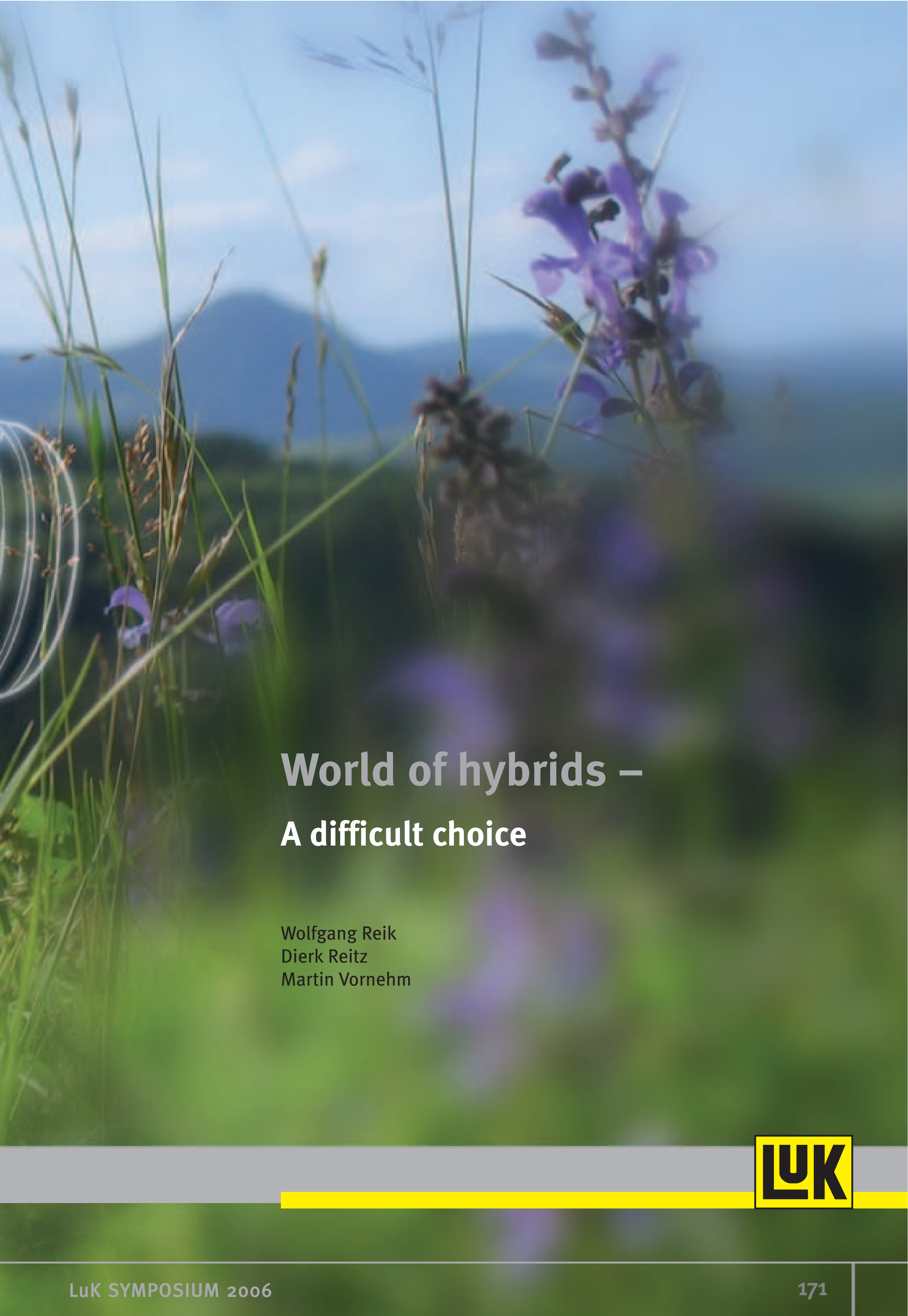

World of hybrids –

A difficult choice

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Introduction

As a result of the threats from greenhouse gases and urban air pollution, that have in some cases reached almost intolerable levels, efforts are being made throughout the world to stem vehicle emissions. Conferences on climate protection are trying to combat impending global warming by setting limits on harmful substances and CO_2. The self-imposed obligation on the automotive industry to reduce CO_2 output presents new challenges to powertrain engineering, which will require and drive forward new concepts.

The CO_2 output of a vehicle in particular is directly related to its fuel consumption. Success in the battle against this greenhouse gas can only be achieved, therefore, by reductions in fuel consumption.

However, careful use of oil reserves is important for another reason. Oil reserves are not infinite. Estimates vary as to how long they will last, depending on which difficult to extract reserves are included in the calculations. There is little doubt, however, that reserves are slowly coming to an end. A striking comparison was presented in [1]. All the oil reserves that have ever existed are equivalent to the volume of Mount Fuji (Figure 1).

Approximately half this volume has already been used up. The remainder will have to be divided up between an ever-increasing number of people. Even if countries such as China or India achieve only a fraction of our standard of living, oil reserves will dwindle rapidly. Working of deposits such as oil sand and oil shale is more difficult, forcing up the costs of production.

Estimates of the remaining life of oil reserves vary widely but are probably within the range presented in Figure 2 [2]. Taking account of increasing population and especially the increases in the numbers of oil consumers, the situation will become critical between 2020 and 2050. Alternative fuels such as biodiesel and liquid fuels derived from natural gas will presumably not be able to fill the gap between supply and demand.

In addition to fuel consumption, emissions are playing an increasingly important role. Unlike other harmful exhaust gases, CO_2 cannot be removed by subsequent treatment using a catalytic converter, and this therefore restricts the continued unlimited use of fossil fuels.

