7

The future comes automatic

Efficient automatic transmissions provide a basis for hybrid capable drive trains

Uwe Wagner
Dierk Reitz

Introduction

The central question currently occupying developers of transmissions is not whether there will be a breakthrough in power transmission but how quickly and in what form this will occur. The relevant boundary conditions are well known and are presented in almost every publication on the subject of drive trains:

- the increasing global importance of CO_2 emissions due to the threat of climate change
- the increasing urbanization of individual mobility and thus the increasing importance of local emissions
- the divergence between the consumption and availability of fossil fuels
- the worldwide growth in population and the strong growth in new markets such as China, India and Russia

The decisive criterion for the implementation of technically feasible measures is and remains the ratio of the price that the end customer must pay for new technologies such as hybrids, range extenders or electric vehicles and the savings that he can achieve through reduced CO_2 emissions. It is still significantly more economical for the driver to emit one gram of CO_2 than to save it through such technologies. It is well known that the main reason for this is the enormous cost of batteries. Their development in terms of price and performance capacity will be decisive in determining the electrification of the drive train in the coming years.

Furthermore, state support will play a highly significant role. The German Federal Government has set the ambitious target that the number of electric vehicles running on German roads should first reach 100 000 by 2014 and then 1 000 000 by 2020. To this end, state support measures are envisaged in both infrastructure and financial terms. In addition to the tax concept, calculation of fleet consumption and payment penalties for non-compliance with defined targets will be of essential importance. Since e-mobility is to be supplied from renewable energy sources according to Government decisions, electric vehicles will be able to be calculated as zero emission vehicles, and

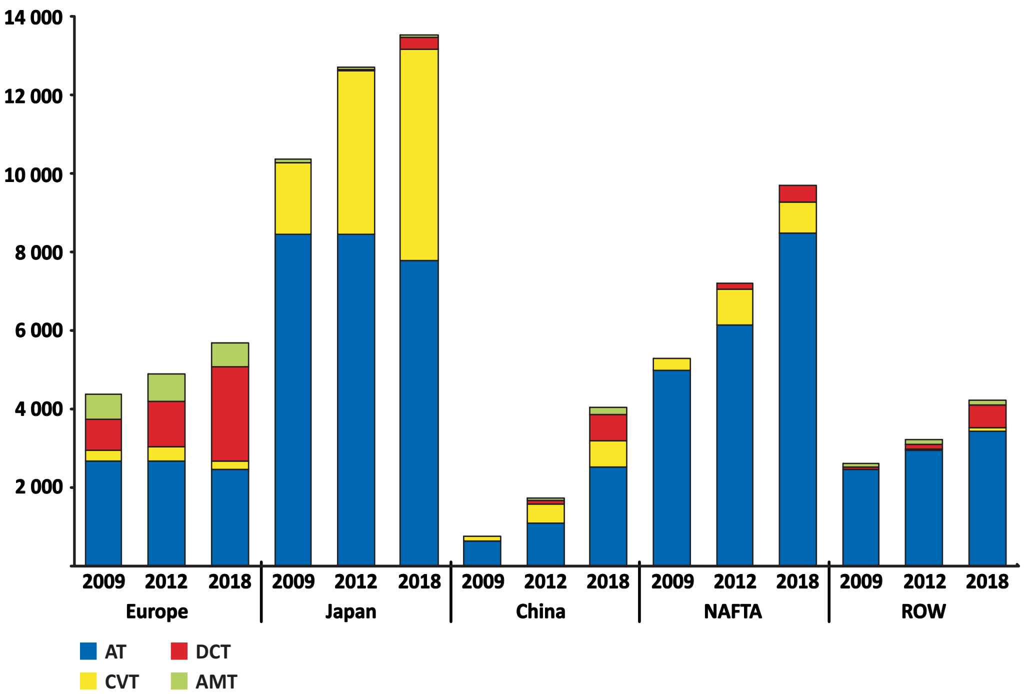


Figure 1 Forecast of quantities for automatic transmissions worldwide (source: CSM)

this will even be possible on a multiple basis in the years 2012 to 2015.

The effects of these boundary conditions on the transmission roadmaps of automotive manufacturers can be clearly seen. While differences can be seen in the weighting given by the different manufacturers to the various technologies and the planned timescale, the central theme is the same almost everywhere. First of all, it is necessary to further optimize the drive trains of internal combustion engines. For transmission systems, this means further improvements in efficiency, spread, the number of gears and the dampers since running substantially without slippage is required (step 1). Stop-start systems will also develop to be the standard in many vehicle segments (step 2). Following this, hybridization (step 3) will also be developed with an increasing proportion of plug-in applications in the direction of range extenders or electric vehicles (step 4).

While the measures in the first two steps are clearly outlined, the implementation and the scale of electrification of the drive train are understandably still relatively unclear. The decisive point is, however, that the internal combustion engine is still seen as the dominant drive system for the next 10 years. Against this background, the automatic transmission will continue to gain in importance since it gives not only outstanding comfort characteristics but also excellent opportunities for this step-by-step electrification of the drive train.

The forecasts for quantities of automatic transmissions up to 2018 are shown in Figure 1. In addition to the above average growth of approx. 25 % up to 2012 and a further approx. 23 % up to 2018, it is clear that the various transmission technologies will grow at significantly different rates in the various markets. While the double clutch transmission will show the strongest growth in Europe, the planetary automatic transmission with torque converter will increase the most in North America and the CVT will show the strongest growth in Japan.

The contribution that Schaeffler can make to this development of automatic transmissions against the background of the step-by-step transition to new drive train concepts will be shown in this paper.

Step 1: Optimization of transmissions

In spite of the highly heterogeneous distribution of transmission technologies across the various markets, the demands on automatic transmissions show a very homogeneous picture in the light of the considerable potential that is attributed to the transmission in terms of the ratio between CO_2 efficiency and costs (see for example [1]):

- further improvements in performance and comfort
- improvements in efficiency
- increases in ratio spread and the number of gears
- reductions in mass, space and costs
- stop-start capability
- suitability for hybridization

The best preconditions for this set of requirements are achieved using the double clutch transmission with dry clutches and electric motor-driven actuators. On the one hand, it offers ideal efficiency due to the dry clutches and on the other hand it can be expanded easily to a stop-start operation or a hybrid system as a result of the actuator system, which does not need to be driven by the internal combustion engine. The first dry double clutch system was put into volume production in 2008 with the VW DQ200 transmission and a double clutch from LuK. Further applications with dry LuK double clutch systems will follow in 2010 [13] with the Getrag transmission 6DCT250 [2] at Renault and Ford and with the Fiat transmission C635 [3]. Current further developments at LuK are dry double clutch systems for torques below 200 Nm and wet double clutch systems with electric motor-driven actuators [14].

