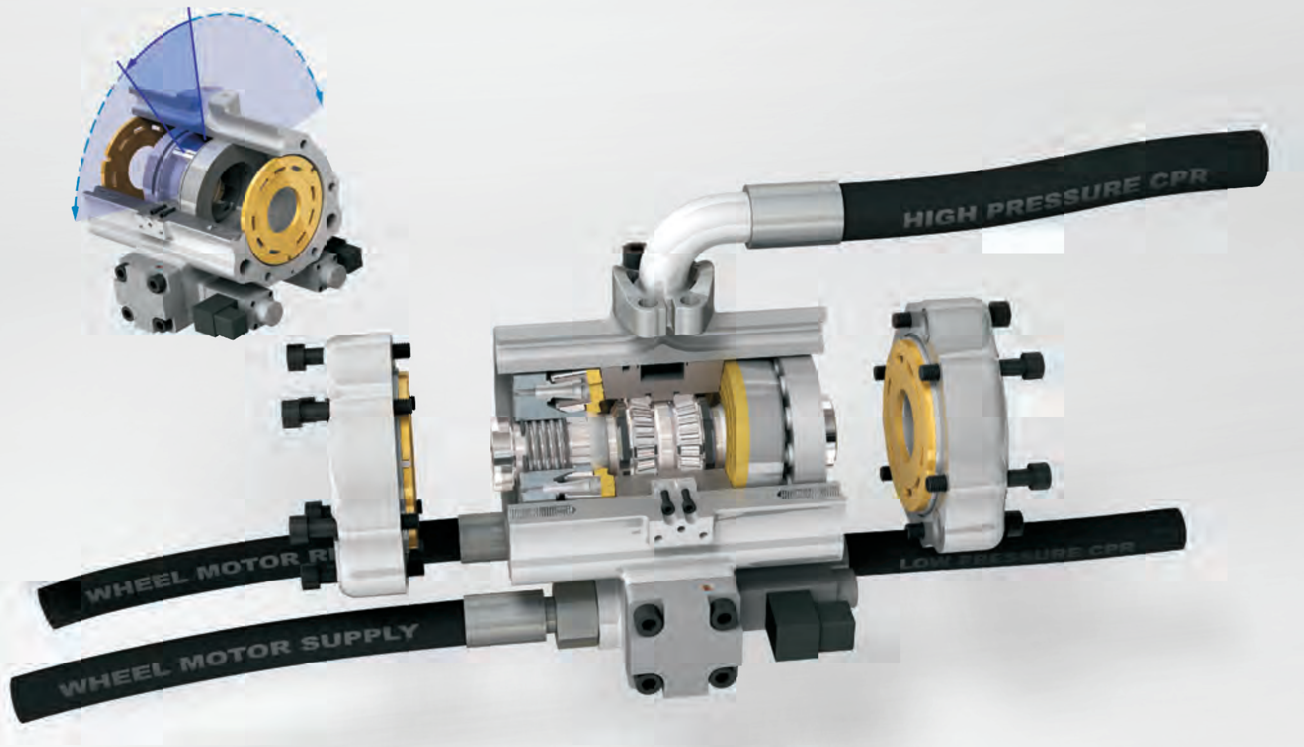

Low-emission Hydraulic Hybrid for Passenger Cars

Two new technologies, the „floating cup"-principle and a new hydraulic transformer, allow the complete substitution of the mechanical drive of a passenger car for a series hydraulic hybrid transmission. The new "Hydrid" power train from Innas and the RWTH Aachen University reduces the fuel consumption of a medium-sized car by 50 %. The CO_2 emissions are reduced to 82 g/km, a level far below the EU-limit for the year 2012 (120 g/km).

