Drive Concepts using Super Reduction Hypoids Combined with Cylindrical Gear Reductions

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Why Transmissions in Electric Vehicles?

Compact electric vehicles require a cost-effective and compact solution for the location of the electric motor and the transmission. Yes, even today electric vehicles require a transmission, if the maximal possible motor efficiency has to be available in the majority of drive conditions. Transmissions also allow higher motor rpm, resulting in smaller size electric motors with improved dynamic properties. The torque and efficiency optimal rpm of an 80 kw electric motor for a compact vehicle is between 6,000 and 10,000 rpm. For example if the nominal driving speed is 80 km/h and the optimal motor speed is 10,000 rpm, the optimal ratio between motor and wheels (using a wheel diameter of 410 mm) is 9.66:

$$i = (n_{Motor} \cdot D \cdot n) / v$$

Whereas:

i	Transmission ratio
n_{Motor}	Optimal motor rpm [1/min]
D	Outer tire diameter [m]
v	Average vehicle speed [m/min]

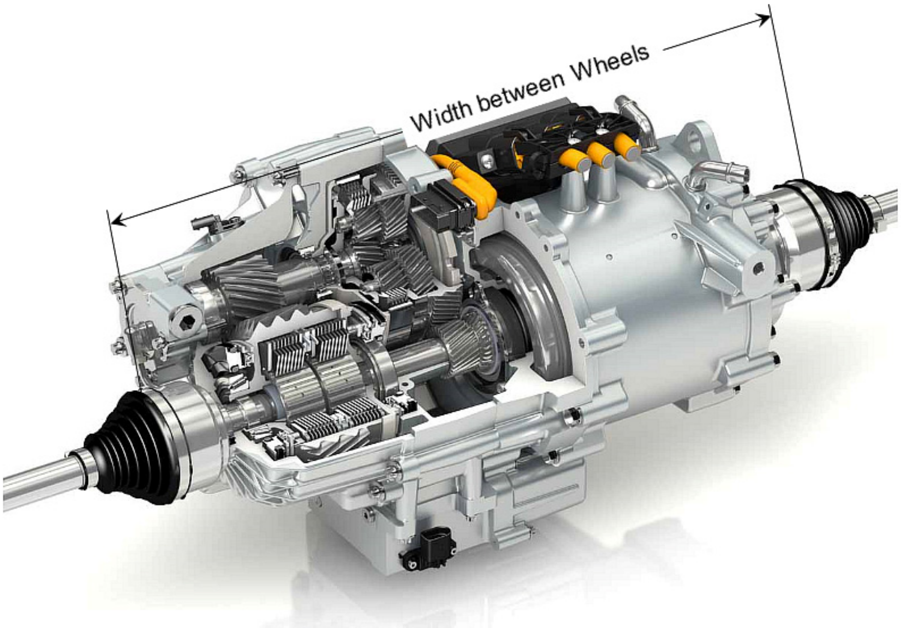

Figure 1 Electric motor in line with transmission and front wheels (Source [1]).

A variety of eDrive concepts have been developed during the past years. One example which has already been introduced in Chapter 1 is the design shown in Figure 1 (Ref. 1). It is very compact, but like most concepts, it does not solve the three major obstacles of the “inline design,” which are:

- Large width between the front wheels used for drive unit
- Asymmetric weight distribution
- Higher heat radiation to the wheel and tire on the side of the electric motor

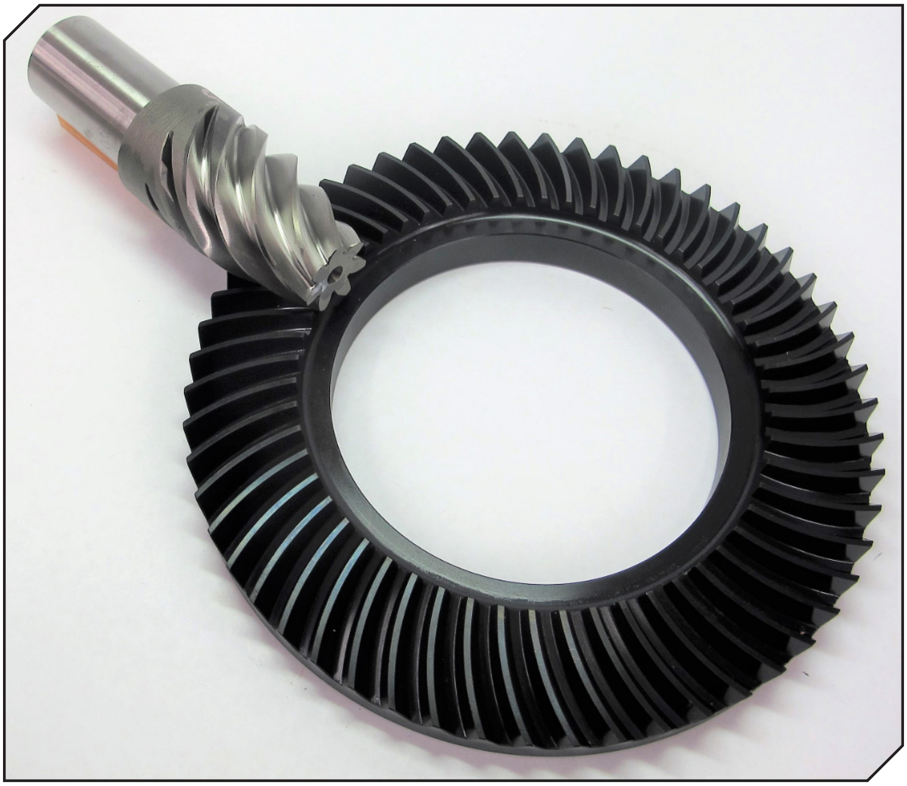

Figure 2 Hypoid gearset with a ratio of 7 × 55.