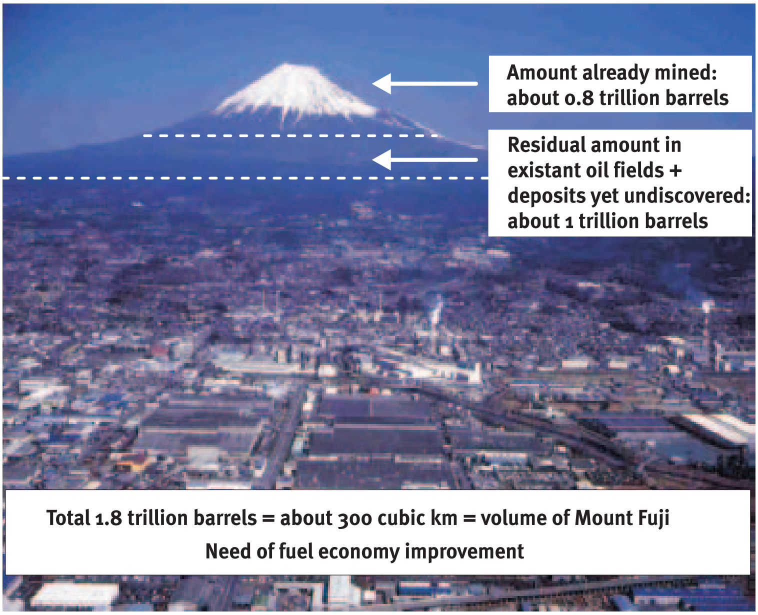
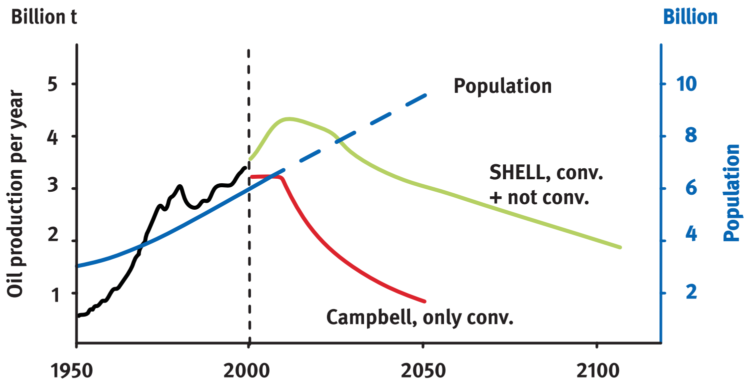


Figure 1 All available crude oil reserves correspond to the volume of Mount Fuji [1]

Ozone concentration has increased substantially in recent years (Figure 3) [3]. If this should actually be attributed to CO_2 and not to natural fluctuations in climate, it will not be possible to avoid strong pressure for reductions in CO_2 emissions and therefore savings in fuel consumption.

Savings in fuel consumption thus have a triple effect:

- protection of the environment
- extended availability of oil
- cost savings



(Source: Bundesanstalt für Geowissenschaften und Rohstoffe, 2000)

Figure 2 Rapid growth in global population and collapse in oil production between the years 2020 (pessimistic forecast) and 2040 (optimistic forecast)

Modern vehicles must therefore be designed for very low fuel consumption in order to eke out the valuable resource of oil for as long as possible. In this way it is also possible to reduce emissions, in particular of CO2.

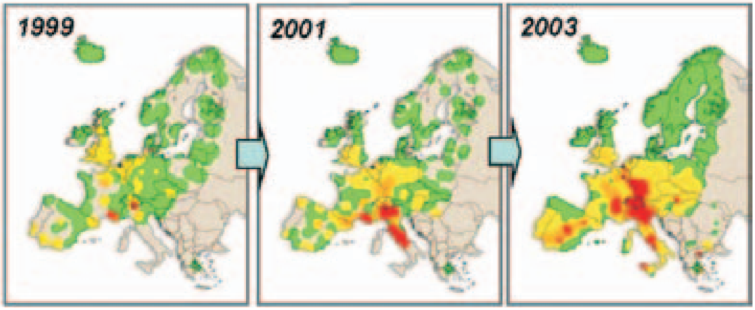
On this point, achieving these necessary objectives will not be aided by simply playing off different consumption-reducing measures against each other, e.g. hybrids, diesel versus petrol, engine modifications such as new combustion methods with variable valve control etc. The decisive question in the future will not be "either or" but "not only but also". Modern vehicles will therefore incorporate a skilful combination and integration of very different measures for reducing consumption. Hybrid technology is ideal for combination with numerous other measures.

Optimum consumption can be achieved under the following preconditions:

- the vehicle must have low aerodynamic drag and rolling resistance
- low vehicle mass
- internal combustion engine with favourable fuel consumption
- basic transmission with very high efficiency
- automatic start/stop system for switching off the internal combustion engine whenever it is not required to generate traction power
- braking energy regeneration.

The hybrid vehicles on the market already exhibit this holistic approach, in an attempt to create an overall concept with favourable consumption through a skilful combination of different measures.

This paper deals with the typical hybrid-related issues of braking energy regeneration and stop/start in combination with an optimised effi-



Source: European Environment Agency

Figure 3 Trend of ozone concentration in Europe

ciency basic transmission. A wide range of different concepts will be described.

Mild hybrid or full hybrid

Depending on their electric power rating, hybrid drives are broadly classified as micro hybrids, mild hybrids or full hybrids (Figure 4).

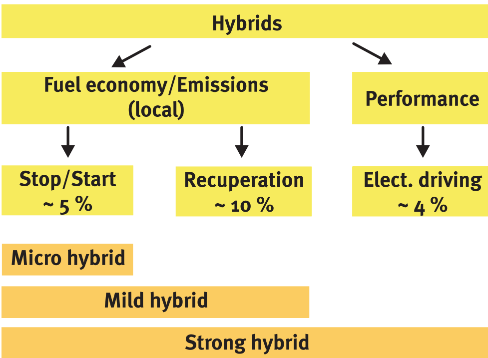


Figure 4 Classification of hybrid systems and their functionality

In micro hybrids, the electric power rating is sufficient to restart the engine automatically after it has stopped. Braking energy regeneration is only possible to a very small extent. Due to the relatively low additional costs of a micro hybrid, such systems will nevertheless continue to appear in vehicles in the future.

If braking energy regeneration is also to be used, electric power ratings must be in the range 10 ... 15 kW. This allows normal deceleration to be covered and a large proportion of the total deceleration energy to be regenerated. A further increase in the electric power rating would allow regeneration of more severe deceleration, but since this occurs relatively rarely, an increase in the available electric power does not seem economically advisable purely in terms of braking energy regeneration.

A mild hybrid does not allow electric driving but only support (boost) to the internal combustion engine.

In terms of fuel consumption savings, this system can achieve practically everything: approximately 5 % through start/stop and approximately 10 % with regeneration. A mild hybrid would therefore be sufficient if there is no requirement for electric driving or for significant power support to the internal combustion engine.

A further reduction of 4 % in fuel consumption is obtained if the internal combustion engine is switched off under operating conditions with low efficiency and the vehicle is propelled by the electric motor alone.

However, this additional consumption benefit comes at a price. The electric power rating is, at 30 ... 50 kW, considerably higher than that of a mild hybrid; costs will be correspondingly higher. In order to achieve increased power, therefore, full hybrids are often developed.

A full hybrid can also be used, however, to achieve downsizing of the internal combustion engine. The resulting drive comprises an internal combustion engine that relies permanently on the active assistance of the high-power electric motor in order to deliver its full performance.

Overall, there are numerous variants and, in addition, there is a transitional area between mild and full hybrid that for example allows electric manoeuvring but not electric driving at higher speeds.