In view of the excellent characteristics of such double clutch transmissions, it is extremely important for the planetary automatic transmissions to fully utilize the maximum potential in relation to efficiency. The torque converter should therefore ideally be locked up immediately after starting and remain locked up until shortly before idling speed. Such a torque converter lockup clutch also offers advantages in relation to performance, since it does not need to be opened during gearshift and a shift feeling similar to a double clutch transmission can be achieved. This can be an important criterion particularly with an increasing number of gears. Since excitation due to the non-uniformity of rotation in modern, supercharged engines increases to the same extent as the requirements for noise comfort, however, this leads to a conflict in objectives that can only be resolved through the use of considerably more effective damper systems for the torque converter lockup clutches. A modular system of such damper concepts up to the centrifugal pendulum damper for use in torque converters is shown in [15].

There is also a growing requirement in CVT for improved efficiency and higher spread. Although CVT is certainly unbeatable especially in the Japanese market from a customer perspective in relation to comfort, it is coming increasingly under pressure due to the improvements of the competitors described above. CVT variators based on link chains from LuK offer enormous potential in this respect, as has been shown in various examples of high performance applications. Furthermore, this variator type offers a highly elegant solution for small transmissions below 200 Nm that can also represent an economical solution when applied in an appropriate overall design [16].

Step 2: Stop-Start

The measures described in Step 1 serve exclusively to optimize the transmission as a mechanical converter in the drive train such that the drive side engine power can be converted as effectively as possible into the drive power required on the output side in relation to spread, grading, dynamics, comfort and efficiency. The next step in reducing consumption and thus CO_2 emissions is the intelligent use of a stop-start function. The potential for reducing consumption as a result is approx. 4 % on the NEDC, so this measure is also a firm fixture on the roadmaps of vehicle manufacturers.

On the transmission side, implementing a stop-start system requires that the transmission is immediately in a position to transmit the drive power of the engine to the wheels when the engine is restarted. The double clutch concepts presented at this Symposium fulfill these requirements since they can be operated completely separately from the engine due to the electric motor actuator system. As a result, gear selection and control of the clutch can be ideally matched to the restart of the engine. A further highly elegant solution has been implemented in the CVT system from LuK. Simply by reducing the leakage in the hydraulic system it is possible to operate the transmission in stop-start mode. In planetary automatic transmissions with torque converters, such measures are not generally sufficient. In this case, an additional device must be provided to supply pressure. This function can be performed, for example, by a pressure reservoir [4]. Another approach to a solution is the so-called “check valve” [15]. In this case, the function of the pressure control valve for the 1st gear clutch is expanded to include a closed position into which the slide can snap and thus hold the pressure in the clutch for restart. Depending on the application, however, the oil volume required can be so high that an additional electric pump must be used. A “power pack” of this type is shown in Figure 2. The design of the power pack has an oil transfer face on the pump head and thus allows its use either as an integral part of the transmission or as an external add-on module. Power is provided by a

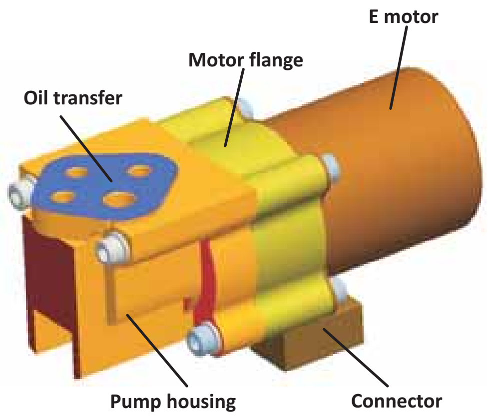


Figure 2 Power Pack for automatic transmission with stop-start function

brushless electric motor with a mean power consumption of approx. 100 W. It drives a pump at a speed of 3000 1/min in order to permit replenishment of leakage losses in the transmission during standstill at up to 3 l/min. The construction also gives the flexibility to match the provision of hydraulic energy to the specific requirements of other transmission types. The power pack can thus also be designed such that it is used to cover peaks in the volume flow during normal operation. This allows a smaller design of the main pump and thus an improvement in the efficiency of the transmission.

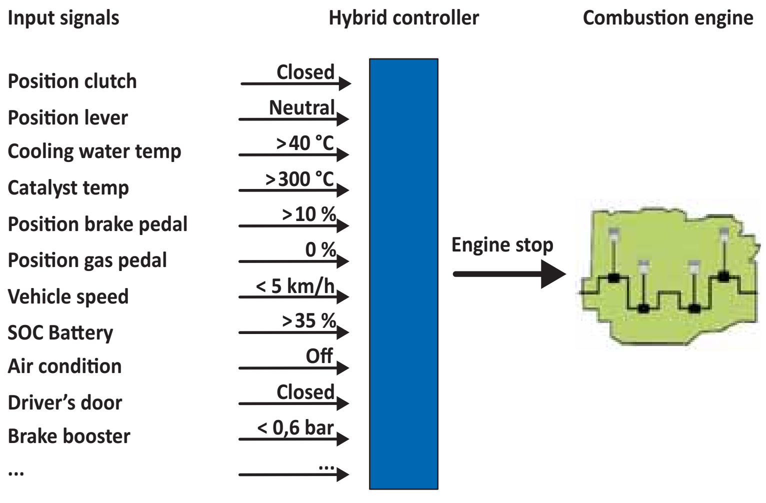


Figure 3 Conditions for implementation of the stop function in the internal combustion engine

On the engine side, the challenge is of course to initiate the restart so quickly that the driver does not feel any undesirable delay. To this end, it is possible to leave the starter permanently engaged and achieve its overrunning by a one way clutch as soon as the engine reaches the appropriate speed. Example designs of such solutions are shown in [15] and [17].

If these requirements on the transmission and engine side are fulfilled, stop-start operation can in principle be activated in any situation when using an automatic transmission as long as this is permitted by the relevant input values such as the charge level of the battery or the engine temperature.

The situation is different in the case of manual transmissions. Since the driver is then responsible for operating the clutch and transmission, it is then fundamentally a matter for him how often the stop-start operation is activated. In order to activate the stop function of the engine in current systems, the gear must be disengaged and the clutch pedal released, to ensure sufficient time for restarting the engine so that the driver cannot stall the starting process with the clutch pedal. Figure 3 shows the necessary conditions for implementation.

This is not fundamentally changed by the use of a Clutch by Wire system [5]. Although it is technically possible to overrule the driver, this can only be applied within certain limits. It is thus certainly possible to prevent stalling of the engine by an appropriate delay in engaging the clutch without the driver experiencing a problem as a result. In principle, however, the requirements for the input values “clutch position” and “gearshift lever position” remain the same. A complete solution could only be found through full automation of the clutch while completely dispensing with the clutch pedal. The clutch can then be controlled in accordance with the requirements of stop-start operation without the driver experiencing “overcontrol” of his clutch requirement.

This electronic clutch management system (ECM) was developed to production more than 10 years ago and was used in the Mercedes A Class. Success in the market failed to materialize, since the benefits as a partial automation lying between a purely manual transmission and an automatic transmission were not obvious to the end customer. The situation could be very different in conjunction with a stop-start system, especially in new markets such as China or India. In such a system, a smart actuator as shown in [14] could be used to control the clutch.