The large width between the wheels requires short drive shafts. Each of the drive shafts has two CV-joints which wear fast in the case of short drive shafts due to the steering inclination and control arm swings. This will also result in a reduced efficiency and front axle noise.

The asymmetric weight distribution

has to be offset with other asymmetric vehicle components such as the battery. However, there will still be an influence on the dynamic behavior of the vehicle.

The permanent heat radiation of the electric motor in Figure 1 might increase the temperature of the adjacent tire by 10 to 20°C. Thermal insulation and an additional cooling fan can reduce the temperature of the hot tire to the e-motor but the consumption of electrical energy for the evacuation of motor heat is not something EV-manufacturers like to see.

Transmissions Establishing Symmetry in the Drivetrain

Gleason suggested the possibility of a high reduction hypoid gearset as shown in Figure 2. The ratio of the gearset in Figure 2 is 7.85 (7 × 55), which is high for an automotive transmission, but appears rather low for a one stage eDrive reduction. The objective of this application is to rotate the electric motor by 90° which would establish a symmetric eDrive unit by accomplishing the required ratio between motor and wheels solely with this one single reduction stage. The gearset in Figure 2 is designed as a regular hypoid with the *Gleason Gear Engineering and Manufacturing System GEMS*. It is not a high reduction hypoid (HRH) or a Super Reduction Hypoid (SRH). The pinion has seven teeth and the ring gear has 55 teeth. This first design was the attempt to do a moderate and predictable step to achieve the major objectives of a single stage eDrive reduction.

Any eDrive reductions require high efficiency as well as a good back driving ability. The back driving is important in two ways. The first reason is the regeneration of electrical energy in case the vehicle driver takes the foot off the accelerator pedal. The electric motor is switched to generator operation and the kinetic energy of the vehicle is used to re-charge the battery rather than being wasted by simply using the brakes. The second reason for the back driving ability is to avoid wheel locking in case of an abrupt release of the accelerator pedal. The gearset in Figure 2 fulfills both requirements very well. The ring gear is phosphatized in order to increase the efficiency of the gearset before break-in and avoid costly polishing. As the phosphor layer breaks down, the break-in of the gearset is finished and the initial efficiency will be maintained. Both members have been ground after heat treatment.

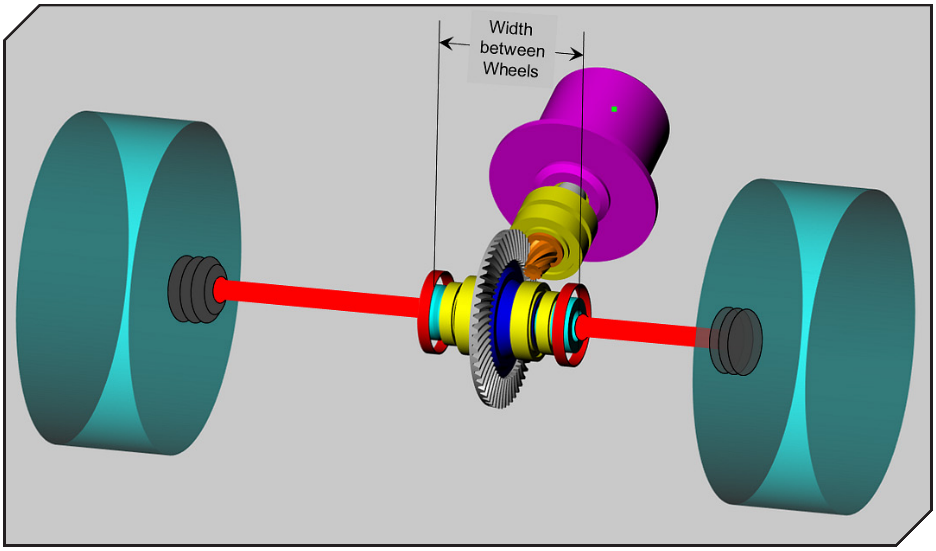

Figure 3 eDrive unit with single stage hypoid reduction, shown without housing between the front wheels of a small sedan [2].

The gearbox design, which accommodates the hypoid reduction and the new orientation of the electric motor was designed and optimized with the Gleason *KISSsoft* development and optimization system. The result of this development is shown in Figure 3 (Ref. 2).

The eDrive unit in Figure 3 has the highest degree of symmetry and moves the heat radiating electric motor away from the tire it was exposed to with the inline design of Figure 1. The distance between the drive shaft flanges presents a very small "width between wheels," which allows for rather long drive shafts. With the possibility to face the motor either towards the front or towards the back, the ideal weight distribution and optimal packaging for a particular vehicle can be achieved. This very compact design with only two gears and two shafts can be manufactured very cost-effectively and presents a very good eDrive solution for a small compact electric vehicle. The remaining question is the possibility to realize even higher ratios with a single stage hypoid gearset. Also the question of whether the concept presented in Figure 3 could be extended to a combination of a hypoid and a cylindrical reduction and still preserve the basic advantages mentioned above, has to be analyzed.