Hybrid concepts

Classification in terms of micro, mild or full hybrid may give an indication of functionality, but says little about the actual configuration and arrangement of the electric motor in the powertrain. In some hybrid concepts, it is simply the dimensioning of the electric motor that deter-

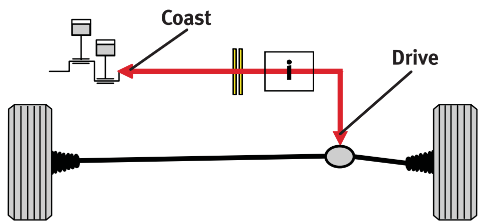


Figure 5 Simple schematic of powertrain to illustrate torque flows during drive and coast operation

mines whether the concept is classified as a mild or full hybrid. An attempt will therefore be made to develop the arrangement of the electric motor in the powertrain and the torque flows as differentiation factors.

This will be presented using simplified schematics of the powertrain (Figure 5). The transmission indicated can be taken to represent any one of the established transmission types.

The generator as a starter generator

Probably the simplest solution is a micro hybrid for stop/start, which can be combined with all existing powertrains, with the conventional generator designed also for operation as a motor (Figure 6). It can then also function as a starter and restart the internal combustion engine with little noise, which is not possible with a conventional starter. This allows stop/start, but not electric driving or regeneration. Typical power ratings for the electric motor are in the range 4 ... 6 kW. This arrangement is only suitable as a mild hybrid.

Special attention must be paid to the belt drive. The torque flow in the belt during start-up is the reverse of the torque flow during generator operation. The belt guidance and tensioning systems must therefore be designed to allow for switching back and forth between taut strand and slack strand.

In diesel engines particularly, the cold start torques required may be well over 100 Nm, beyond the capacity of a normal belt drive. In such cases, the conventional starter can provide cold starting of the engine. Stop/start will be used from an exhaust gas perspective and only on a warm engine. The torque required is well below 100 Nm and can be applied by the starter generator via the belt drive with little noise. This is one of the main requirements for acceptance of stop/start systems.

Further it is possible to integrate a planetary gear set into the belt drive for cold start [5].

Crankshaft starter generator

In the crankshaft starter generator, the electric motor sits directly on the crankshaft where the flywheel is normally mounted. The rest of the powertrain is downstream (Figure 7).

The starter generator must be designed such that cold starting of the engine is possible since it is not really feasible to accommodate a conventional starter. Typical power ratings are in the range 10 ... 15 kW. This requirement marked the first step into hybrid technology for many automotive manufacturers. In general, however, some system-related weaknesses prevented its adoption for volume use. Stop/start can be achieved neatly, with little noise and quickly. However, regeneration and electric driving are only possible to a limited extent since the internal combustion engine cannot be decoupled from the starter generator.

In both regeneration and electric driving, the internal combustion engine must be dragged along against its internal friction. As a result, there is almost nothing left to be regenerated.

In principle, the crankshaft starter generator is compatible with all transmission types. It must be noted, however, that for the vehicle to start quickly and move off immediately, all the nec-

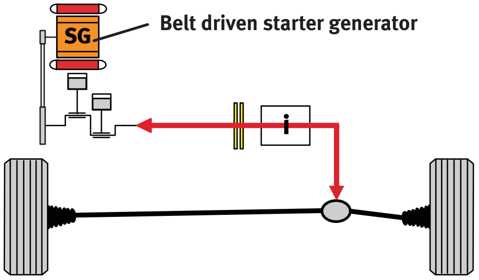


Figure 6 Belt starter generator

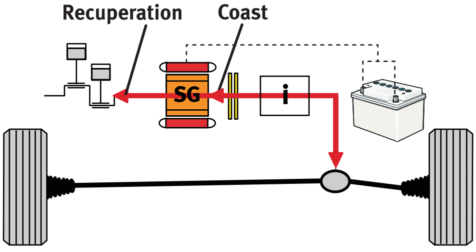


Figure 7 Crankshaft starter generator with electric motor on the crankshaft

essary torque-transmitting elements of the transmission must already be in a position ready for operation. This is not the case in conventional automatic transmissions, in which the pressurised oil required for the actuation is supplied by an oil pump driven by the internal combustion engine. For restart, the pump must first move the oil, the pipes must be filled and elasticities preloaded before pressure can be built.

Significant fractions of a second are lost in this process. When restarting, the driver experiences an unacceptable delay. An (additional) electrically-driven oil pump must be fitted in such automatic transmissions. This impairs the efficiency of the powertrain and increases costs.

The crankshaft starter generator category also includes the Honda Insight CVT. As shown in Figures 8 and 9, the crankshaft starter generator is combined with a CVT. This combination is perhaps not very imaginative, but is notable for its simplicity and low consumption of approximately 4 l/100 km.

An advantage of the CVT compared to a stepped transmission is that driving is frequently possible in overdrive ratios that can be set without comfort-impairing gearshifts. Due to the low engine speed, drag losses are reduced and regeneration is possible, with restrictions, even without a separating clutch between engine and electric motor.

All the Honda system lacks is pure electric driving. In addition to a further clutch, this would require even more additional outlay for the CVT clamping system. The hydraulic pump is normally driven by the internal combustion engine, so it would need an alternative power source in electric driving.

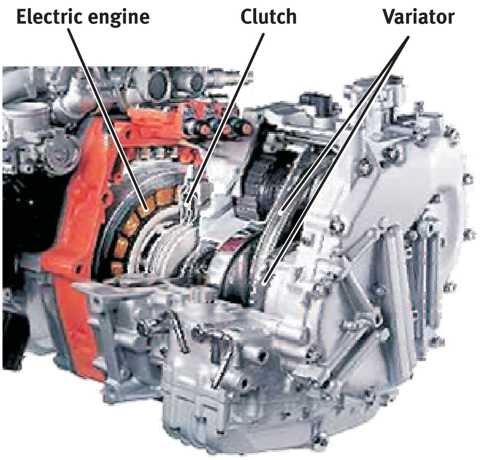


Figure 9 Cutaway of CVT with starter generator in the Honda Insight

Starter generator between two clutches

If regeneration and electric driving is required, it must be possible to decouple the internal combustion engine from the electric motor and the rest of the powertrain. This gives rise to the requirements in Figure 10. The internal combustion engine can now be shut down and decoupled from the rest of the powertrain. The deceleration energy to be regenerated can be used in full to drive the generator. In electric driving, the friction losses of the internal combustion engine no longer have an unfavourable influence.

Depending on the drive rating, this concept can be realised as a mild or full hybrid.

With electric motor ratings up to approx. 12 kW, only stop/start and regeneration are possible. If the rating is 20 kW or higher, electric driving can also be achieved.

