axles

– The drive unit has increased power density and a modular design so that traction and active torque distribution can be offered as separate functions.

The progress achieved in development is apparent if one considers the main key figures of the third generation (Figure 2). For example, the diameter was reduced by 70 mm to 230 mm and the weight of the unit was reduced by 41 kg to 79 kg. The peak power was reduced to 65 kW due to the voltage range of 270 to 360 V of batteries used in plug-in hybrids. Peak power is now available for up to 60 seconds. The maximum torque is 2,000 Nm due to the high ratio of the two-speed transmission. The continuous torque of 1,200 Nm is sufficient for all conventional driving situations. Torque vectoring with torque differences of up to 1,200 Nm can also be implemented at very high speeds.

Schaeffler's high-voltage electric axle can achieve the high levels of electric power, which are typical for hybrid and plug-in hybrid vehicles as well as range-extenders and electric vehicles. The system is currently undergoing field tests with automobile manufacturers.

The mini hybrid with 48-volt on-board electric system

After it became clear that mini hybrid vehicles with 48-volt on-board electric subsystems would be introduced in increasing numbers in the coming years [2], the question arose at Schaeffler as to whether the electric axle drive could also be used for these vehicles. The objective of using a 48-volt hybrid must be considered: A significant CO_2 reduction must be achieved at acceptable costs. The key to achieving this

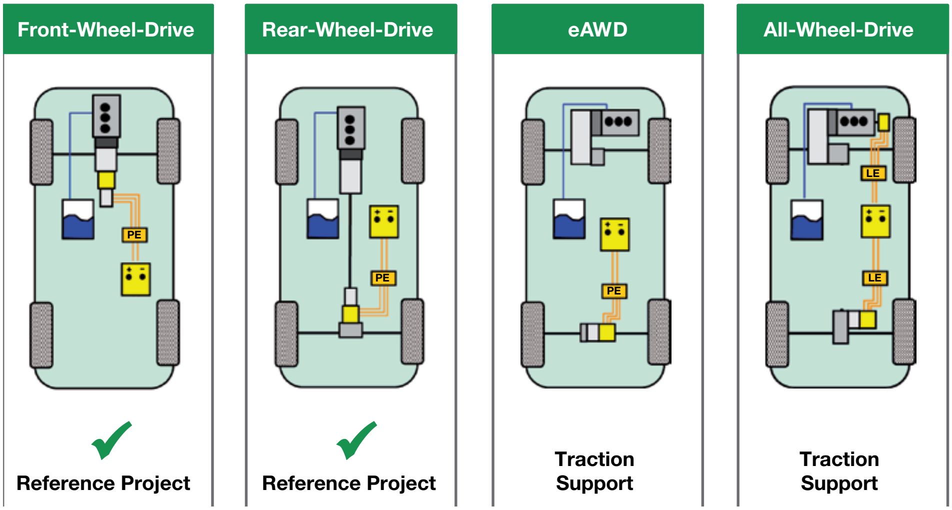

Figure 3 Basic topologies of a 48-volt hybrid powertrain

objective is not only the battery, which is still the largest cost block, but also the lower overall safety requirements for drive systems with a peak voltage of less than 60 V. A low-voltage system is the subject of significantly lower requirements in all steps of the value added chain, from assembly through to maintenance.

The maximum CO_2 saving is also dependent on the electric power of a 48-volt hybrid system. The decisive factor is not only the acceleration to be achieved by the vehicle, but above all the maximum braking energy to be recuperated. The maximum power achievable with current technology is approximately 12 kW. This electric power not only enables recuperation in generator mode, but also a displacement of the operating point of the internal combustion engine in the data map and electric driving in a low speed range, for example, during maneuvering or in traffic jams.

The integration of a corresponding low-voltage electric axle into the powertrain can be carried out in different configurations (Figure 3). The driven axle can be provided with motor assistance in both front-wheel and rear-wheel drive vehicles. An electric rear axle drive can also be implemented in a front-wheel drive vehicle, a configuration, which is occasionally described as an "electric all-wheel drive". Lastly, the electric drive force can also be distributed between the front and rear axle, although this means that two electric motors and two power electronics units are required.