The Super Reduction Hypoid Solution

In order to increase the ratio of the hypoid gearset in Figure 3, the conventional hypoid calculation appears to be unsuitable. Several sample calculations, using the SRH design applet, delivered very good results (Ref. 3). In the sample calculations, the pinions had 4, 5 and 6 teeth. SRH creates a face milling duplex design which can be optimized regarding tooth depth, pinion diameter and face angles specifically to the requirements of an eDrive.

One point of attention is the maximal sliding velocity generated by the hypoid offset of the pinion. During the SRH analysis, the sliding velocity is calculated. Hypoid gearsets with an offset as used in automotive and truck applications have about 125 m/min relative sliding velocity when the vehicle is driving at a speed of 100km/h (62.5 mph). An eDrive hypoid with a ratio of 9.66 generates at a motor speed of 10,000 rpm a relative sliding velocity of 333 m/min.

This is more than twice the relative surface sliding of the conventional hypoid gearset. It will be required to use high-pressure synthetic hypoid oil. It also was discussed whether surface coatings are required in order to achieve the necessary gear life with respect to surface damages.

The number of teeth is not the only indicator of the back driving ability of a hypoid gearset; it is also the pinion spiral angle. The larger the spiral angle the lower the back driving ability becomes. The following categories of spiral angles are defined:

Small spiral angle: 0° to 20°
Medium spiral angle: 20° to 35°
Large spiral angle: 35° to 65°
Very large spiral angle: 65° to 90°

Two examples — one with a large spiral angle and one with a very large spiral angle are shown in Figure 4. A certain number of teeth on a small diameter results in a lower spiral angle than the same number of teeth on a large diameter. In order to take the opposing effects into account, the UNICAL dimension sheet program (Ref. 3) calculated the back driving ability by considering the correct geometry and an assumed coefficient of friction of 0.08. The program calculates the back driving opposing force T_{br} and divides it by the back driving force T_{dr}. The fraction T_{br}/T_{dr} called the Back Driving Coefficient C_{BD} (Ref. 2). A value of $C_{BD} = 1.0$ and above indicates a self-locking condition. A value of CBD = 0 would be ideal but cannot be achieved because it would require the absence of any friction losses. In Table 1 the results of C_{BD} for five different real hypoid gearsets are listed.

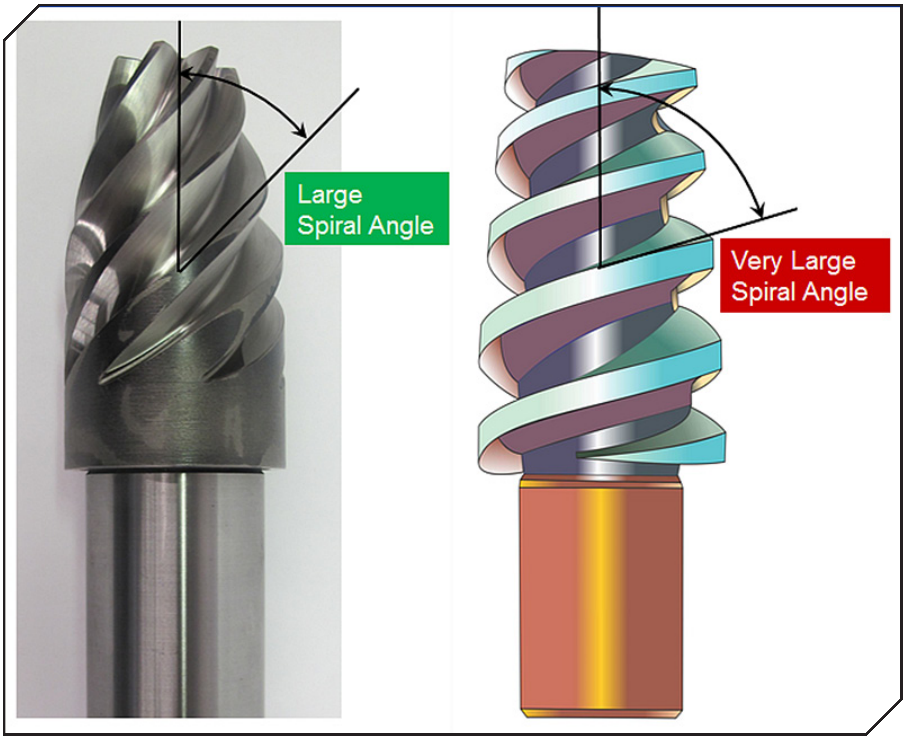

Figure 4 Large pinion spiral angle (left) and very large spiral angle (right).

While the 17-tooth automotive hypoid pinion has a C_{BD} of 0.091, which is excellent, the 1-tooth pinion example is self-locking with a C_{BD} of 1.295. The 2- to 5-tooth pinions have very similar coefficients, with the unexpected low coefficient of the 3- tooth pinion, which is lower than the 5-tooth pinion. This shows that optimizing the right parameters will allow reducing the pinion tooth count to 3 in order to still achieve a reasonably good back driving ability. The values in Table 1 are part of the SRH Dimension Sheet output (Ref. 3).