Step 3: Hybridization

Mild hybrids

Hybrid drives with an electric power rating of 10 - 15 kW, normally described as mild hybrids, currently represent the best economic compromise between the achievable reduction in consumption and the expenditure required for hybridization (consumption potential approx. 10 %). In general, the electric motor is connected directly to the crankshaft without an additional separation clutch ("P1 hybrid") which means, however, that electric driving is generally not possible. Since the stop-start mode is also a significant component of the mild hybrid concept, the above statement to the manual transmission applies also to the hybrid systems. Mild hybrid operation that cannot be significantly influenced by the behavior of the driver would only be possible by automation of the clutch with omission of the clutch pedal.

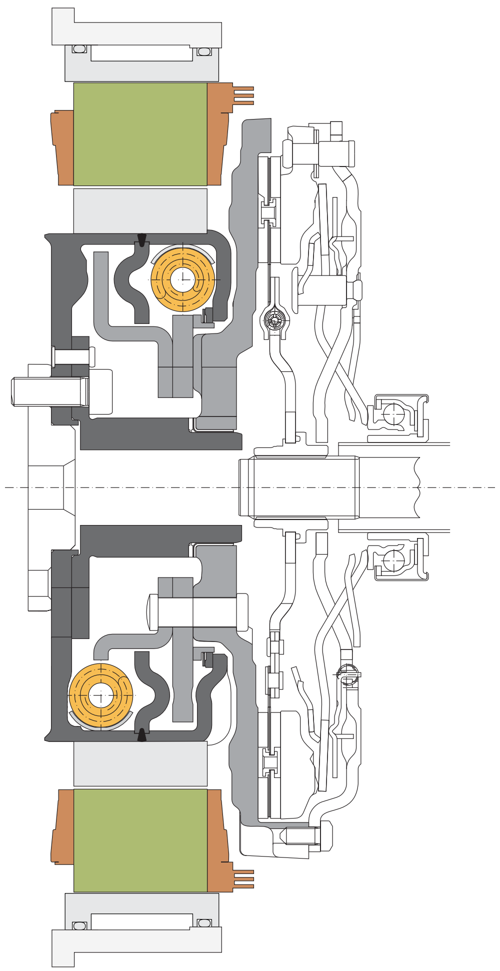


Figure 4 Double row arc spring damper integrated in the rotor for P1 hybrid

In order to minimize the elongation of the drive train required by the integration of the electric motor in a P1 hybrid, the damper of the dual mass flywheel can be radially integrated in the rotor. In order to achieve an adequate spring capacity with the reduced effective radius, two arc springs arranged in parallel are used and are completely integrated according to the length of the rotor. The space previously required for the basic damper is now available for the stator. Figure 4 shows the design of a manual transmission. The damper, which is characterized by its very small influence on the centrifugal force, has already been tested for use with double clutch transmissions.

A different concept of the mild hybrid concept was presented at the LuK Symposium 2006 [6]. This was a demonstration vehicle built at LuK on the basis of a double clutch transmission with a dry double clutch and an electric motor mounted on a parallel axis, known as an electric shift transmission (ESG). The maximum continuous power level of the electric motor was restricted to approx. 10 kW. As a result, comfortable stop-start operation is possible and the major proportion of the braking energy can be recovered through the decoupling of the internal combustion engine. Due to the relatively small motor, the function "electric driving" was not implemented.

Full hybrids

The ESG concept described above is being developed further in several projects. Initial volume production dates for such projects are planned for 2013. The basic functions correspond to those shown for the vehicle in [6], but the electric motors are dimensioned such that electric driving is possible. These are thus full hybrid drives. Due to the expanded functionality as well as the option of downsizing the internal combustion engine, consumption savings of up to approx. 25 % can be achieved.

A different full hybrid system using LuK components will be put into volume production in 2010 as the "P2 hybrid" on the VW Colorado platform. The application in the VW Touareg is a 3.0 l 440 Nm supercharged gasoline engine in conjunction with an 8 speed automatic transmission. In order to expand this to a hybrid, a unit is integrated between the crankshaft and the torque converter comprising an electric motor with a power rating of approx. 34 kW and the separation clutch necessary for P2 hybrids. This clutch makes it possible to use the complete hybrid functionality such as decoupling of the internal combustion engine during coasting, the stop-start function and pure electric driving.

One of the critical driving situations for acceptance of the overall P2 hybrid concept is restarting of the internal combustion engine from electric driving after a "tip in". This starting process gives rise to important requirements relating to the separation clutch. When the start command is given, the clutch is first controlled under highly dynamic conditions up to the torque of approx. 100 Nm necessary for tow starting of the internal combustion engine. This requires highly dynamic closing together with good controllability of the clutch in this torque range. Furthermore, the inertia of the clutch components must be reduced as far as possible in order to minimize the power required for acceleration of the crankshaft. The value achieved for the system described above is less than 0.1 kgm^2 (flywheel and clutch) and is in the range of the primary side of the current volume production DMF.

The clutch plate in the separation clutch is characterized by the special feature of an integrated arc spring damper. This is used first to displace the resonance points associated with the electric motor and the separation clutch into the non-critical range of approx. 400 1/min. In combination with the second damper integrated in the converter, an isolating effect is achieved that allows full load operation without slippage in the converter lockup clutch from a speed of 900 1/min. This individual measure leads to a reduction in consumption of approx. 2.5 % on the NEDC.

In order to prevent damage to the thrust bearing on the crankshaft through the 1.2 million towing cycles over the service life, a release mechanism with a rigid cover is attached directly to the clutch in this system for the first time [17].

The main characteristics of the separation clutch can be summarized as follows:

- very low inertia of the clutch components
- highly dynamic closing of the clutch
- good controllability in the torque range 50 - 150 Nm
- low drag torque with an open clutch
- release forces are not supported by the crankshaft
- towing cycles possible up to 3000 min^{-1}
- clutch system "normally closed" (fail safe)

Figure 5 shows the cross-section of the hybrid module with the flex plate as the linkage for the converter of the 8 speed automatic transmission.