1 Introduction

Innovation is driven by changes in the economic environment. A change of market demands and requirements leaves the industry no other option: it has to innovate. The automotive industry is currently facing the most fundamental changes of its history: strong fluctuating fuel prices, new CO_2-limits and an unprecedented cost pressure. Given these circumstances the industry has to innovate and is indeed willing to do so. The new economic and legal demands seem to be both defying and conflicting. For the reduction of fuel consumption and CO_2-emissions, all hope is focussed on the (parallel) hybrid electric drive train, with the all-electric transmission on the horizon as the ultimate solution. The electric components however cause a strong increase of the manufacturing cost, resulting in a limited market acceptance. Recent studies showed a very limited potential for hybrid electric vehicles of less than 10 % of the total sales volume by the year 2035 [1, 2]. The hybrid electric transmission is also by far the most expensive option for CO_2-abatement [3].

The cost increase of hybrid electric transmissions is inevitable. Being a parallel hybrid solution, the electric system is an add-on to the mechanical transmission, and by definition increases complexity, weight and cost of the vehicle. Despite mass production, electric transmission components are still an order of a magnitude too expensive [4, 5]. Furthermore, the poor average cycle efficiency of the batteries and the electric motors result in a limited reduction of the fuel consumption.

A better solution would be to replace the mechanical transmission by a hydraulic transmission having accumulators for energy recuperation and power management. The result is a "Hydrid", a series hydraulic hybrid vehicle [6, 7], which has the same basic architecture as a series electric hybrid drive train, **Figure 1**. However, compared to electric batteries, motors and controllers, hydraulic transmission components are extremely robust, have a much higher power density and have much lower manufacturing cost. It is furthermore expected that a hydraulic transmission will have the same weight and manufacturing cost as the mechanical transmission it replaces. Key for the success of the Hydrid is the introduction of hydraulic transformers (depicted above) for power control. Furthermore a new multi-piston principle is applied which strongly reduces the noise, vibration and harshness issues related to conventional hydraulic motors. Simulations of the new drive train have indicated that the fuel consumption will be reduced by more than 50 %. Although the average cycle efficiency of the hydraulic transmission is not as high as of the mechanical transmission, this is more than compensated by the efficiency advantages of the hydraulic transmission due to its capabilities for power management and energy recuperation.

The new "Hydrid" transmission does not exclude the electric battery. On the contrary, it facilitates the introduction of a base load electric system which can now be much smaller than of current hybrid electric vehicles. But even without the help of batteries, small hydraulic accumulators with a volume of 10 to 20 l are sufficient to handle most of the brake energy recovery and all of the power and traction transients of the vehicle.

2 Maintaining the Performance

The drive train of a vehicle is dimensioned for peak performance, for instance for being able to climb a mountain pass with a trailer load or for fast acceleration from 0 to 100 km/h. These peak requirements differ very much from average, day-to-day driving conditions, **Figure 2**.

The engine operation has an enormous influence on the fuel consumption. When accelerating or cruising dur-