With regard to the following considerations, Schaeffler assumes that vehicles with an electric axle based on 48-volt system will always have a belt-driven starter generator with a nominal voltage of 12 or 48 V because it is not possible to start the internal combustion engine with the electric axle motor. In addition, the starter generator is already part of the modular system from the vehicle manufacturer's point of view. This has the advantage that safety-critical functions such as electromechanical torque vectoring are always available irrespective of the battery's state of charge because the battery can be recharged by the starter generator at any time. The use of the electric axle as a "electric four-wheel drive" is also dependent on the state of charge. Four-wheel drive functionality is available without limitations when moving off.

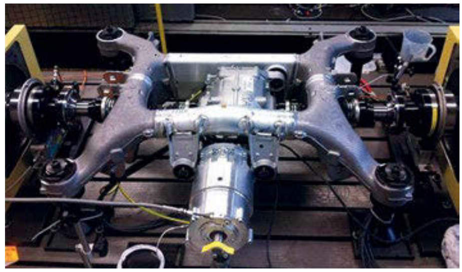

Figure 4 Prototype of an electric rear axle drive for a rear-wheel drive vehicle

Design of the 48-volt axle drive

After taking the fundamental decision to derive an electric rear axle from the high-voltage system based on a 48-volt system, Schaeffler began development of a relevant system, which would fit in an actual current volume-produced vehicle with rear-wheel drive. It was apparent that the electric motor could be fitted around the propshaft without having any affect on the space requirement (Figure 4). An existing asynchronous motor from a belt-driven starter generator is used. The 48-volt axle drive is also equipped with a two-speed transmission as in the latest generation of the high-voltage variant.

The drive was designed so that it can be offered as an additional variant with a single-speed or two-speed transmission in a volume-produced vehicle without necessitating changes to the vehicle body or chassis. This required a very compact design. In this particular case, the diameter of 180 mm was less than the diameter of the propshaft tunnel. The entire drive unit is located coaxially relative to the propshaft directly in front of the axle drive (Figure 5). Water cooling was also not required.

In first gear, the force flows from the electric motor via the sun wheel of the first planetary gear set (Figure 6). The planet carrier is connected with the sun wheel of the second gear set and the force is transmitted to an intermediate shaft via the planet carrier. The force flows between the planet carrier and the intermediate shaft via a switchable selector sleeve. In second gear, however, the planet carrier of the first gear set is connected with the intermediate shaft so that only the ratio of this planet carrier is effective. The second gear set rotates free of load. The transmission is stationary when disengaged and the vehicle behaves like a conventional vehicle.

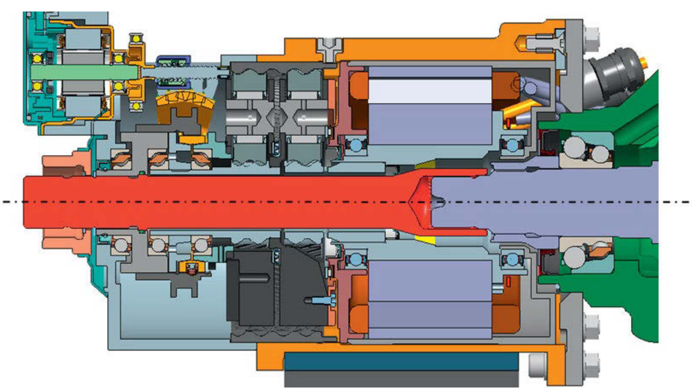

Figure 5 Section through the electric rear axle drive integrated around the propshaft