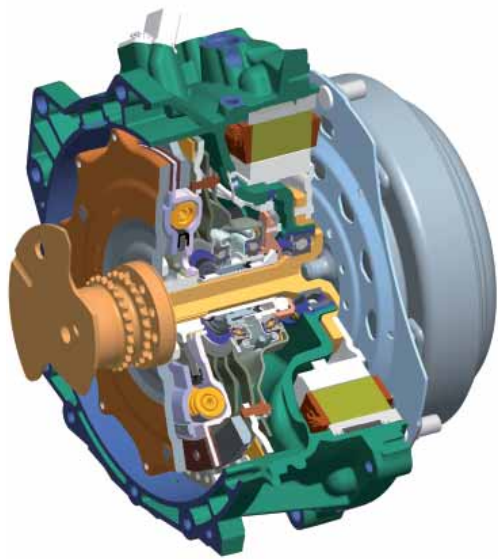


Figure 5 P2 hybrid module of the VW Touareg Hybrid

For the development of the next generation P2 hybrid, one of the most important requirements is a further reduction in the space required for the complete system. In principle, it is possible to integrate either the damping system or the separation clutch in the rotor. After an assessment of the various requirements and design envelopes, it appears more attractive to design the separation clutch for integration in the rotor. In the design of the clutch, it is important first to determine the method for starting the internal combustion engine. The so-called direct start method, in which the mixture is ignited in the combustion chamber while the crankshaft is still stationary, has been taken into consideration in the design. The clutch no longer has to tow the crankshaft to the required target speed of the electric motor but is used to ensure run-up through an initial torque pulse. This leads to reduced requirements for the power of the electric system since the torque previously required to tow the engine of approx. 80 - 100 Nm and the period for which the clutch is run with slippage can be reduced. The torque reserve of the electric motor is therefore almost completely dispensed with. Furthermore, a more compact design of the clutch due to the lower frictional energy during startup can be achieved while maintaining the previous high dynamic charac-

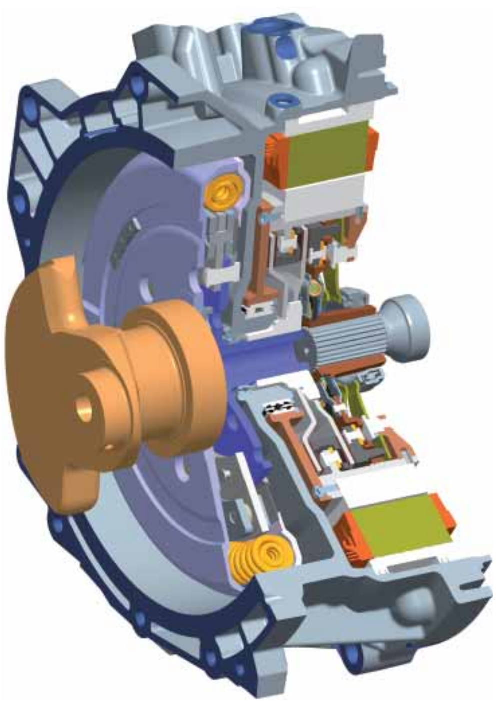


Figure 6 P2 hybrid module with dry separation clutch integrated in the rotor

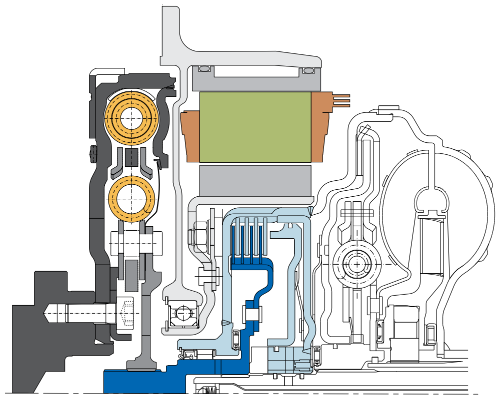


Figure 7 P2 hybrid module with wet separation clutch integrated in the rotor

teristics. The good controllability of the clutch in the lower torque range is maintained. The release forces of the clutch are not supported on the crankshaft in this design either. The bearing arrangement for the clutch and rotor as well the operation of the clutch are located on the transmission side, as shown in Figure 6. The hybrid module is premounted on the transmission housing. The engine and transmission are joined by an axial spline with clearance between the damper output and the clutch plate. Alternatively, the clutch can be of a wet design as shown in Figure 7.

A further reduction in design envelope could be achieved by integrating both the damper and the clutch in the rotor [15]. The feasibility of this option depends to a large extent on whether adequate damper capacity can be achieved in the limited design envelope for the specific application.

A technically quite different concept is being pursued by the companies GM, Chrysler, BMW and Daimler in the realization of the “two mode” transmission [7]. In order to develop a damper for this new transmission concept that can ensure sufficient isolation in all operating ranges, comprehensive simulations of the entire drivetrain were necessary. Modeling was thus required both of the dynamic processes such as stop-start, starting from electric driving, transitions into recuperation, range switching and of the change to constant driving in order to allow optimization of the components in their entirety. This results in dampers that, although the same basic transmission is always used for the vehicles, differ significantly from one another in relation to type (dry or wet), inertia and characteristics. Figure 8 shows the cross-section of the transmission [7] as well as the model for simulations of rotational and longitudinal dynamics.

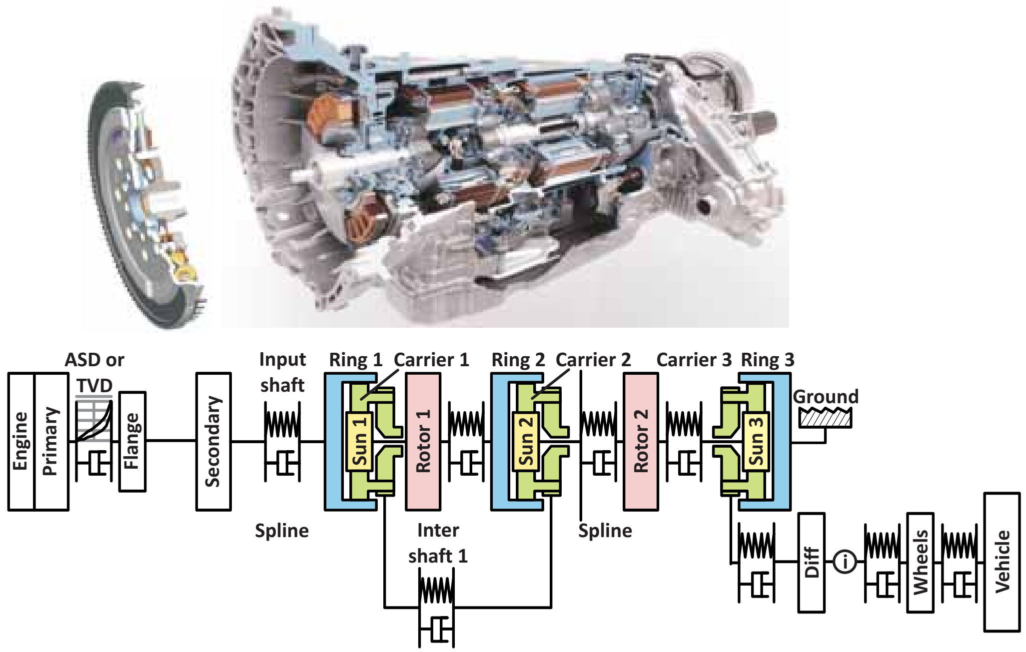


Figure 8 AHS-C transmission in the BMW X6 [7] and the associated rotary oscillation model for the entire drive

Step 4: Range extenders and electric drives

The hybrid systems shown in Step 3 have so far been designed such that, while they have two drive sources – internal combustion engine and electric motor – they only have one energy source on board that can be replenished from outside – generally diesel or gasoline. The electrical energy is substantially produced by regenerative means and is used to increase the efficiency of the drive train. The battery in such a system is designed for approx. 1 - 2 kWh, which means that electric driving over significant distances is not possible. If a larger battery is used and the facility for “filling up” with electrical energy from the mains electricity network is provided (“plug-in”), this gives as a first step a “range extension” of the internal combustion engine operating mode. If the system is then designed as described in [8], the relationships are transposed and this gives the “pure range extender” [8] in which the range of electric driving is extended by additional filling with diesel or gasoline. The concept of the “range extender” in the literal meaning thus encompasses a broad spectrum of technical implementation options, whose essential characteristic is the additional possibility of “filling up” from the mains electricity network. As a result, the range extender represents the fluid transition between the pure internal combustion engine drive and the pure electric drive.