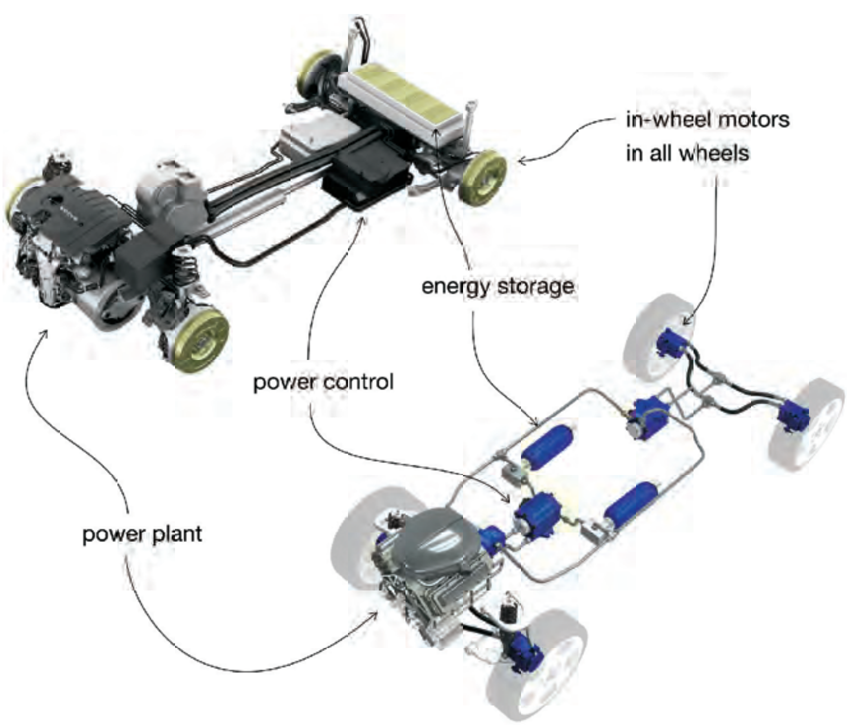

Figure 1: Comparison of a series electric hybrid (left) and a series hydraulic hybrid transmission (right)

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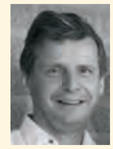

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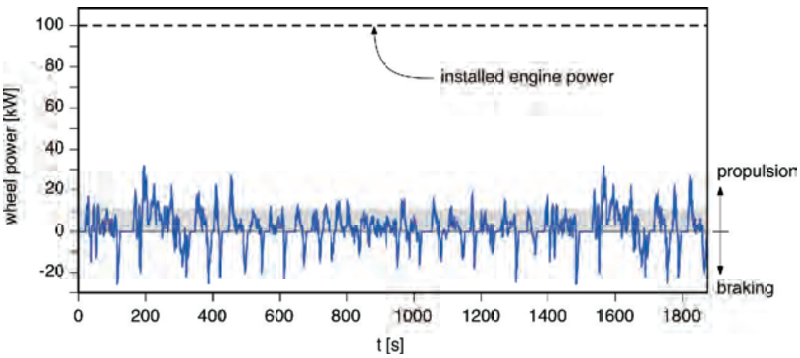

Figure 2: Required total wheel power for a mid-sized passenger car with a curb weight of 1450 kg driving the US FTP-cycle, in comparison to the installed engine power. During 80 % of the propulsion time, the required wheel power is less than 11 kW (indicated by the grey band in the diagram)

ing the FTP-cycle, the maximum required wheel power is 32 kW, less than one third of the installed engine power. During 80 % of the time the power demand is less than 11 kW and for half the time even less than 5 kW. At these power levels the engine has a very poor efficiency, which is the main reason for the high fuel consumption of passenger cars, especially when driving in the city. Low load operation of the engine can however be completely avoided by applying an energy storage system in the drive train. The engine power does not need to be reduced and the vehicle performance is not compromised. The energy storage allows the engine to be operated at relatively high loads and power outputs, even when the vehicle only requires a low propulsion power. Whatever the engine produces in excess can now be supplied to the energy storage system.