If an ideal ratio for an eDrive hypoid reduction is in the range of 15, then it seems realistic to select 4 pinion teeth and 60 ring gear teeth (better 59 or 61 because of hunting tooth advantage). Such a SRH gearset should be optimized with the goal to achieve a back driving coefficient $C_{BD} = 0.3$ or below.

Table 1 Back driving analysis results for 5 different hypoid gearsets.

Number of Pinion Teeth	Coefficient of Friction	Back Driving Coefficient C_{BD}	Condition of Back Driving
17	$\mu = 0.08$	$T_{br}/T_{dr} = 0.091$	Not Self Locking
5	$\mu = 0.08$	$T_{br}/T_{dr} = 0.324$	Not Self Locking
3	$\mu = 0.08$	$T_{br}/T_{dr} = 0.305$	Not self Locking
2	$\mu = 0.08$	$T_{br}/T_{dr} = 0.336$	Not Self Locking
1	$\mu = 0.08$	$T_{br}/T_{dr} = 1.295$	Self Locking

The SRH system has several advantages versus HRH or regular hypoid gears. It is possible for a given ring gear spiral angle to search for the lowest spiral angle difference between pinion and gear. This is possible by changing the pinion diameter and the offset for given gear diameter and spiral angle. The pitch angle of the gear can be adjusted in order to achieve optimal roll conditions. It also proved to be advantageous for eDrive SRHs to increase the depth factor to 30% above the standard tooth depth. Pressure angles can be entered asymmetrically into the SRH calculation to assure the desired contact ratio balance between drive and coast side.

Different Hypoid Transmission Types

Compact and low-priced electric vehicles require a simple, compact and cost- effective transmission between electric motor and front or rear wheels. Small compact vehicles with eDrive mostly do not require top speeds above 90km/h. Their major application is inner city driving for commuting or shopping. All important objectives for such a vehicle can be fulfilled with a single-stage hypoid transmission, as shown in Figure 5.

The small width between the wheels makes for a slick compact vehicle solution which allows optimal packaging and an ideal vehicle weight distribution. The ratio can be below 12 and so a second gear reduction which can serve to adjust the vehicle speed more optimally to the eMotor rpm is not really required. The transmission in Figure 5 has a ratio of 7.85 (7 × 55) and a back driving coefficient of about 0.3, which is acceptable for energy recuperation during coast operation.

A second eDrive transmission concept is shown in Figure 6. This concept is a dual- stage reduction with a first cylindrical reduction of 2.33 (21 × 49) and a second hypoid reduction of 4.4 (11 × 51), which results in an overall ratio of 10.27. The driving efficiency of the dual-stage transmission will be higher than the transmission in Figure 5 and the back driving coefficient of about 0.15 is also better than the transmission in Figure 5.

Midsize or premium electric vehicles would benefit from the transmission concept in Figure 7. An electromagnetically actuated clutch unit can activate either a ratio of 1.46 (26 × 38) or a ratio of 3 (16 × 48). The hypoid reduction has a ratio of 3.85 (13 × 50). In forward driving with lower speeds (e.g., up to 50km/h (31.3 mph)) the overall ratio can be switched to $3 \cdot 3.85 = 11.55$. As the speed increases above 50 km/h (31.3 mph), the eMotor will operate with less efficiency and the second cylindrical gear pair can be activated. Now the overall ratio changes to $1.46 \cdot 3.85 = 5.62$, which enables the motor to reduce its rpm to a more efficient operation.

The transmission in Figure 7 becomes very interesting in coast operation when the motor is switched to generator mode to utilize the kinetic energy of the vehicle to recharge the battery. For example, if the speed is 80km/h (50 mph) with a transmission ratio of 5.62, the transmission will switch within some milliseconds to the higher ratio of 11.55 in order to give the generator (motor) more rpm for a more efficient electricity generation. Although this concept does not benefit from the originally discussed single-stage transmission, its flexibility makes it a very attractive solution. The advantages like packaging, good weight distribution as well as heat radiation away from one of the wheels are all maintained.

In order to complete the possibilities of

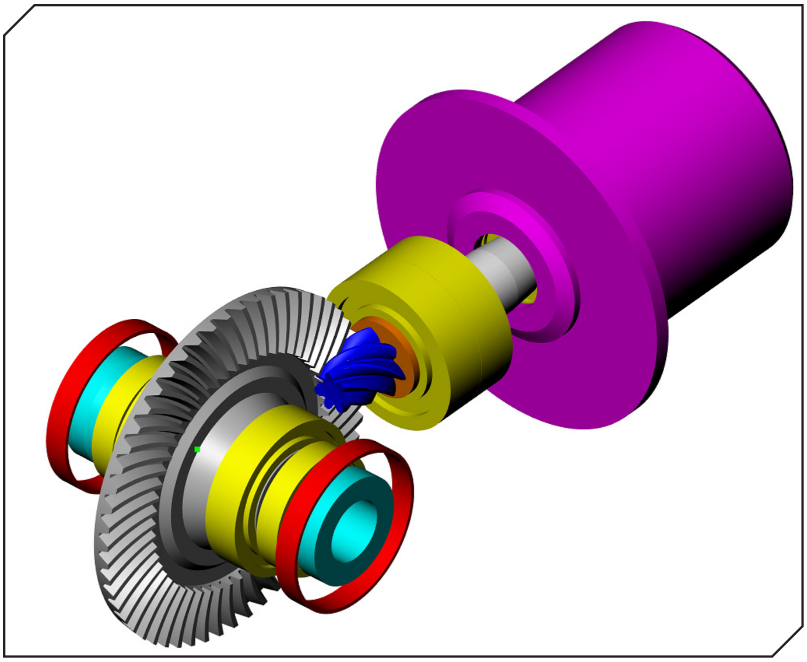

Figure 5 Single stage hypoid transmission – Design 1.