How good are such drive concepts, however, in comparison with the drive trains shown in the previous steps? This is not intended in any way to call into question the range extender and electric drive trains. In light of the current discussions on the environment and natural resources, it is without doubt that they are drive concepts for the future. Such a comparison can give an impression, however, as to how quickly such concepts can be implemented and on which factors this will depend. The three criteria that should be used to give at least an approximate answer to the question are efficiency, CO_2 emissions and costs. The effects due to recuperation are not taken into consideration here since this effect can be assumed to be equivalent in hybrid systems with and without plug-in operation. The cost comparison is only prepared in general terms on the basis of published data.

Efficiency comparison of internal combustion engine and electric drives

The following analyses were carried out for various classes of vehicles. As an example, the results are shown here for a vehicle of the lower medium-size category.

For the internal combustion engine drive, a supercharged 0.7 l 3-cylinder gasoline engine with turbocharging and power rating of 70 kW in conjunction with a manual 5 speed transmission is used. No account is taken in the comparative studies of the losses in the transmission or the losses in the transmission for the electric motor described below, since these can be assumed to be of equal magnitude. The efficiency of power provision efficiency for gasoline fuels varies widely in the technical literature between 6 and 18 %. In the comparisons shown below, this is assumed to be a standard value of 10 %.

The map for the electric vehicle is generated by an electric motor as a synchronous machine with continuous excitation including the electronic performance system. Torque is transmitted to the wheels via a single speed transmission with a ratio of 7 that is assumed, like the internal combustion engine drive, to be free of losses. The efficiency of the energy reservoir is taken into consideration as constant for the charging process (slow overnight charging) and for discharging from the loss model in accordance with the electric power rating. The power provision efficiency for electrical energy from the public network is assumed, on the basis of the value applicable to Germany in 2008 [9], to be 38 %.

In order to illustrate in which operating ranges the efficiency advantages of the specific concept lie, the two maps are overlaid in a differential map (Figure 9). It can then be seen that the advantage of the electric vehicle is lower by 2 - 5 % over a very wide area of the map. The advantages of the electric drive are only significant at very low power ratings. It can also be seen for operating points relevant to the cycle (NEDC constant driving: red, NEDC accelerating: blue) that there is no significant difference between the drives. On the basis of these relatively small advantages of an electric vehicle, the propagation of such drives is rather unlikely.

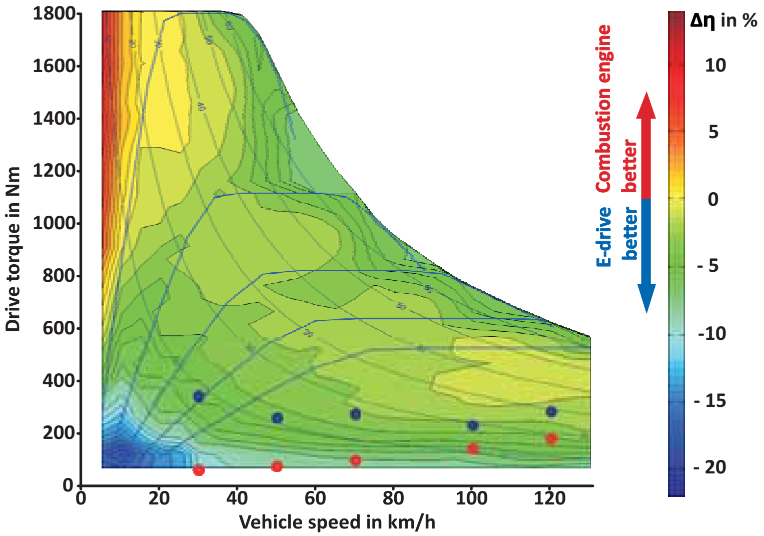


Figure 9 Eta differential map for vehicles with internal combustion engine drive and electric motor drive with a power provision efficiency for electricity of 38 % for 2008 [9]

If the power provision efficiency of electrical energy is altered, the dominant influence of this value on the map becomes apparent. For 2020, a value of 45 % is forecast for Germany. This gives a corresponding shift in favor of the electric vehicle (Figure 10). At most operating points, the advantages are now more than 7 %.

The comparison becomes even clearer if it is assumed that the efficiency is that of a combined-cycle power plant (cogeneration unit with combined heat and power generation) which is approximately 60 %, thus taking account of distribution losses a further 10 % better than the power plant efficiency that forms the basis of Figure 10. This comparison is of decisive importance for the future of the internal combustion engine, since the question of whether fuel is derived from fossil or renewable sources becomes irrelevant in the comparison of internal combustion engine drive and electric drive. From the pure perspective of efficiency and CO_2 emissions, the burning of fuel in cogeneration units and its conversion into electrical energy is the better solution.

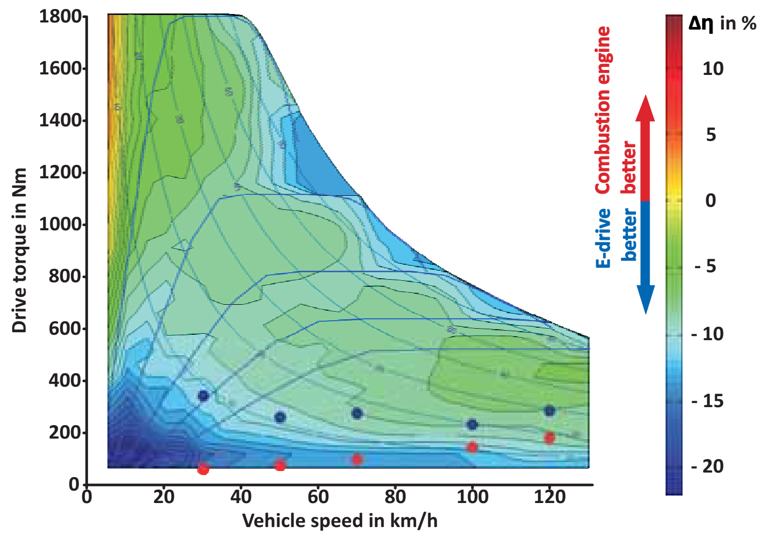


Figure 10 Eta differential map for vehicles with internal combustion engine drive and electric motor drive with a power provision efficiency for electricity of 45 % as forecast for 2020

Comparison of CO_2 emissions from internal combustion engine and electric drives

When the two drives are compared on analogous terms in relation to CO_2 emissions, this already gives a clear advantage to the electric vehicle. The provision of electrical energy is calculated on the basis of the value applicable to Germany in 2008 of 590 gCO_2/kWh [9]. Over a large area of the map, the advantage is approx. 20 %, while at the lower constant driving points in the NEDC it is up to 38 % (Figure 11).