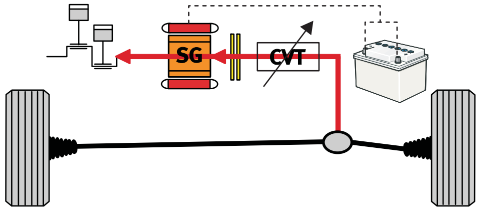


Figure 8 Combination of crankshaft starter generator and CVT in the Honda Insight

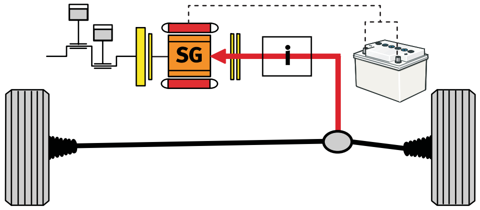


Figure 10 A powertrain with a starter generator between two clutches

In principle, all transmission types can be operated with this system.

The restrictions mentioned in the preceding section are valid here too. Restart can only be achieved with acceptable promptness if either an electrically-driven pressurised oil pump is provided or, even better, the actuator systems required for the gearshift and clutches are driven directly by electric motors.

In practically all projects, the clutch separating the internal combustion engine and transmission is a dry clutch. This is possible because this clutch is not used as a starting clutch, so very little frictional energy must be transferred. Furthermore, it must have a low drag torque. This can be best achieved with a dry clutch.

A dry clutch always has one side with a high mass moment of inertia, namely the side with the cast friction elements, and one side with the clutch plate, which has a low mass moment of inertia.

It is now possible in design terms to allocate either the high or low mass moment of inertia to the crankshaft. If the high mass moment of inertia is on the crankshaft, this operates like a normal flywheel (Figure 10). The engine can therefore run even when the separating clutch is open.

During restart, however, the relatively large mass moment of inertia of the clutch must accelerate as well. This means a higher working load on the clutch, a longer start time and a sensible deceleration of the vehicle, if the motor is started using vehicle momentum.

The reversed arrangement was therefore also considered (Figure 11).

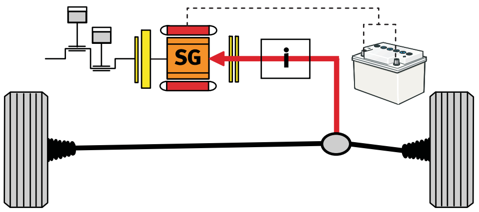


Figure 11 Arrangement as in Figure 10, but the light side of the clutch is linked to the crankshaft

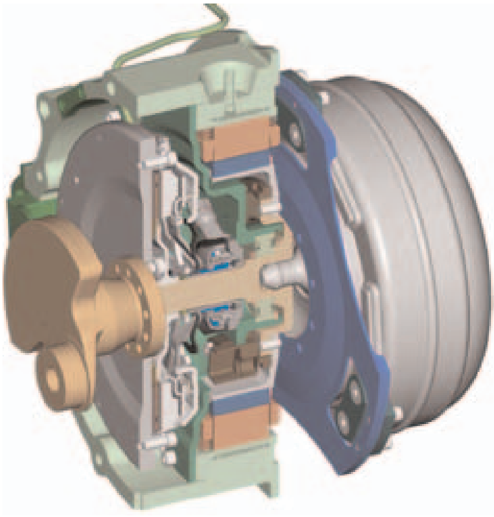


Figure 12 Dry clutch between crankshaft and electric motor in automatic transmission with converter. Heavy side of clutch on crankshaft

In this case, only the extremely light clutch plate sits on the crankshaft. Together with the crankshaft, connecting rod and piston, its mass moment of inertia is not sufficient to keep the engine turning when the separating clutch is open. However, this is not required in any case.

The advantage of this arrangement takes effect in the restart. With a small power level split off from the powertrain, the internal combustion engine can be abruptly brought up to speed. Extremely rapid starts are thus possible.

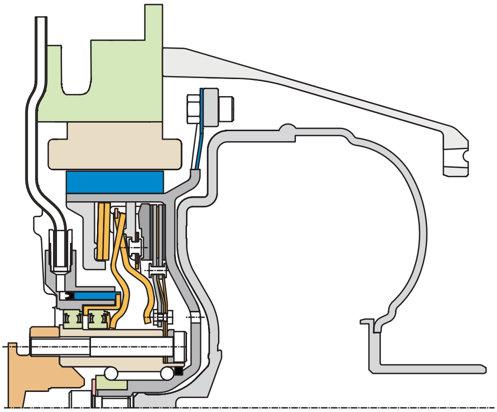


Figure 13 Separating clutch between crankshaft and electric motor with light side of clutch on crankshaft

However, the separating clutch must be capable of transmitting without slippage not only the static engine torque but also the torque fluctuations caused by the non-uniformity which, especially in diesel engines, can be several times the engine torque. This is not an easy requirement for the clutch but is one that can only be fulfilled using a dry clutch.

In the arrangement "electric motor between two 2 clutches", there are therefore projects with the heavy side and with the light side on the crankshaft. Figures 12 und 13 show examples of such clutches with the associated electric motors.

Serial hybrid with clutch between two electric motors

In the serial hybrid (Figure 14), the powertrain can be completely separated in mechanical terms. Power can be transmitted by purely electric means.

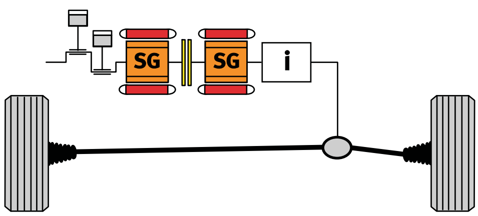


Figure 14 Serial hybrid

The two electric motors arranged in series, the first acting as a generator to give electrical power that is converted in the second back into mechanical energy, can also be regarded, when the clutch is open, as an electrical transformer or an electric, continuously variable transmission. Such arrangements have long been used in diesel-electric units in locomotives.

This is of particular interest for the CVT, which requires considerable outlay for a reverse gear with a planetary indexing set and a separate clutch. In the serial hybrid, appropriate dimensioning of the two electric motors allows a reverse gear to be realised by regulating the output to give reverse motion (Figure 15).

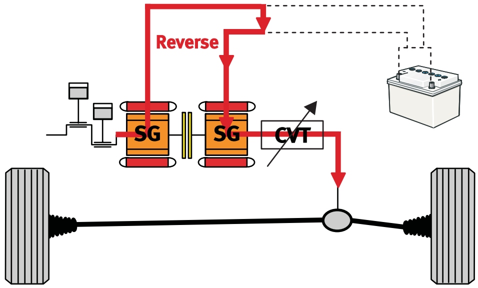


Figure 15 Reverse travel in serial hybrid with CVT

In a further variant of the serial hybrid, the first electric motor is driven by the accessory drive and thus replaces the normal generator (Figure 16).