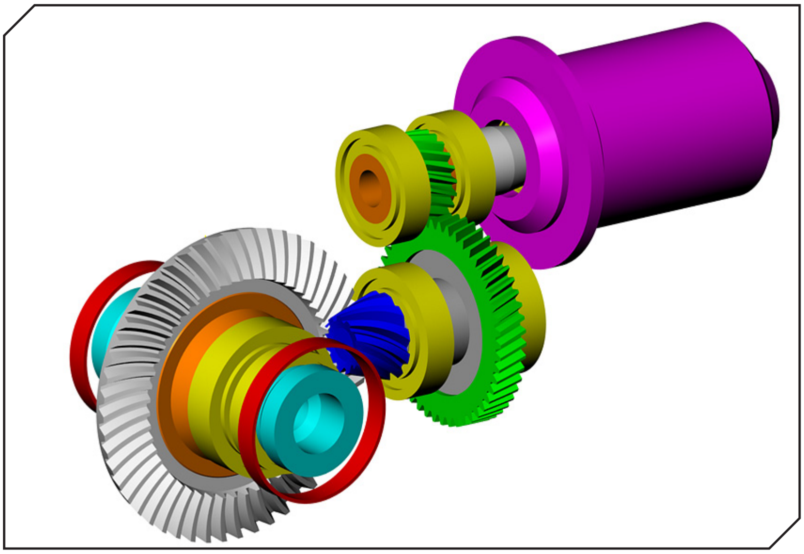

Figure 6 Dual stage cylindrical-Hypoid transmission – Design 2.

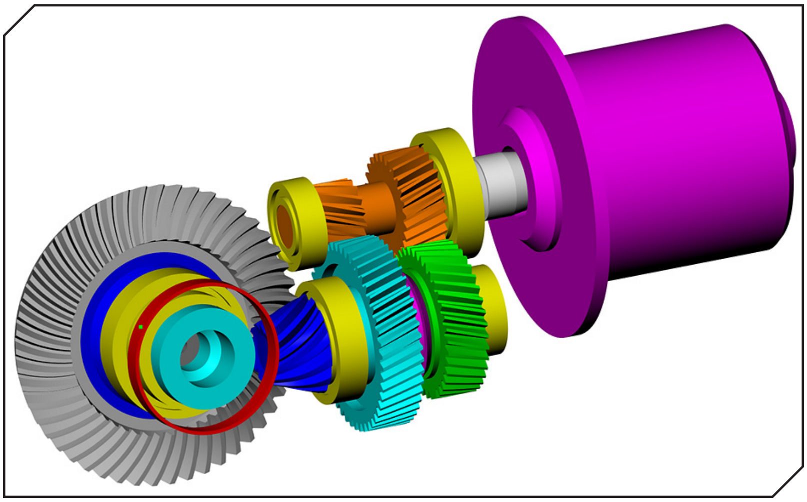

Figure 7 Dual speed cylindrical-hypoid transmission – Design 3.

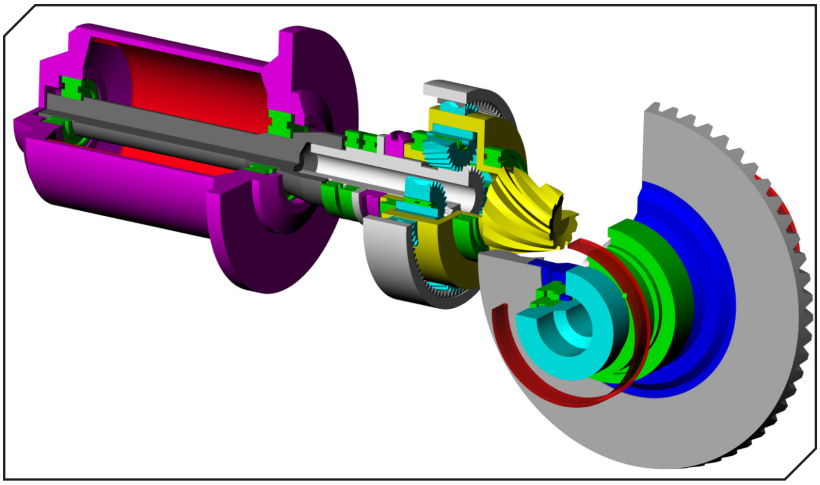

Figure 8 Planetary-hypoid reduction – Design 4.