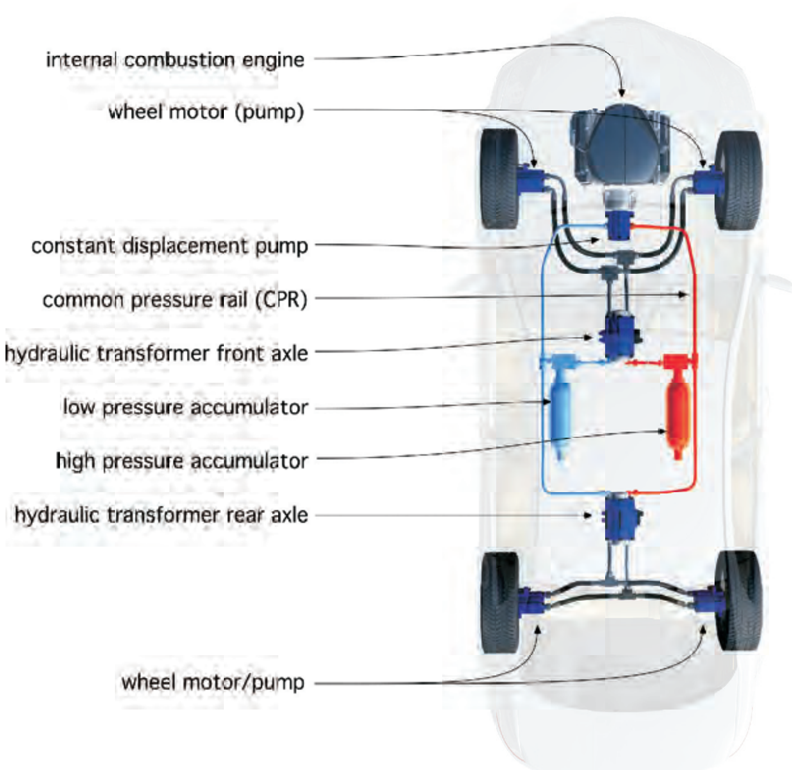

Figure 3: Lay-out of the Hydrid: a series hydraulic hybrid transmission

There are several advantages for having an energy storage system integrated in the transmission of a passenger car. The engine operation is strongly improved, without compromising the maximum performance of the engine or the vehicle. Moreover, the storage system facilitates start-stop-operation of the engine, thereby eliminating idle losses of the engine. Furthermore, the energy storage system can also be used for recuperating the kinetic energy of the vehicle when braking. Contrary to most expectations, passenger cars do not need a large energy storage for energy recuperation. Most brake actions only require a storage capacity of about 30 Wh, much less than the capacity of an average starter battery. However, the power demands for such a storage system are quite high, **Figure 2**. Any energy storage system for a passenger car must therefore be capable of handling and managing high and strongly varying power levels: it foremost needs a high power density, not a high energy density.

3 Replacing the Mechanical Transmission

Hydro-pneumatic accumulators fulfil these demands. An accumulator is basically a pressure vessel having an internal nitrogen volume. When oil is supplied to the vessel, the nitrogen is compressed thereby increasing the pressure of both the oil and the nitrogen. Accumulators are extremely robust, and although the energy content is much lower than that of batteries, they have an unparalleled power capacity of more than 20 kW per kg. Due to weight and cost constraints, the size of the accumulators have to be kept small, somewhere between 10 and 30 litres for an average passenger car.

The accumulators are connected to the common pressure rail or CPR, **Figure 3**, which is the power grid of the system. The internal combustion engine is no longer hard coupled to the wheels, but is instead only used to drive a hydraulic pump. The pump is a simple constant displacement pump for which the torque demand T is proportional to the pump pressure differential Δp:

$$T = \frac{\Delta p \cdot V}{20 \cdot \pi} \quad \text{Eq. (1)}$$

Hydraulic accumulators have a limited pressure range, for instance between 200 and 400 bar. Assuming a displacement volume V of the pump of 60 cc/rev, it can be calculated that the pump (and engine) torque T varies between 191 and 382 Nm. The engine can therefore only be operated at high loads. Strong part load operation is completely avoided. The hydraulic power plant is only operated if and when this is required for maintaining a certain pressure level in the high pressure accumulator. In case the accumulator does not need to be charged, the engine is shut down completely, thus avoiding any idling losses.

By means of the hydraulic transmission, the vehicle traction is directly created at the wheel shaft by the hydraulic motors. The traction is controlled by changing the pressure differential across the in- and output ports of these motors. When reversing the pressure differential, the hydraulic motors will act as pumps, thereby decelerating the vehicle while recuperating the brake energy and storing it in the accumulators. The hydraulic transmission can be an all-wheel drive, Figure 3, having a variable traction for both axles and allowing energy recuperation on all four wheels.