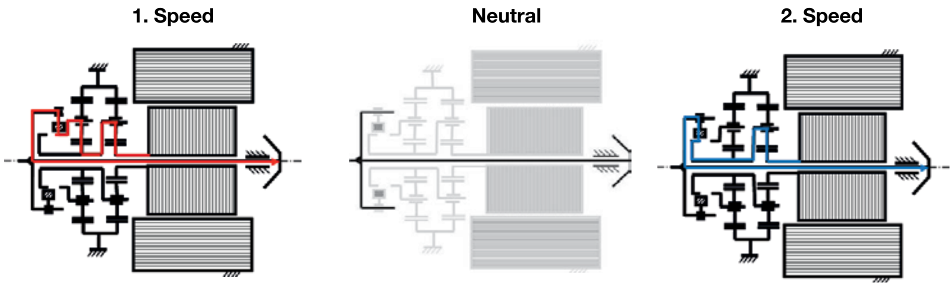

Figure 6 Flow of force in the electric rear axle drive

A very high transmission ratio has been selected for first gear in order to achieve a sufficient starting torque of at least 1,000 Nm despite the relatively small electric motor. In the prototype, a ratio i of 19.6 was selected for first gear taking into account the ratio of the hypoid stage of the rear differential. In second gear the ratio i is 4.4. The relatively high ratio steps were selected because the asynchronous motor reaches its maximum speed in first gear at slightly above 20 km/h.

Functions of a 48-volt mini hybrid

CO_2 optimization

Without a doubt, the reduction of CO_2 emissions is the primary motivation for introducing a mini hybrid drive system. The decisive reduction for homologation should also be reflected in the lowest possible actual fuel consumption for end customers. Schaeffler has therefore carried out simulations of several driving cycles for a vehicle with an electric rear differential (Figure 7). The simulations were based on a very heavy luxury class vehicle with a weight of more than 2 tons and a V-8 gasoline engine.

The simulations show that consumption can be reduced by up to 9 % in the NEDC, compared with a vehicle equipped with a start-stop function. In the ARTEMIS cycle, which is aimed at simulating the actual fuel consumption of a theoretical average customer, there is a reduction in consumption of around 6 %. These simulations were created using models, which take the overall efficiency chain into consideration. For example, the actual reduction in power of the electric motor with increasing temperatures was also considered.

It was however assumed in the simulations shown that the internal combustion engine was switched off during sailing. This is not always the case in all foreseeable applications for the future so that the fuel consumption of the internal combustion engine during idling must also be added if required.

Electric driving functions

Schaeffler's electric axle differential has sufficient torque to enable driving using electric power only in a low-speed range of 0 to 20 km/h. We prefer to use the term "moving off using only electric power" as a synonym to ensure that any reference to