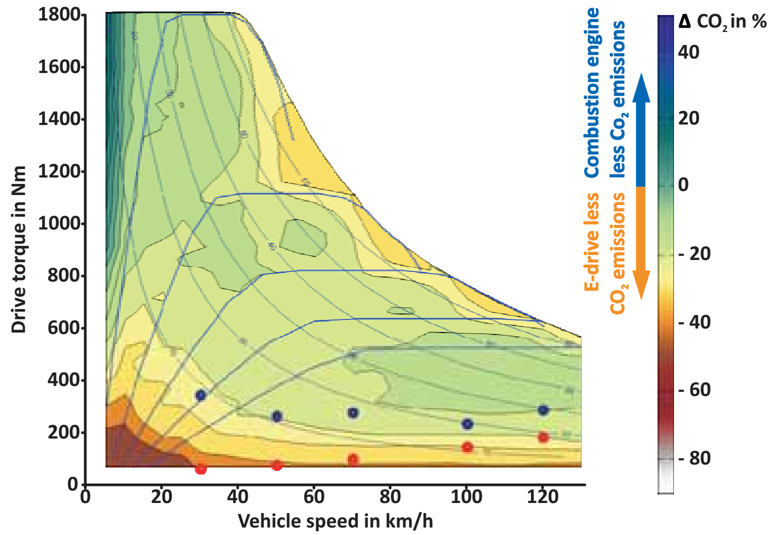


Figure 11 CO_2 differential map for vehicles with internal combustion engine and electric motor drives

Efficient automatic transmissions 7

Comparison of internal combustion engine drive and range extender

For the generation of electrical power, the following comparison is based on a combination of the internal combustion engine previously described (3-cylinder gasoline engine with turbocharging) and an electric motor (PSM = synchronous machine with continuous excitation) to form a range extender with optimized efficiency. This module is dimensioned such that the maximum required driving power can be provided. The performance achieved with this range extender is then overlaid in accordance with the specific map for electric motor drive used above. This gives an electric motor-based tractive-power chart taking account of the best possible generation efficiency in each case that without a battery can be considered as an electric continuously variable transmission or E-CVT. A serial hybrid is achieved by the integration of a battery into the system.

If the differential map is now created for the efficiency between the E-CVT drive and the tractive-power chart for the pure internal combustion engine, this shows a disadvantage as expected for the E-CVT at almost all map points. The E-CVT only has an efficiency advantage in the range of very small drive power values up to approx. 2 kW.

If the E-CVT is expanded to include a battery as an intermediate reservoir, the differential map is displaced in favor of this drive described as a serial hybrid. Due to the generation of electrical energy close to the best point of the range extender at a power rating of approx. 20 kW and the intermediate storage in the energy reservoir, the power provision efficiency is significantly increased. For power ratings above this level, an intermediate storage facility makes little sense in terms of efficiency, since internal combustion engine efficiency decreases and the increasing charging and discharging losses oft he battery lead to a further reduction in the overall efficiency. From the perspective of the complete system, this behavior is an argument against 2 point operation (best efficiency and maximum power). In this area of the map, only the exact power should be generated that is currently required in the drive. Since the absolute conversion losses (mechanical → electrical → mechanical) for the design being considered are larger from a vehicle speed of 105 km/h (constant driving) than the advantage due to the map displacement in range extender operation, the power generated by the internal combustion engine of the serial hybrid above this speed should be directed more efficiently directly to the wheels.

In comparison with the purely internal combustion engine drive, the serial hybrid is now advantageous up to a drive power of approx. 6 kW, as shown in Figure 12. This means, however, that the internal combustion engine drive is still the more efficient drive concept from a speed of approx. 70 km/h with constant travel. For this comparison, the use of recuperation or stop-start should also be seen as comparable and does not therefore need to be taken into consideration. Since gasoline fuel is fed in as the primary energy source in both drives, the aspects described above apply to the same extent for the CO_2 analysis.

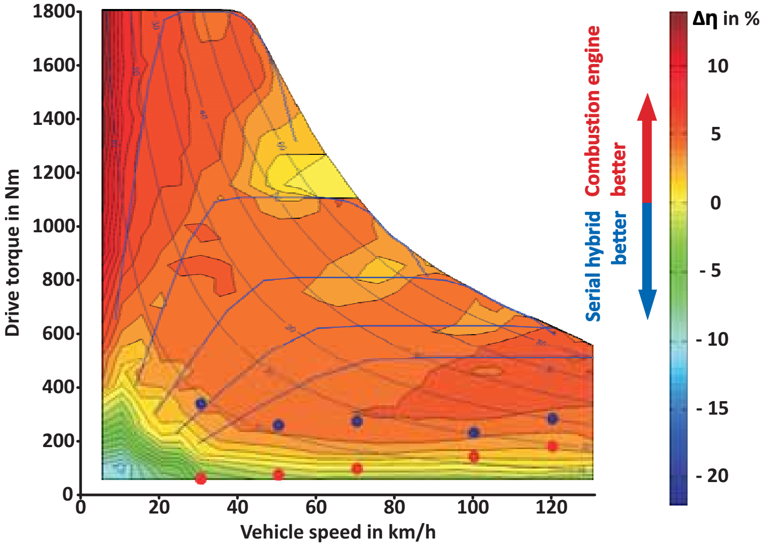


Figure 12 Eta differential map for internal combustion engine drive and serial hybrid drive train

From these results, it is clear why the range extender concepts designed as a serial hybrid only give a real advantage with a high plug-in content, in other words substantial usage of the vehicle with energy from the electricity network, in terms of efficiency and the CO_2 balance sheet.

Cost comparison

In [10], the pure operating costs of an electric vehicle are compared with those of a vehicle with an internal combustion engine drive. The fuel and depreciation costs are considered over a period of four years. For 2008, this gives an advantage of approx. 5 ct per km for the vehicle running purely with an internal combustion engine. Assuming a halving of battery costs with an annual increase in energy costs and electrical energy of 6 %, however, this will change by 2020 to an advantage of approx. 5 ct for the electric vehicle. If it is assumed that equivalent taxation will be applied to electrical energy used on a mobile basis, however, this will again result in a disadvantage in 2020 for the electric vehicle of approx. 2 ct per km.