4 A New Hydrostatic Principle

In a conventional drive train the vehicle traction and speed is directly related to the engine torque and speed. The new Hydrid transmission separates the power supply from the load control and the wheel traction is directly created at the wheels. This makes the vehicle extremely responsive, but it also sets high demands for the wheel motors which now have to fulfil all extreme demands of the vehicle, and have to run in a wide speed and torque range. The maximum torque needs to be delivered at low vehicle speeds where conventional hydraulic motors have high friction losses. Furthermore the noise, vibration and harshness (NVH) is extremely critical for the design of a passenger car. The direct connection of the hydraulic motors to the wheels eliminates the opportunity of using dampers and flywheels to reduce torque ripples. The wheel motors therefore need to have an extremely constant torque output.

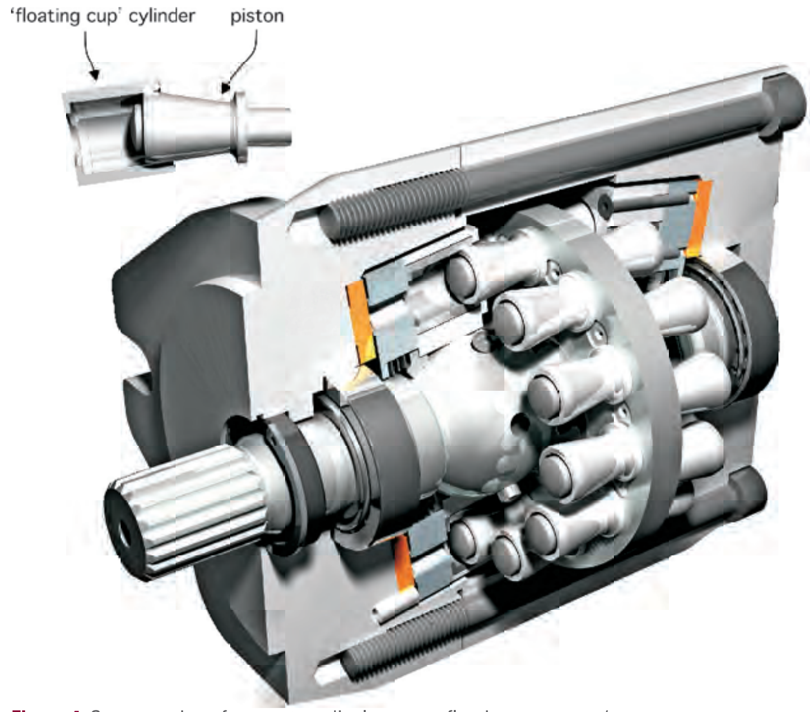

Figure 4: Cross section of a constant displacement floating cup motor/pump

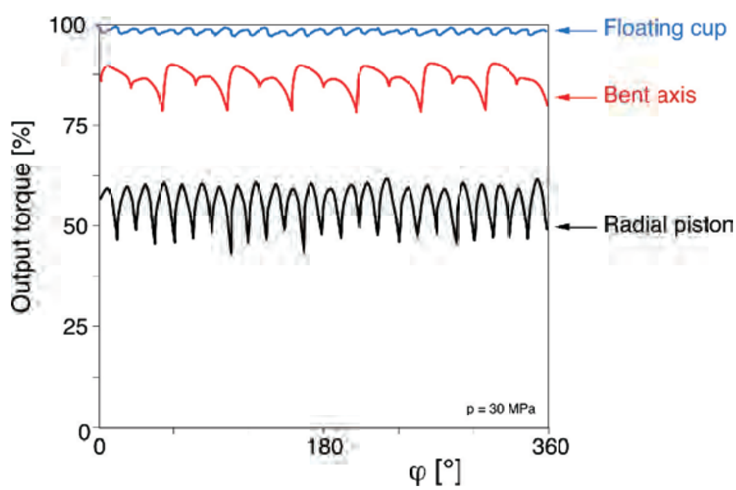

Figure 5: Measurement of the torque output of three different hydraulic motors, relative to the theoretical maximum torque output. The measurements are performed at 300 bar and rotational speeds below 1 rpm

In the past few years a new hydrostatic principle has been designed to fulfil all these requirements [8]. The main characteristics of this „floating cup" principle, **Figure 4**, are:

- multi piston design typically having around 24 pistons
- mirrored configuration for reducing the hydrostatic load on the bearing
- a direct conversion of hydraulic pressure forces to torque (and vice versa) with very low friction losses
- fit for low-cost mass production technologies like deep drawing, sintering, fine blanking and sorting.