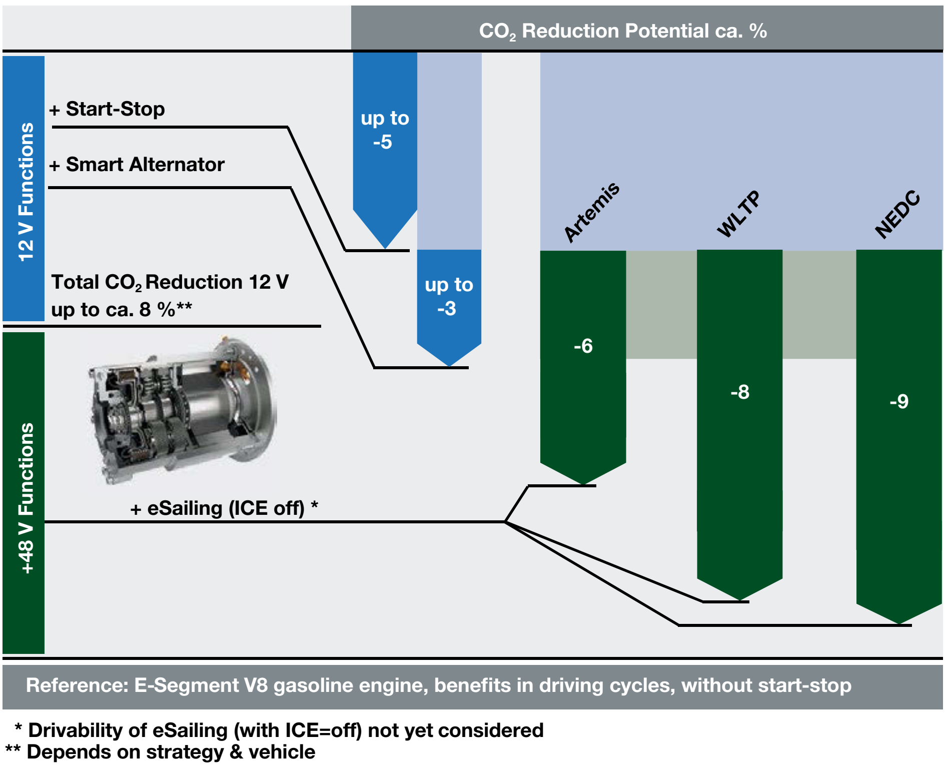

Figure 7 Potential reduction in CO_2 emissions of a mini hybrid drive system in different driving cycles

"electric driving" does not lead to unrealistic customer expectations. There are major advantages in terms of comfort for the customer, particularly in stop-and-go traffic and during maneuvering. Control of longitudinal dynamics can be carried with the brake pedal alone, as in a vehicle with an automatic transmission – and with the internal combustion engine switched off. The torque that can be currently achieved on the axle is sufficient to accelerate a vehicle from a standstill on a gradient of up to 10 %. The potential for reducing CO_2 by moving off solely under electric power is less than 3 % in the premium segment sedan considered above. The possible range of electric operation is also limited to several hundred meters or just a few kilometers depending on the size of the currently available low-voltage batteries. The described advantages in terms of comfort and the experience of electric driving, in combination with the minimal additional complexity for end customers, are a thoroughly convincing argument for deciding to buy a hybrid vehicle.

Active torque distribution

If the unit is fitted coaxially relative to the vehicle's axle, the electric differential in 48-volt design can also be used in order to operate active torque distribution in a transverse direction (so-called torque vectoring). This form of variable drive torque distribution be-

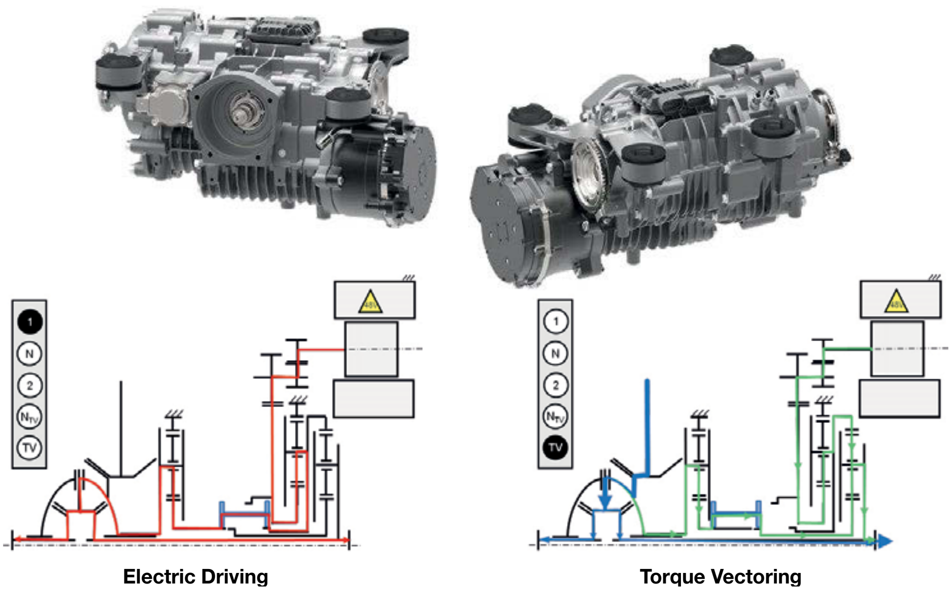

Figure 8 48-volt axle drive with an electric motor and a two-speed transmission

tween the wheels has two basic advantages:

- Increased traction if the friction coefficients of both wheels are unequal, for example, when driving on snow-covered or icy roads.
- Improved lateral dynamics due to targeted adjustment of the torque, which counteracts understeer or oversteer of the vehicle during cornering.