A more advanced approach is selected in [11]. A full cost assessment is carried out in this case on a “maneuverable city car” that takes account of additional factors such as willingness on additional charges and other stimuli such as travel prohibition in inner cities. For implementation by 2014, this gives a cost gap of only 3000 to 5000 Euro for cumulative operating costs over four years. If it is assumed that there is, in accordance with [8], a one-off cost advantage of almost 5000 Euro for a range extender in a city car for an electric range of approx. 100 km in comparison with an electric vehicle, such a city car based on a range extender could in the foreseeable future become a reality as a genuine high volume solution.

This simple calculation using the rule of three is based, however, on very uncertain assumptions and simply shows that the main problem for these drive concepts lies in the costs. As stated at the beginning, it is essentially the support measures provided by governments and developments in battery costs that will determine whether and how quickly such a cost calculation gives advantages for the electric drive. Furthermore, the proportion of renewable energy in the energy mix will play a significant role. If this continues to increase, the demands on the flexibility of the remaining power generation facilities will increase, since these must compensate for the strong fluctuations in the renewable sector. In particular, this will cause difficulties for the large power stations. It may be cheaper for them to give their electricity away or even pay something for consumption than to allow power station outputs to fluctuate too strongly. Electric vehicles whose batteries are charged overnight would be welcome consumers in this case.

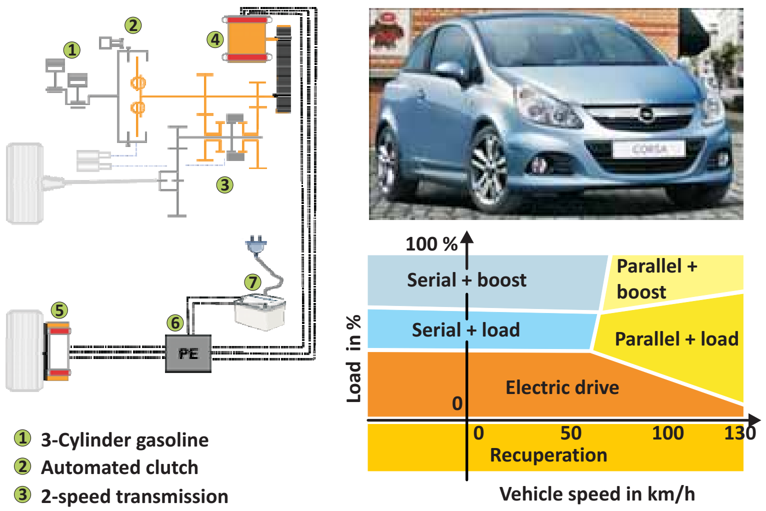
Conclusions

For range extenders that will have a significant proportion of driving using internal combustion engines, the above considerations lead to two significant conclusions:

1. An internal combustion engine cannot be limited to run at two operating points in terms of efficiency as a range extender. Such an engine will continue to require a certain variability.
2. Direct drive-through of the internal combustion engine is appropriate for constant travel from approx. 105 km/h (see also [8] and [12]). For the clutch required in this case, an electric motor actuator is appropriate, such as described in [13] or [14].

The “pure range extender” [8] and the electric vehicle are drive concepts whose implementation on the basis of the above considerations is not improbable in the foreseeable future. The efficiency advantages of the electric drive, which are only slight at present, will improve further with the power station mix of the future. If the efficiency of modern cogeneration units only is considered, it would already be more efficient to burn fuel centrally and convert this to electrical energy. Even an increasing proportion of renewable fuels derived from biomass does not therefore make any change to this statement. In terms of CO_2 analysis, the situation is even clearer. In this case, the electric drive has clear advantages even on current analysis that will only increase in future. Essentially, it is the costs and performance capability of batteries and the as yet incomplete infrastructure that are still an obstacle to the electric drive.

In order to allow further investigation of these drive concepts, two test vehicles were built at Schaeffler, the “Schaeffler Plug-in Hybrid” based on an Opel Corsa and the “Schaeffler Electric Vehicle” based on a Skoda Octavia shown in [18].



① 3-Cylinder gasoline
② Automated clutch
③ 2-speed transmission
④ Central E-motor
⑤ In wheel E-motor
⑥ Power electronics
⑦ Battery

Figure 13 Concept vehicle Schaeffler Hybrid

The drive concept of the Schaeffler Hybrid is divided into a hybrid drive on the front axle and a pure electric drive for the rear axle. On the front axle of the vehicle, a synchronous machine with continuous excitation can be coupled by means of an automated 2 speed step transmission. This electric motor is arranged on a parallel axis and connected to the transmission input shaft via a chain. A 3-cylinder gasoline engine can be connected by means of an automated separation clutch. The rear wheels are each driven by a wheel hub motor with continuous excitation. As a result, the front axle can have a parallel hybrid drive and when the transmission is in neutral a serial hybrid drive is possible as a range extender in combination with the electric drive on the rear axle. When both operating modes are activated at the same time, all-wheel drive can also be presented. Furthermore, the wheel hub motors allow filling up of tractive power during gearshifts. The total wheel torque during electric driving is a maximum of 2100 Nm. Figure 13 shows the complete drive and an example of the operating strategy for a low charge state of the energy reservoir.

The focus will now be on the following key development issues:

- active vibration damping
- filling up of tractive power by electric motor during gearshift
- behavior of the “range extender operation”
- acoustics in electric driving
- drivability of unsprung masses in wheel hub motors or drive close to the wheel
- distribution of tractive power to the front and rear axle
- assessment of actual battery capacity
- active torque vectoring to the front and rear axle

A further point to be analyzed with the aid of the concept vehicle is the question of the necessity of a 2 speed transmission for the electric drive. At a constant gearshift speed, simulations show a consumption advantage (as energy removal from the battery) of 3 %, with an advantage of up to 6.4 % with optimum map gearshift without gearshift hysteresis, depending on the possible transmission ratio spread. This is in turn deci-

sively dependent on the following influencing factors:

- maximum wheel torque
- total drive power
- maximum vehicle speed
- the necessary gearshift hysteresis
- power drop of the electric motor in the maximum speed range

In addition to influence as described above on energy consumption, the transmission is also the value around which the electric motor can be downsized and the reduced costs for the electric system can be weighed up in comparison with the additional costs for the second gear.

For vehicles in the A/B segment with current typical driving characteristics and a drive power rating of 30 - 80 kW, the use of a 2 speed powershift transmission appears sensible and economically favorable. Simple structures were sought that could be used to fulfill the demands on the transmission as economically as possible. The very good controllability of the electric motor and its short-term overload capability are preconditions for the design of the transmission, as shown in Figure 14.