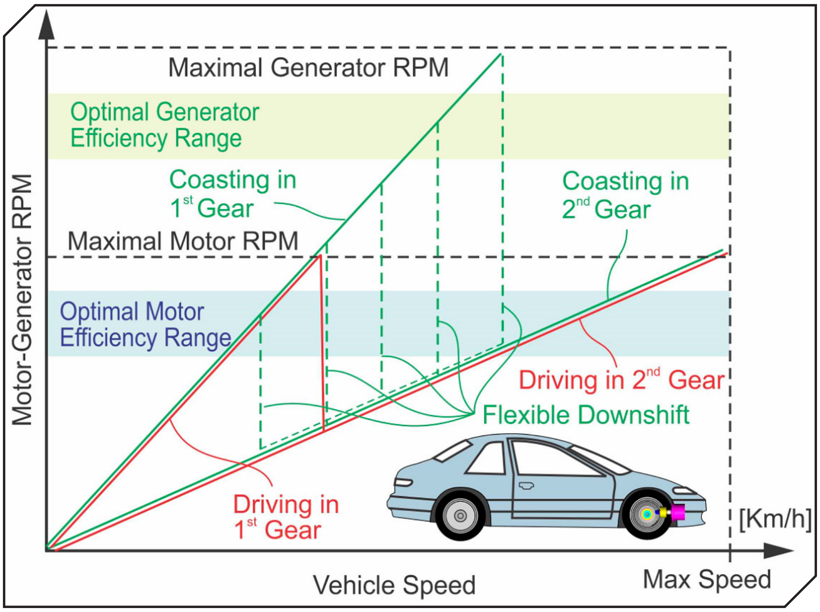

Figure 9 Speed diagram for single speed transmission.

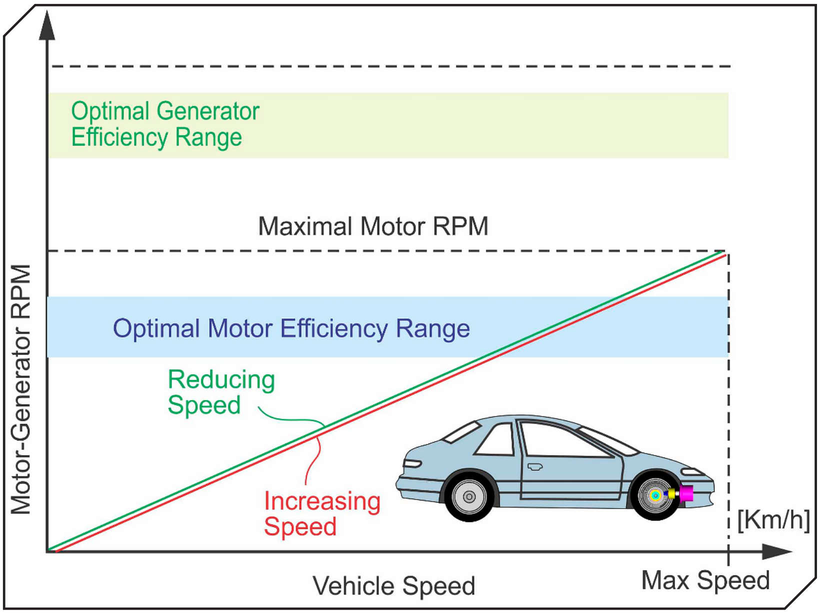

Figure 10 Speed diagram for dual speed transmission.

combined transmission solutions, a planetary concept design was also developed, which is shown in Figure 8. The motor shaft is connected to the sun gear and the hypoid pinion is connected to the cage as planetary output. With the planets having the same number of teeth as the sun gear (29) and the internal ring having three times the number of teeth of the sun gear (87), two ratios are possible. The planetary transmission requires a clutch which can connect the internal ring gear to either the sun gear (ratio 1.0, 1st gear) or to the transmission housing (ratio 4.0, 2nd gear). Because one of the two possible ratios is always 1.0, the flexibility of the planetary transmission is lower than the dual- reduction cylindrical-hypoid version. In Figure 8, the hypoid ratio is 5.18 (11 × 57). The overall ratio in 1st gear is 1.0 × 5.18 = 5.18 and in 2nd gear 4.0 × 5.18 = 20.72.

Motor Speed Versus Vehicle Speed

In the case of the single-speed transmission the relationship between motor rpm and vehicle speed is of course proportional, as shown in Figure 9. This applies if the electrical prime mover is in either motor or generator mode. The efficiency optimal operating rpm of a motor which is rated for 15,000 rpm maximum is in the vicinity of 6,000 to 10,000 rpm. This is the speed range with high efficiency in case of average load. If the load is small, then the efficiency optimal rpm is lower, and vice versa if the load is higher. The ratio of a single-stage transmission has to be defined such that the majority of the driving falls into the optimal efficiency range (see blue range in Figure 9). Figure 9 also indicates that the red speed increasing graph is only for a short period within the optimal efficiency range. In case of taking the foot off the accelerator pedal, the motor-generator control can disconnect the motor from the current flow and the vehicle coasts down naturally. If the brake pedal is applied, then the control can switch the motor to generator mode while the disk brakes are not yet engaged. Only when the brake pedal is pressed hard will the disk brakes kick in and support the electric generator brake.