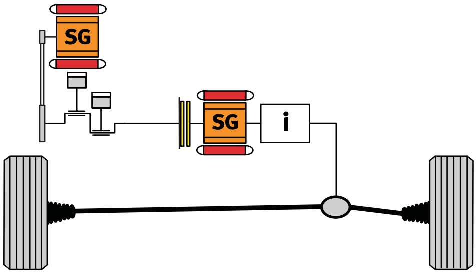


Figure 16 Serial hybrid with first electric motor arranged instead of normal generator in accessory drive

The power level is limited, however, because the power required for a full hybrid certainly cannot be transmitted by means of a belt drive.

Hybrids with power splitting

A quite different path was pursued by Toyota some years ago. The power flow of the internal combustion engine is split along two paths by a planetary gearbox (Figure 17).

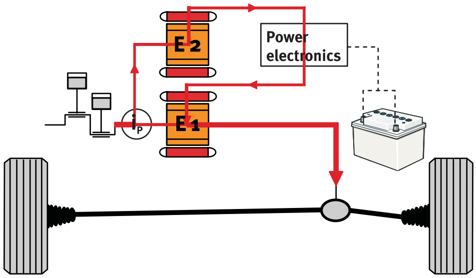


Figure 17 Power splitting in the Toyota Prius

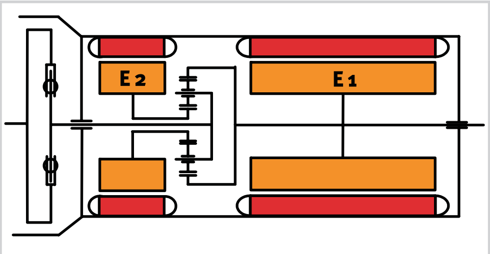


Figure 18 Schematic design of Toyota Prius hybrid transmission

The first path leads directly to the output, the other to a generator. Depending on how much the generator curbs this path, a corresponding speed occurs at the output. The output speed can even be continuously regulated by means of the braking torque of the generator.

During braking, the generator of course produces a large quantity of electrical power that cannot be stored (completely) in the battery. An electric motor is therefore mounted on the input that feeds this electrical power back into the powertrain.

Power is thus transmitted via a mechanical path direct to the output as well as an electrical path.

This concept is impressive for its simple mechanical design but requires two high-power electric motors with a total power rating of approximately 50 kW (Figures 18 and 19). A further disadvantage lies in the large quantity of power flowing via the electrical path that, due to the numerous conversion steps (mechanical to electrical energy, frequency converter, back to mechanical power) does not have optimum efficiency and thus, at least to a certain extent, has a sapping effect on the fuel consumption savings.

As a result, there has been no lack of effort to compensate at least partially for this disadvantage.

It was found that progress toward the objective could be achieved by splitting the power in mul-

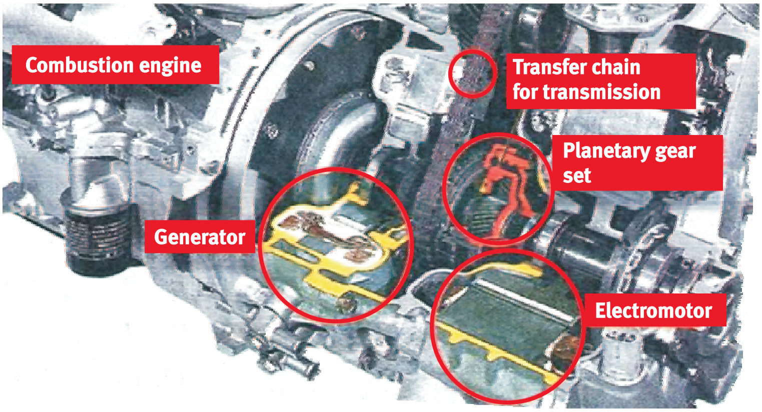


Figure 19 Toyota Prius transmission, cutaway

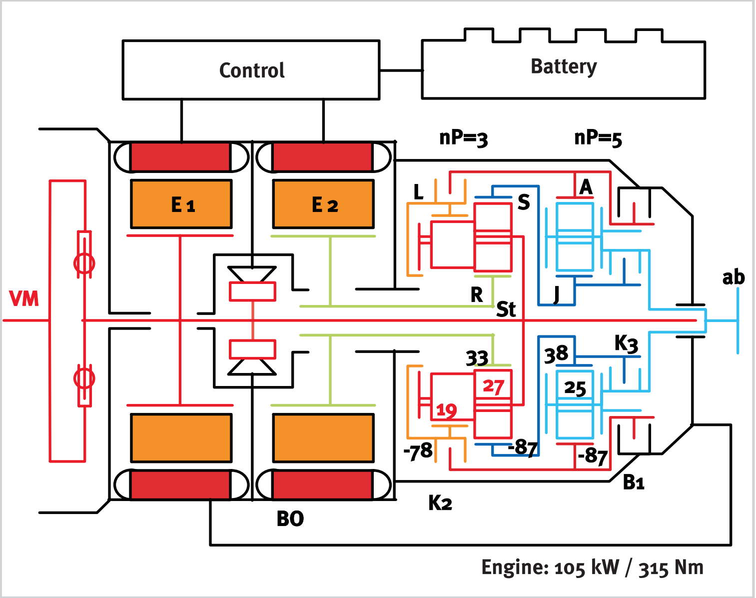


Figure 20 Power splitting with multi-range transmission [5]

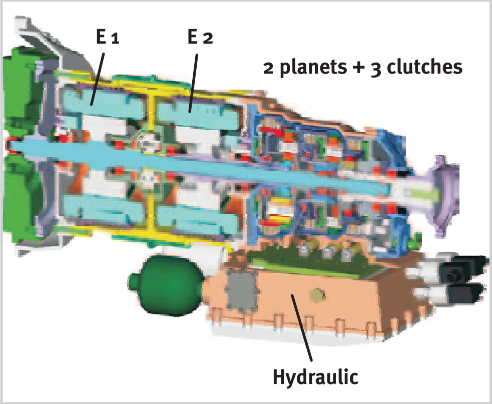


Figure 21 Hybrid with power splitting with multi-range transmission according to Tenberge [5]

tiple ranges. In simple terms, this is best described as follows: instead of a planetary set with a fixed ratio, various planetary sets with different ratios are used. Depending on the running range (engine speed, torque, vehicle speed), the planetary set is used that gives the smallest possible flow of electrical power (Figure 20).

Switching between planetary sets is similar to that in a stepped automatic transmission. The great advantage, apart from the smaller losses, is the considerably reduced power ratings of the electric motors, in the range of approx. 20 ... 30 kW. This significantly reduces the size of the power electronics, reducing the costs involved.

The change between the different ranges may be a disadvantage if they are not designed to be sufficiently comfortable.