Active torque distribution is increasingly regarded as a comfort function. For example, it would be possible to completely compensate for the influence of strong side winds on the direction of travel in an energy efficient manner by using torque vectoring. The input variable for such functions is the yawing moment about the vertical axis of the vehicle, which is already continuously recorded by the ESP sensors. The introduction of such functions is the subject of detailed discussions about the personal responsibility of the driver.

The design of a 48-volt mini hybrid with an electric rear axle is based on the idea of torque distribution so that a single electric motor can be used – in contrast to the high-voltage module shown in Figure 1. In addition, the architecture of the two-speed transmission should be used for both the drive and torque distribution (Figure 8). The two-speed transmission with a torque vectoring function can be combined with a planetary differential but also with a standard bevel gear differential.

Shifting between the three planetary gear sets is carried out sequentially with a single actuator, which reduces the complexity and costs of the gearshift system. This type of actuation concept with one actuator offers additional advantages with regard to functional safety because the risk of faulty gearshift operation (double gearshift operations) can be reduced. The ratios are designed so that the vehicle can be driven at approximately 20 km/h using electric power only. Subsequently, the system shifts from first to second gear. Boosting, recuperation and load point shifting of the internal combustion engine are possible within a speed range of approximately 20 to 80 km/h. Planet gears 1 and 3 are used for the traction mode.

Active torque distribution is possible from second gear after passing through another neutral position. The force now also flows via the center planet gear, which is connected with both the differential cage and the side shafts. The side shafts are "rotated" in relation to each other due to the torque applied by the electric motor, resulting in a difference in speed. Torques of up to 1,200 Nm (peak) and 800 Nm (continuous torque) can be achieved with this type of system, which is comparable with the hydraulic systems already established on the market. It must be emphasized that the torque vectoring position is independent of the actual vehicle speed, i.e. it can also be selected when the vehicle is stationary.

Torque vectoring or electric drive can be selected automatically by means of suitable sensors and prioritization depending on the vehicle speed and other input variables. An additional option is the targeted activation of functions by the driver using a "sport button", "economy button" or "city mode button".

This has the following advantages for the electric axle based on a 48-volt system with integrated electromechanical torque vectoring:

– Moving off using electric power only and active torque distribution are possible in contrast to a standard rear differential.
– A significant reduction in fuel consumption is possible compared to a hydraulic system for active torque vectoring. An electromechanical system has maximum actuating speeds of 60 ms, virtually independent of the temperature.
– The 48-volt system is significantly less complex and therefore more cost effective compared with the high-voltage system according to Figure 1, which is the "non plus ultra" in technical terms.

With its recently presented system, Schaeffler is pursuing a strategy of maximizing the integration of functions by means of innovative drive technology and minimum product complexity. Schaeffler has succeeded in integrating three functions into the rear differential using an electric motor, an actuator, and transmission architecture: Moving off using only electric power, a significant potential for reducing CO_2 in hybrid mode and an increase in vehicle agility and comfort by means of torque vectoring.

This type of "three-in-one" modular concept combines the demands for efficient mobility with the maximum requirements for vehicle dynamics and emotionality of future vehicles and acceptable purchase costs. The resulting added value for end customers can be a decision-making criterion for the acceptance of low-voltage hybridization and accelerate the hybridization of vehicle drives worldwide.

Schaeffler is currently equipping a sporty coupé in the compact vehicle class with an electric axle and integrated torque vectoring based on a 48-volt system in order to test these advantages, which are directly noticed by end customers.