Figure 5 shows a comparison of the measured torque at near-to-zero speed conditions for three different hydraulic motors relative to the theoretical maximum torque. Only the floating cup motor shows almost no torque losses due to friction at these operating conditions. It also is apparent that the torque variations of conventional hy-

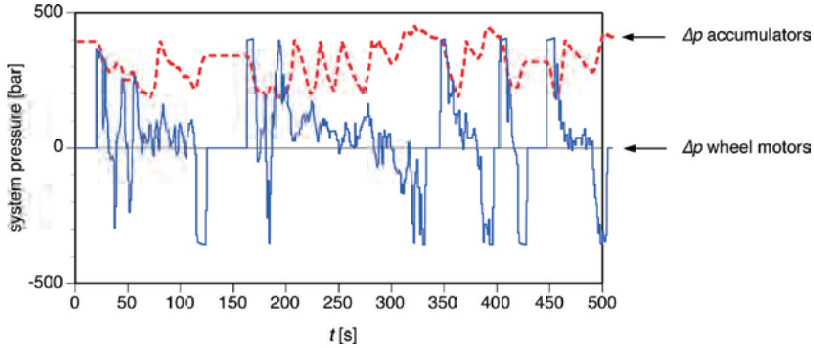

Figure 6: Pressure differential between the high and low pressure accumulators and the demanded pressure differential at the wheel motors during the first 500 seconds of the FTP75-cycle

draulic motors are not acceptable for a direct wheel drive in a passenger car. Only by means of a substantial increase of the number of pistons, the torque variations can be reduced to acceptable levels.

The floating cup principle is capable of running in a wide range of operating conditions. As a motor it can directly drive the wheel without the need of a gear transmission. It can also be operated at high pressures, thereby creating a high wheel torque with a relatively small motor. At a pressure of 500 bar, a floating cup motor having a displacement of 56 cc delivers a wheel torque of 446 Nm. Having four-wheel motors, the total torque created is sufficient for a gradability of 44 %, or for accelerating the car from 0 to 100 km/h within 9 s.

5 The hydraulic transformer

The pressure level in the high pressure accumulator varies depending on the state of charge. The pressure level rises when recuperating the brake energy or when charging the accumulator with the engine-pump-combination. The pressure in the accumulator differs strongly from the pressure needed for creating the required traction at the wheels. **Figure 6** shows the calculated pressures for the first 500 s of the US FTP75 cycle. In the simulation the vehicle is only driven by two- wheel motors; the other two are disengaged. A positive pressure differential indicates a propulsion mode of the vehicle, whereas a negative pressure differential occurs when the vehicle is braking.

The gap between the two pressure differentials is bridged in the Hydrid by means of a hydraulic transformer. This transformer is the hydraulic equivalent of a CVT, converting pressure and flow instead of torque and speed:

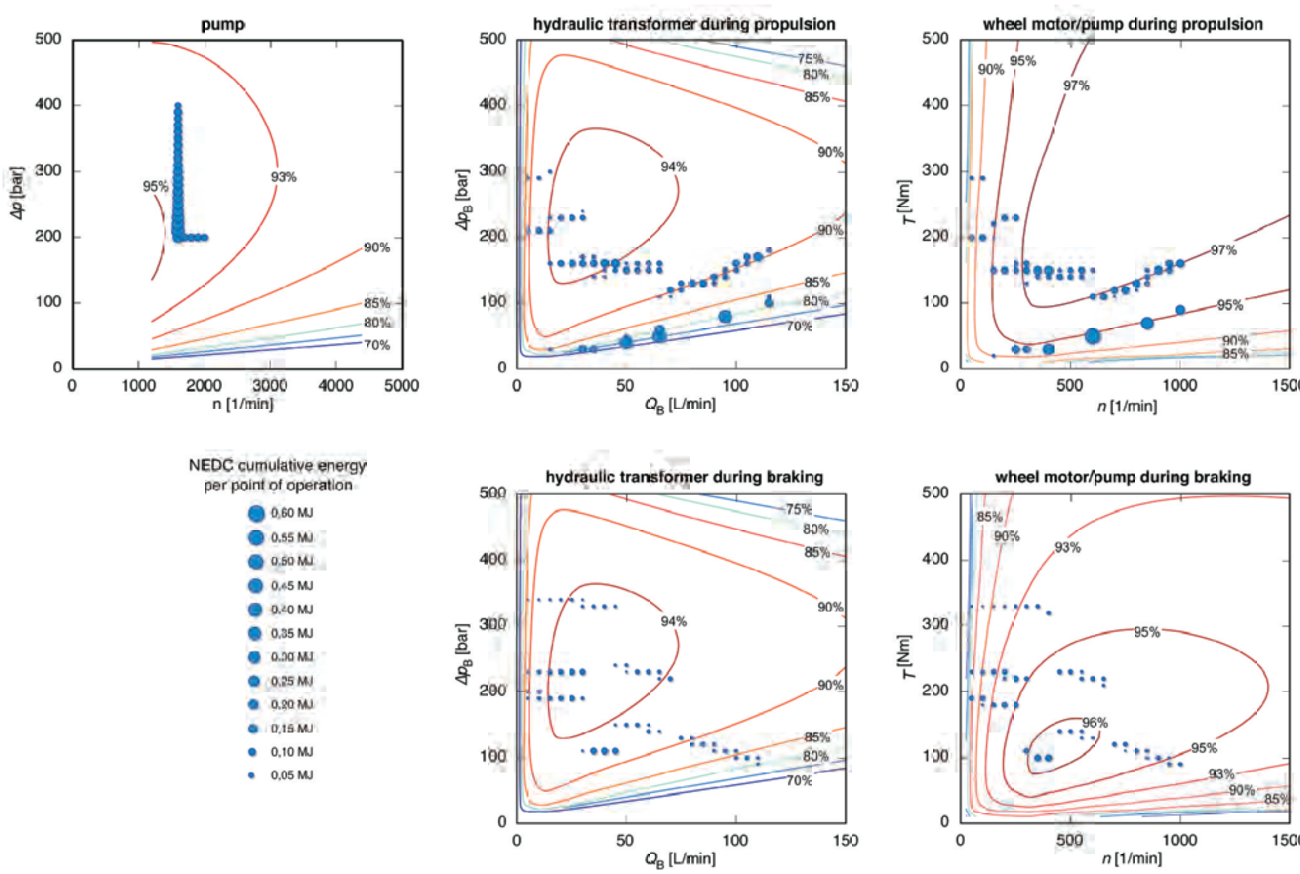

Figure 7: Efficiency maps of the main transmission components of the Hydrid, including the NEDC operating points

$$(\Delta p \cdot Q)_{in} = (\Delta p \cdot Q)_{out} \quad \text{Eq. (2)}$$

A new transformer has been designed on the basis of the floating cup principle to fulfil the requirements of automotive transmissions [9]. The transformer allows a full 4-quadrant operation of the vehicle (forward propulsion, forward braking, reverse propulsion and reverse braking). One of the most important features of the transformer is its ability to amplify pressures. This is especially needed for fulfilling demands concerning gradability, acceleration performance and elasticity, when the total required wheel torque is much higher than the torque needed for driving the NEDC or FTP-cycle. The hydraulic transformers allow the application of simple, small, robust and efficient constant displacement motors for driving the wheels. The motors can be kept small since the transformers can amplify the pressure level to a boost pressure of 500 bar, even when the pressure level in the accumulator is only 200 bar.