A design for 400 Nm called SEL (Stufenlos Elektrisch Leistungsverzweigt = Continuous Electric Power Splitting), is shown in Figure 21 [4]. However, the cost and design envelope content of the two electric motors is still considerable and it also includes many components of an automatic transmission (pump, hydraulics, planetary sets, clutches, brakes).

Through the road

A further interesting variant is shown in Figure 22. The front wheel drive, transverse powertrain arrangement remains unchanged. In addition, the rear axle is driven by an electric motor. Both

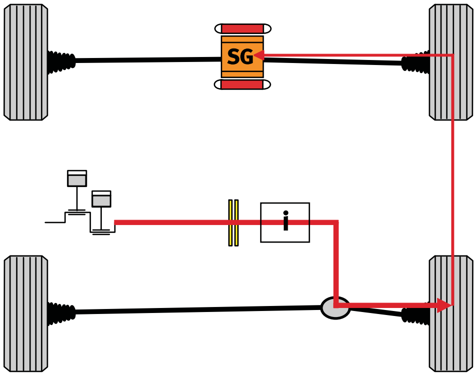


Figure 22 Hybrid drive "through the road"

electric driving and regeneration are carried out via the rear axle as a function of the battery charge condition.

In order to achieve highly dynamic stop/start, the vehicle is first started up under high load in electric-only mode via the rear axle while the internal combustion engine is started in parallel.

In addition to the hybrid functions, it is possible to achieve all-wheel drive in which the torques can be split between the front and rear axle in any proportion required, within the power limits of the two drives.

The power flow is via the road in different driving situations, for example in generator mode with driving under engine power. Hence the description "through the road".

Hybrid with double clutch transmission

The double clutch transmission (Figure 23) can be expanded to a hybrid drive by inserting an electric motor and a separating clutch for the

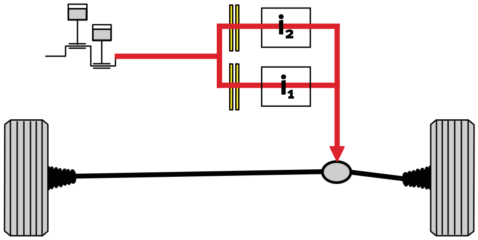


Figure 23 Schematic of double clutch transmission

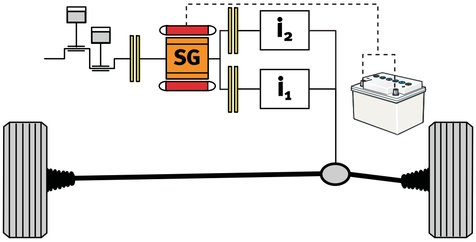


Figure 24 Expansion of double clutch transmission into hybrid

internal combustion engine (Figure 24). In accordance with the subdivision, this arrangement would fall into the category "between two clutches".

This can be simplified considerably if the electric motor is mounted on the sub-transmission for the even ratio gears. No additional clutch is then required since the existing double clutch can achieve separation from the internal combustion engine (Figure 25).

This gives a hybrid variant named ESG that fulfils all hybrid functions with particularly low outlay, but is only appropriate in conjunction with a double clutch transmission [5-7]. With this arrangement of the electric motor, the axial length of the complete drive is unchanged from the basic drive which, considering the restricted space conditions in the front wheel drive, transverse powertrain design, is a major advantage in comparison with coaxial mounting between the engine and transmission.

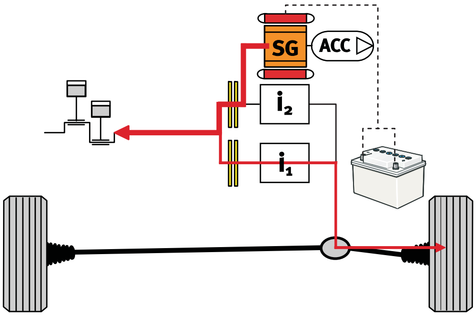


Figure 25 Simplified arrangement of electric motor double clutch transmission

Figure 25 describes the restart process, in which the electric motor starts the internal combustion engine via the clutch for the even ratio gears while the first gear clutch is simultaneously activated in order to split off part of the torque which is fed to the wheels. The driver therefore senses an immediate response from the vehicle even before the internal combustion engine is fully started. The good response behaviour is made possible by an electric actuator system that allows complete closing of the clutches while stationary irrespective of the powertrain speed.

Figure 26 shows the torque flow during regeneration in schematic form. Since the climate control compressor is directly connected to the electric motor, regeneration can be carried out as electrical energy or into the climate control compressor. This arrangement also allows stationary climate control since the electric motor can drive the climate control compressor with an open clutch and synchronisation devices in the transmission.

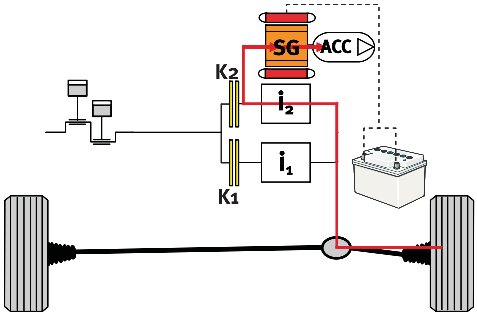


Figure 26 Regeneration, either in electric motor or climate control compressor

In terms of powertrain dynamics, the most critical situation is the switching on and switching off of the internal combustion engine during driving. In particular, restart as a reaction to operation of the gas pedal requires very rapid response behaviour.

The internal combustion engine is switched off after a specified time by transferring the torque from the active clutch K2 onto the electric motor. Once the clutch is opened, the internal combustion engine decelerates to zero and the electric motor picks up the coast torque as a generator.

Figure 27 shows the precise structure of the powertrain in which the two subtransmissions normally used in double clutch transmissions are

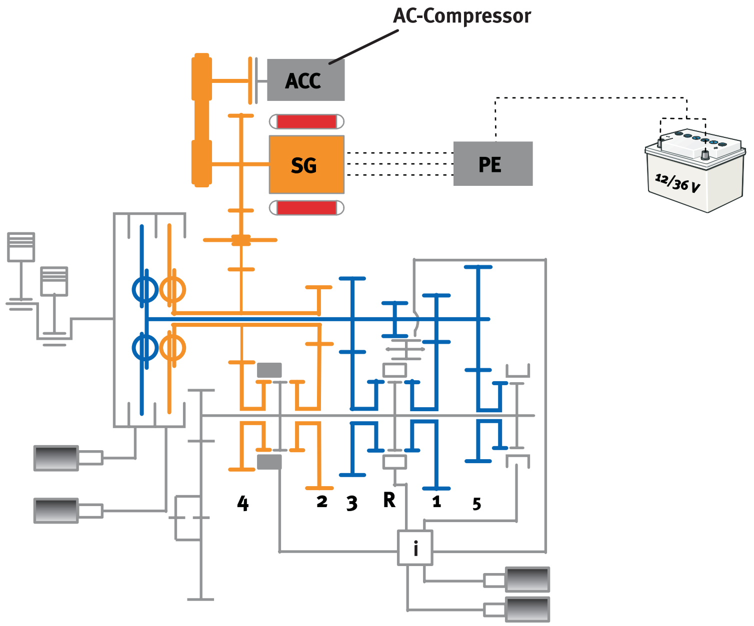


Figure 27 Structure of double clutch transmission with electric motor and climate control compressor

nested in a single transmission. The electric motor is located with a parallel axis to the transmission and is driven via two cylindrical gears by the 4th gear fixed wheel and a ratio of approx. 1,2.