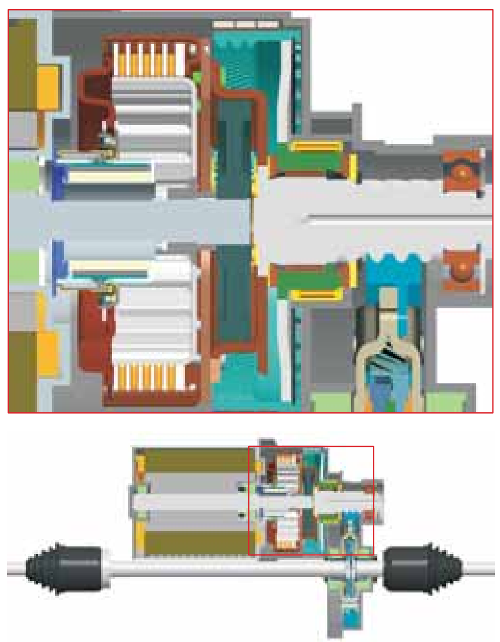


Figure 14 2 speed powershift transmission for electric vehicles

The housing comprises a planet set on the input side whose crown wheel is either locked against the housing by means of a brake or is locked up by means of a wet clutch. In conjunction with a constant spur gear output step, this gives total ratios of 13.5 and 5.6 for a vehicle with a drive power rating of 70 kW. The powershift is controlled exclusively via the clutch. The brake is designed as an economical “black/white” actuator. The differential is represented as a lightweight differential of a planetary design [19], giving significant design envelop advantages in the total length of the drive.

Summary

In light of the demands for low consumption and reduced CO_2 emissions with a simultaneously growing requirement for increased comfort, it is to be expected that market shares for automatic transmissions will show disproportionately high growth in future. The significant preconditions in case are further improvements in efficiency, spread, mass, design envelope and costs. With concepts for dry and wet double clutch transmission systems, effective damper solutions for automatic converters and new ideas for CVTs, LuK has developed the appropriate components to allow the necessary objectives to be achieved in the various transmission technologies.

In order to achieve further reductions in consumption and CO_2 emissions, the stop-start systems will succeed over wide areas. For future automatic transmissions, this gives rise to the requirements for operation independent of engine operation during standstill and the ability to restart the engine in the shortest possible time. To this end, LuK has developed various system solutions for double clutch transmissions, CVT and also planetary automatic transmissions.

The double clutch transmission with electric motor actuation offers ideal conditions for hybridization. Such a vehicle was built by LuK as a mild hybrid and shown at the LuK Symposium 2006. The concept is now being pursued in several projects as a full hybrid, with the first volume applications expected from 2013. Alternative full hybrid systems are the P2 hybrid that is entering production at VW on the basis of the Colorado platform in 2010 with a separation clutch system from LuK, and the power-split two mode transmission in which dampers from LuK are used to fulfill the challenging isolation functions.

A comparison of internal combustion engine and electric motor drives shows that the electric drive already represents the clearly better drive type in relation to CO_2 emissions. In terms of efficiency, the result of the comparison is not so clear but the developments in power station technologies show that the electric drive will also be the better alternative in future in many operating ranges in this respect. In light of the intensifying public discussions of environmental and energy matters, it must therefore be expected that the proportion of plug-in technologies will show strong growth. The only real hurdle to the rapid spread of these drive concepts currently lies in the inadequately low energy density and the excessively high costs of batteries. Current cost forecasts and developments towards “open” battery systems show, however, that this will change by 2020. For this reason, the Schaeffler Hybrid Vehicle and Schaeffler Electric Vehicle were built at Schaeffler as a development platform for new drive concepts. Such complete systems are being used at Schaeffler as a basis for developing the transmission and electric motor technologies for future mobility.

Literature

[1] Liebl, J.: Electric mobility – the next step at BMW EfficientDynamics?, 8th International CTI-Symposium Innovative Automotive Transmissions, 2009

[2] Pollak, B.: How much transmission is needed for electrification or hybridisation?, 8th International CTI-Symposium Innovative Automotive Transmissions, 2009

[3] Vafidis, C.: FPT’s high torque density dual dry clutch transmission (HTD-DDCT), 8th International CTI-Symposium Innovative Automotive Transmissions, 2009

[4] Bek, M.; Schiele, P.: Hydraulic Impulse Storage – How ZF Automatic Transmissions Contribute to CO_2 Reduction, 29th International Vienna Motor Symposium, 2008

[5] Küpper, K.; Seebacher, R.; Werner, O.: Think Systems – Software by LuK, 7th LuK Symposium, 2002

[6] Reik, W.; Reitz, D., Vornehm, M.: World of Hybrids, 8th LuK Symposium, 2006

[7] Braun, H.; Krauß, M.; Rattei, F.; Bohne, W.; Engelmann, M.; Deuke, U.; Di Pierro, M.: The Full Hybrid Powertrain for BMW ActiveHybrid X6, ATZ 11/2009

[8] Fischer, R.; Fraidl, G.; Hubmann, C.; Kapus, P.; Kunzemann, R.; Sifferlinger, B.; Beste, F.: Range Extender Module – Enabler for Electric Mobility, ATZ 10/2009

[9] FG I 2.5: Strommix 2007, Umweltbundesamt

[10] Diez, W.: Zurück ind die Zukunft? – Hochspannung! Das Comeback des Elektroantriebes, Automotive Agenda 01, 2008

[11] McKinsey & Company: Roads toward a low-carbon future: Reducing CO_2 emissions from passenger vehicles in the global road transportation system, March 2009

[12] Erjawetz, K.: Drives for electric vehicles and range extended electric vehicle, 8th International CTI-Symposium Innovative Automotive Transmissions, 2009

[13] Kimmig, K.; Bührle, P.; Henneberger, K.; Ehrlich, M.; Rathke, G.; Martin, J.: Success with efficiency and comfort – The dry double clutch has become established on the automatic transmission market, 9th Schaeffler Symposium, 2010

[14] Müller, B.; Kneissler, M.; Gramann, M.; Esly, N.; Daikeler, R.; Agner, I.: Smaller, more flexible, more intelligent – Advance development components for double-clutch transmissions, 9th Schaeffler Symposium, 2010

[15] Lindemann, P.; Krause, T.; Swank, M.; George, P.; Hemphill, J.; Marathe, B.: Torque Converters – Launching over new challenges, 9th Schaeffler Symposium, 2010

[16] Englisch, A.: CVT – high value and high performance, 9th Schaeffler Symposium, 2010

[17] Zink, M.; Hausner, M.: LuK Clutch Systems and Torsional Dampers – Key Elements for Efficient Drive Trains, 9th Schaeffler Symposium, 2010

[18] Smetana, T.; Biermann, T.; Höhn, B.-R.; Kurth, F.: Schaeffler active *e*Differential – The active differential for future drive trains, 9th Schaeffler Symposium, 2010

[19] Biermann, T.; Smetana, T.; Höhn, B.-R.; Kurth, F.: Schaeffler lightweight differentials – A family of differentials reduced in space and weight, 9th Schaeffler Symposium, 2010

7