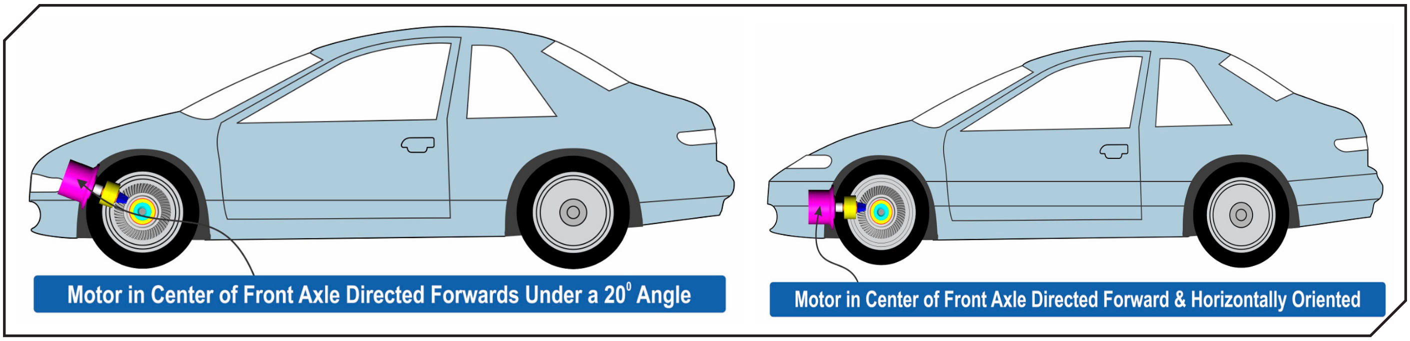

Figure 11 Possible orientations of hypoid transmission in front of axle.

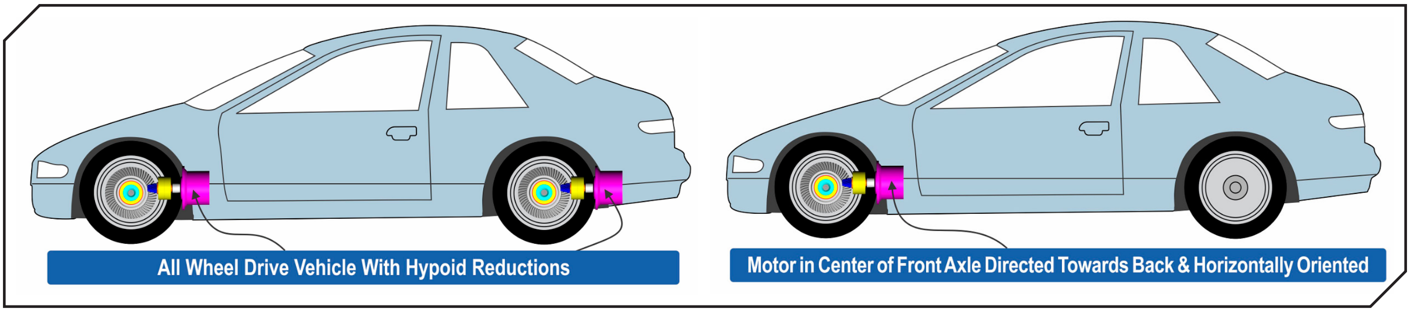

Figure 12 Possible orientations of hypoid transmission for front or all-wheel drive.

In case of a dual-speed transmission, the electronic control module can decide which of the two ratios with respect to the load will provide better motor efficiency. Figure 10 shows a typical speed diagram with the first ratio larger than the second. The first gear is active until the maximal motor rpm is reached. Then the clutch switches to the second gear, which stays active until maximal motor speed is reached again. The speed graph in Figure 10 has two sections which pass the optimal efficiency range. Depending on the duty cycle of the vehicle, the two-speed transmission can double the operating time within the optimum efficiency speed range and reduce the vehicle's energy consumption significantly.

Depending on gentle coasting to a full stop (leads off motor) or breaking light or hard, the electronic control module can regulate the downshift in order to optimize the brake force and maximize the battery re-charging. The flexible downshift is shown in Figure 10 as green dashed lines. The following breaking conditions are proposed:

- *Foot off the accelerator:*
  Coasting with leads off the motor/generator
- *Pressing the brake pedal up to 30% of its travel*:
  Braking force proportional to the pedal force by controlled downshift and a controlled generator charging conditions (ABS function still active by generator pulse charging)
- *Pressing the brake pedal beyond 30% travel:*
  Mechanical brake applied in addition to the generator brake

Some electric vehicles, even larger premium models, realize braking by releasing the accelerator pedal. This technology reduces the driving comfort, is counterintuitive and can lead to unsafe driving conditions. It requires a steady and unnatural foot position which also fatigues the driver — not merely the foot pressing the accelerator.

Possible Orientations of Hypoid Transmission in Vehicles

As mentioned earlier, the hypoid reduction allows placing the eMotor in the center of the front or rear axle between the wheels. The images of a small-size compact sedan in Figure 11 show the eMotor in front of the front axle. With a battery location below the passenger cabin floor (between front and rear wheels), the motor orientation as shown in Figure 11 presents a good weight distribution and could become part of the passive passenger impact safety concept. It is possible to reverse the direction of the hypoid offset (motor higher or lower) and find a packaging optimal motor orientation angle as shown in the left example in Figure 11.

In case of an all-wheel drive passenger car, the same transmission unit which is propelling the front wheels can be used to propel the rear wheels as well. The images in Figure 12 show a front wheel drive with the motor pointing to the rear (left graphic) and an all-wheel drive arrangement with both motors pointing backwards.