LuK has built a prototype with such a transmission in conjunction with a 1,3 litre diesel engine. The electric motor in the prototype (Figure 28) has a power rating of 10 kW, is entirely adequate for this performance class and this vehicle for the purposes of regeneration and thus represents a mild hybrid. If the same construction is retained but the electric motor is scaled up, a full hybrid can be achieved. The climate control compressor is positioned directly under the electric motor and is driven by means of a poly-vee belt. With this arrangement, interior climate control can be maintained during regeneration and also while stationary.

Figure 28 Prototype transmission with electric motor flange mounted on side

The controllers for the internal combustion engine, transmission, starter generator and energy storage facility communicate via the existing CAN. Co-ordination of the hybrid functions and energy management was integrated in the transmission management system.

As mentioned, the dynamics involved in restarting the internal combustion engine and building up wheel torque are decisive in determining acceptance of the stop/start function in conjunction with an automated transmission. Figure 29 shows measurement of creep behaviour after release of the brake. The electric actuator system prepares for the next start during the stationary phase by completely closing clutch K2 and setting start-up clutch K1 to creep torque (cf. Figure 26). After magnetisation of the electric motor (TT ˜ 70 ms), the starting torque rises to the value of approx. 140 Nm necessary for acceleration of the internal combustion engine. In parallel, clutch K1 directs 10 Nm to the output via the engaged 1st gear. 140 ms after release of the brake pedal, the clearances in the drive are overcome and the vehicle starts to accelerate. This leads to significantly better response in comparison with drives designed on the basis of ASG. Approximately

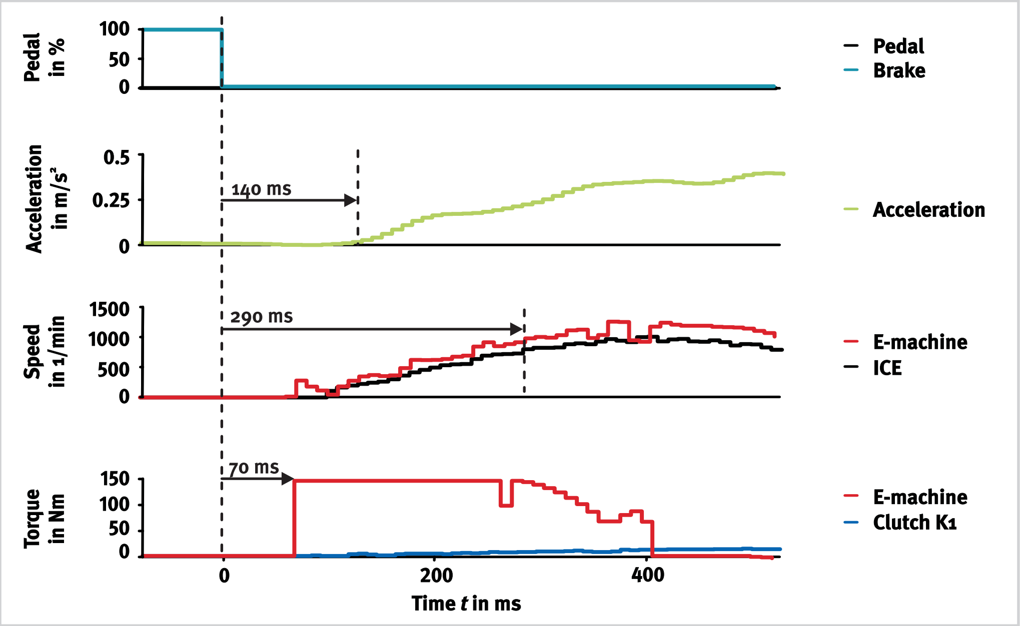


Figure 29 Start-up from stop/start (measurement)

290 ms after release of the brake pedal, the internal combustion engine achieves idling speed and ignition occurs.

Time is just as critical in restart of the internal combustion engine from a coast phase. Figure 30 shows the activation of the internal combus-

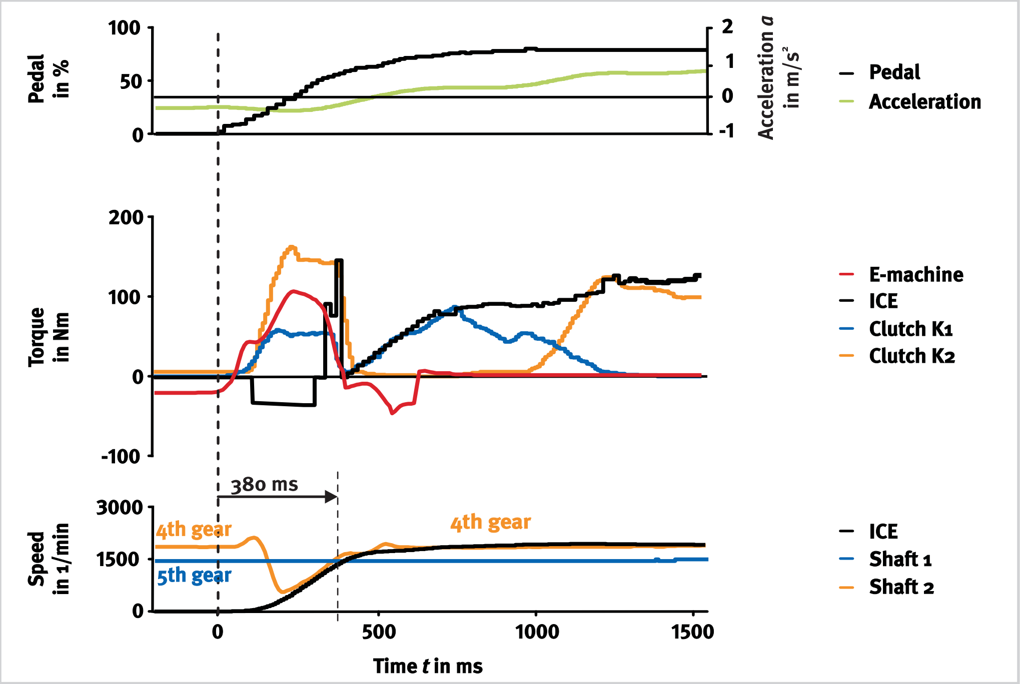


Figure 30 Start-up of internal combustion engine after regeneration phase (measurement)