Outlook

The CO_2 reductions that can be achieved with a mini hybrid drive are of course significantly less than the values, which can be achieved with a high-voltage electric drive. However, the ratio of costs and benefits according to the first simulations is so positive that Schaeffler is continuing intensive further development. The potential identified in the simulations will be checked by designing a demonstration vehicle and carrying out practical tests.

There is a strong correlation between the CO_2 reduction and the electric power of the system as described above. This is clear if the speeds driven in the NEDC are plotted over the corresponding axle torque and compared with the data map of the electric motor (Figure 9).

Consequently, a significantly higher proportion of operating points could be covered with a performance-enhanced electric motor of 12 to 18 kW. This also applies for the braking performance and thus the quantity of recuperated energy. Schaeffler is therefore also working on the further development of an electric drive with higher power in addition to a prototype equipped with a 12-kW motor.

An increase in the available continuous output would also be possible by changing the method of cooling used in the electric motors in the prototypes from cooling via the air gap to oil cooling and this is therefore also part of further development work.

Schaeffler can also envisage that radical optimization of the rolling resistance of the tire in combination with active electromechanical torque distribution will become a further field of research. This work is based on the idea of compensating the reduced cornering forces of particularly narrow tires with a low rolling resistance by means of torque vectoring. Initial estimates indicate a potential reduction in rolling resistance of up to 30 % – without any risk to the active safety. The implementation of this idea still raises many questions. For example: How can it be ensured that these types of tires are only fitted on vehicles with active torque distribution? Is permanent roll stabilization of a vehicle by means of the active intervention of an electromechanical system permitted?

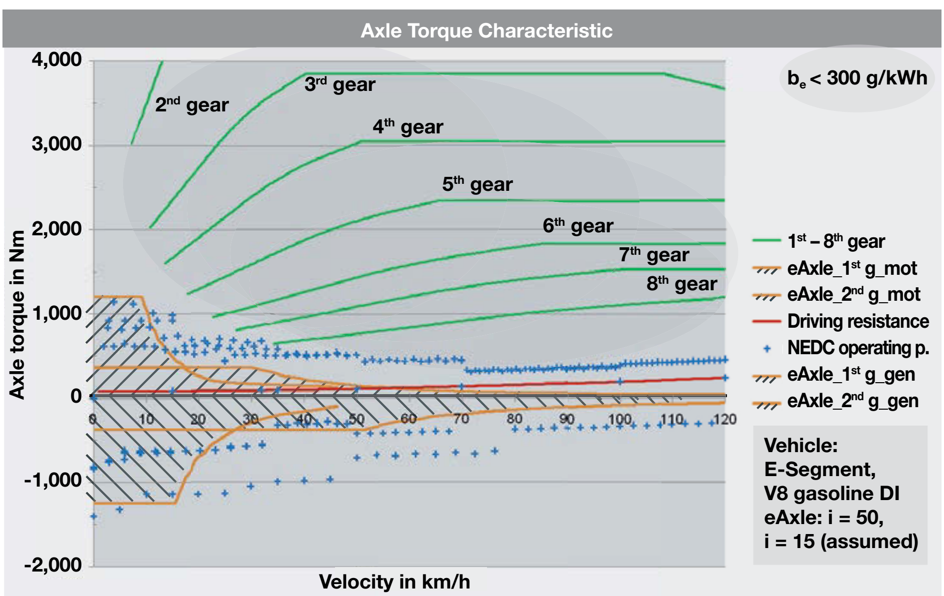

Figure 9 Operating points in the NEDC and torque output of the electric motor

At Schaeffler, we regard innovation as a continuous search for new concepts and we pursue radical ideas, whose one hundred percent feasibility must still be proven as part of research and development projects. We are always open to further inspiration and ideas from our customers, suppliers, and development partners!

Literature

[1] Smetana, T.; et al.: Schaeffler active eDifferential: The active differential for future drive trains. 9th Schaeffler Symposium, 2010

[2] Gutzmer, P.: Individuality, efficiency and comfort: Paradigms for future mobility. 10th Schaeffler Symposium, 2014

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