The concepts in Figures 11 & 12 provide a feeling of how compact the hypoid e-drive is and how well it can adjust to the given packaging constraints in a given overall vehicle concept. Many more e-transmission orientations are possible which accomplished tailored solutions for all already existing electric vehicle designs.

Application Examples

For the application in premium mid-size electric vehicles as shown in Figure 13, a multiple-speed transmission as discussed with Figures 7 and 8 would be most suitable. Optimal motor and generator operating speeds are important if the mass of a vehicle is high. A multiple-speed transmission can assure that also larger vehicles operate with a good efficiency.

Some compact and micro electric cars are shown in Figure 14. Those cars can benefit from a single-stage SRH reduction without any further transmission elements. Especially the two shown micro cars in the center and to the right in Figure 14 have to be attractively priced in order to be appealing people who mostly do inner city driving with rather low speed.

Driving in congested inner cities does not allow much time for shifting between different ratios. The energy gained by optimal motor rpms does not make up for the lost energy due to constant up and down shifting. The inner city delivery micro truck to the right in Figure 14 has many applications, where the driving distance per day is below 100km (63 miles) and the start-stop duty cycle makes it the ideal candidate for a single-stage Super Reduction Hypoid application. The simplicity of a micro car often promotes a rear-wheel drive. A good weight distribution is given by the location of the battery, which makes those small rear-wheel drive vehicles safe and good handling cars with a stunningly small turning radius.

Figure 13 **Premium midsize electric cars.**

Figure 14 **Compact and micro electric cars.**

Table 2 **Comparison of some key parameters for the four presented designs.**

	Design 1	Design 2	Design 3	Design 4	
Ratio	7.86	10.82	13.91	18.55	[-]
Power	60	60	60	60	[kW]
Mass	33	35	35	35	[kg]
Power Density	1.85	1.73	1.72	1.73	[kW/kg]
Gear Life	5,130	30,748	7,058	7,058	[h]
Gear Efficiency	95.2	95.4	94.3	94.5	[%]
MotorSpeed	6,252	8,609	11,068	14,758	[RPM]
Motor Torque	92	67	52	39	[Nm]

Summary

An eDrive concept, employing a hypoid reduction, was discussed in this chapter. The hypoid reduction brings a variety of advantages. Symmetric weight distribution and heat radiation away from one of the driving wheels, but also away from the batteries, can be accomplished very well. The speed drop which is possible with SRH hypoids is a multiple of what is realistic for cylindrical gearsets (ratios between 6 and 15 have been realized for eDrive developments). This makes it possible for small-size compact vehicles to limit the transmission to one fixed but large ratio. The result is a simple and low-cost transmission with pinion shaft equal motor shaft and only one additional shaft for the ring gear. Of course, just like in all axle drives with hypoid gears, the differential cage fits conveniently inside of the pinion-ring gear silhouette without additional space consumption.

This Chapter also discusses several transmission examples as combinations of the hypoid reduction and a cylindrical gear reduction. This solution is ideal for mid-size and premium electric vehicles and can be extended to dual-reduction for increased motor efficiency and higher efficiency in energy recuperation while the vehicle reduces speed in coast condition.

A variety of possible hypoid eDrive orientations and placements in an electric vehicle were proposed in Figures 11 and 12. Those examples suggest that there are numerous possibilities and the potential of the new solution is tempting for electric vehicle designers.

Refereces

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Dr. Hermann J. Stadtfeld is the Vice President of Bevel Gear Technology and R&D at the Gleason Corporation and Professor of the Technical University of Ilmenau, Germany. As one of the world's most respected experts in bevel gear technology, he has published more than 300 technical papers and 10 books in this field. Likewise, he has filed international patent applications for more than 60 inventions based upon new gearing systems and gear manufacturing methods, as well as cutting tools and gear manufacturing machines. Under his leadership the world of bevel gear cutting has converted to environmentally friendly, dry machining of gears with significantly increased power density due to non-linear machine motions and new processes. Those developments also lower noise emission level and reduce energy consumption.

For 35 years, Dr. Stadtfeld has had a remarkable career within the field of bevel gear technology. Having received his Ph.D. with summa cum laude in 1987 at the Technical University in Aachen, Germany, he became the Head of Development & Engineering at Oerlikon-Bührle in Switzerland. He held a professor position at the Rochester Institute of Technology in Rochester, New York From 1992 to 1994. In 2000 as Vice President R&D he received in the name of The Gleason Works two Automotive Pace Awards—one for his high-speed dry cutting development and one for the successful development and implementation of the Universal Motion Concept (UMC). The UMC brought the conventional bevel gear geometry and its physical properties to a new level. In 2015, the Rochester Intellectual property Law Association elected Dr. Stadtfeld the "Distinguished Inventor of the Year." Between 2015–2016 CNN featured him as "Tech Hero" on a Website dedicated to technical innovators for his accomplishments regarding environmentally friendly gear manufacturing and technical advancements in gear efficiency.

Stadtfeld continues, along with his senior management position at Gleason Corporation, to mentor and advise graduate level Gleason employees, and he supervises Gleason-sponsored Master Thesis programs as professor of the Technical University of Ilmenau—thus helping to shape and ensure the future of gear technology.