tion engine at a travel speed of 55 km/h. This is initialised by activating the gas pedal. First, the electric motor is decoupled from the output by deselecting the active gear and switched from generator to motor torque. Clutch K2 is closed rapidly, accelerating the crankshaft. In addition to the power supplied by the electric motor, activation of clutch K1 feeds additional power from the output to crankshaft in order to further reduce the time until ignition of the internal combustion engine. However, this torque can only be maintained for a short period, otherwise the driver will experience this as a delayed response. The initial reaction to activation of the gas pedal felt by the driver is a reduction in the coast torque to zero. Approximately 340 ms after activation of the gas pedal, the crankshaft reaches the speed of transmission input shaft 1. From this point, torque is built up at clutch K1 and, after 380 ms, the vehicle begins to accelerate.

The behaviour of the vehicle under acceleration from standstill can also be significantly improved. The torque available from the electric motor is first fed to the internal combustion engine in order to reach start-up speed quickly. In accordance with the increasing torque of the internal combustion engine, the torque of the electric motor is then reduced. The boost function is only active during periods of low internal combustion engine speeds. The maximum torque of the internal combustion engine is not exceeded, in order to give the driver reproducible acceleration behaviour even over several cycles. The vehicle accelerates

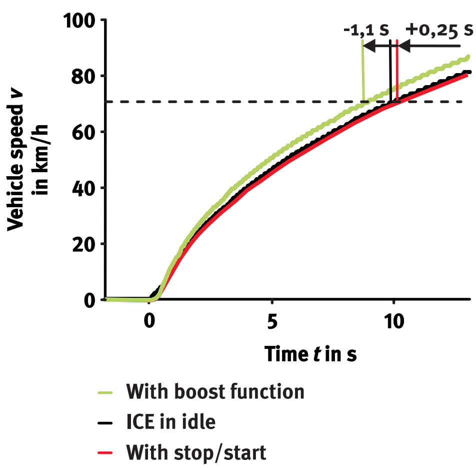


Figure 31 Vehicle acceleration: PSG versus ESG, 0 – 70 km/h (measurement)

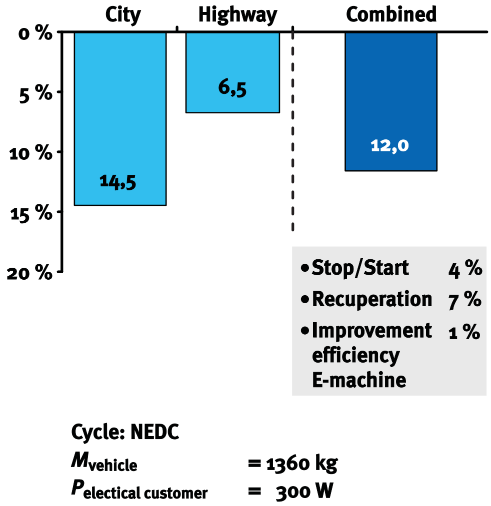


Figure 32 Reductions in consumption measured over cycle

from stop/start by means of the boost function, also with highly dynamic characteristics. Figure 31 shows the acceleration advantage to 70 km/h of approx. 1,1 s compared to the base vehicle.

Following function testing, consumption savings with the prototype vehicle were measured as shown in Figure 32. This is based on the double clutch transmission, already with significantly improved consumption behaviour, and the hybrid functions of stop/start and braking energy regeneration gave a further advantage of approx. 12 % fuel saving over the mixed cycle.

Comparison of concepts

Figure 33 shows an attempt to compare the various concepts. It should be pointed out first of all that this was only possible to a limited extent since, for each concept, there is a large number of possible designs that cannot be included in such an assessment. Nevertheless, some significant statements can be made that may assist in reaching a preliminary decision on selecting the right hybrid system.

The first question is which concepts are suitable for mild or full hybrids. Figure 33 shows that most are in principle suitable for both, depending on the dimensioning of the electric motor(s). There may even be a fluid transition between mild and full hybrids in the future, for example where electric manoeuvring but not full electric driving is required.

The two columns "Mild hybrid" and "Full hybrid" show which of the functions start/stop, braking energy regeneration and electric driving are possible.

For example, the variant "between two clutches" can be expanded to mild hybrid or full hybrid depending on the size of the electric motor. Typical electric power ratings for regeneration are 10 ... 15 kW. This is somewhat over-dimensioned for start/stop. Electric driving would require approximately 30 kW or higher.

Some hybrid concepts can only be used in conjunction with particular types of transmission or require a transmission type that would not function at all without a hybrid. This applies mainly to the variants with power splitting.

Costs will play an important role. In addition to the electric motor, critical issues will be the power management electronics and power storage in the battery and super-capacitors. It is difficult to make reliable assessments here since the components are not yet available on the world market in a form suitable for volume usage.

Nevertheless, some statements can be made. In approximate terms, the costs of an electric motor will be underpropotional to its power. The same effect exists for the storage media of batteries and super-capacitors.

Hybrid concepts using two electric motors will, for the same total electric power rating, be more expensive than if only one unit is used. In this case too, there will be additional outlay in the transmission, for example an additional clutch and the associated actuator system. Alternatively, an electrically driven oil pump will be required in automatic transmissions to allow a start/stop function.

A whole range of these concepts are already used in small production quantities or are in development, as shown by the reference in the final column of Figure 33.

	Type		Function					
	mild/ micro	strong	start/ stop	recupe-ration	electric driving	combi-nable with transmission	additional cost	in production or published
belt driven starter alternator	✓		✓			all		PSA
crankshaft starter alternator	✓	✓	✓			all		GM Honda
between two clutches	✓	✓	✓	✓	✓	all	2nd clutch	AUDI VW
power split		✓	✓	✓	✓	special transmission required	2nd E-Motor	Toyota GM / DC / BMW
serial		✓	✓	✓	✓	all	2nd E-Motor	DC
through the road		✓	✓	✓		all		DC Toyota
ESG	✓	✓	✓	✓	✓	double clutch transmission		LuK

Figure 33 Comparison of hybrid concepts

It should be assumed that, in the next few years, there will be a phase comprising consolidation and concentration on the concepts that promise the most success. There will also be a quite decisive question to be addressed: whether a hybrid must also allow electric driving or will only be used to achieve reductions in fuel consumption. This will decide whether full or mild hybrids will ultimately make the breakthrough.

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