Without a transformer, variable displacement motors would be needed to meet the variable torque requirements at the wheels. However, the maximum torque of a variable displacement motor is determined by the pressure level in the high pressure accumulator. The advantage of pressure amplification is lost and the displacement of the variable motor needs to be increased to compensate for the lower pressure level. In order to create the same maximum torque, even when the accumulator pressure is only 200 bar, the motors would require more than double the displacement volume. Aside from the extra weight and cost of these larger variable displacement motors, the larger size also results in a stronger part load operation and a poor part load efficiency of the motors during normal operating conditions.

6 Fuel Consumption and CO_2-emissions

The Institute of Fluid Power Drives and Controls (IFAS) at RWTH Aachen University has performed an analysis of the specific fuel consumption and CO_2-emissions of the Hydrid. On the basis of efficiency tests, efficiency maps of all pumps, motors and transformers were derived, **Figure 7**. These maps were implemented in a DSHplus simulation model of a passenger car, including the most relevant valve losses, accumulator losses and losses in the connecting hydraulic lines. A mid-sized European passenger car has been taken as a benchmark, see the **Table** for the specifications. The fuel consumption has been calculated for both the NEDC and the US FTP75-cycle.

The energy flow in a transmission with energy recuperation is always more com-

Table: Hydrid car parameters

empty curb weight	1450 kg
maximum traction	5700 N (4-wheel drive)
maximum vehicle speed	190 km/h
frontal area	2.26 m^2
drag coefficient	0.26
dynamic wheel diameter	0.63 m
rolling resistance coefficient	0.008
engine	100 kW diesel engine
size of the accumulators	20 Liter
pressure range of the accumulator	200-420 bar
pump displacement	56 cc/rev (constant displacement)
size hydraulic transformers	56 cc/rev (pump equivalent)
size of the wheel motors	56 cc/rev (constant displacement)
maximum Δp wheel motors	500 bar

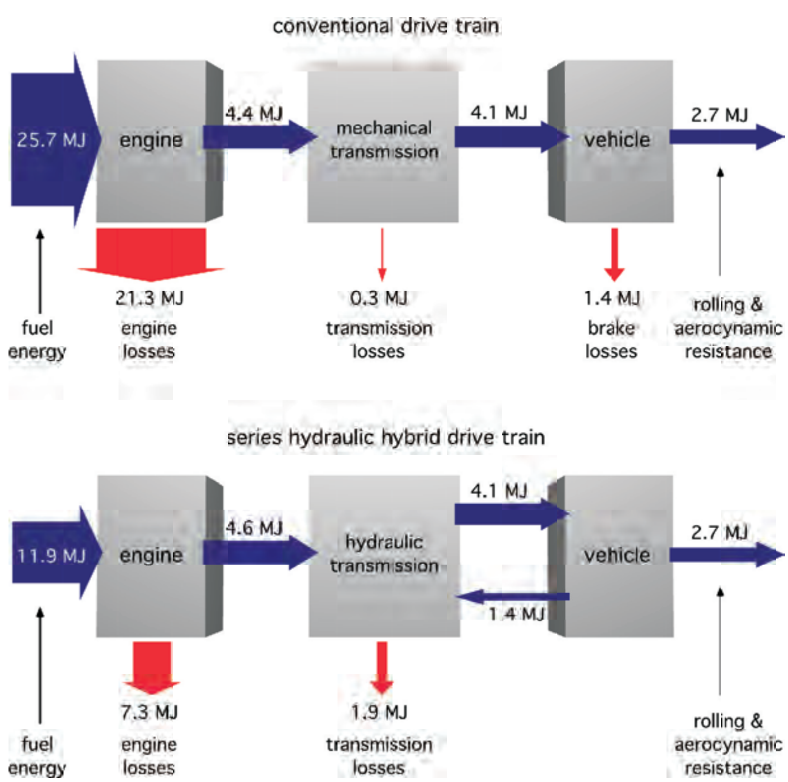

Figure 8: Calculated energy flows for a conventional mechanical transmission (six-speed, manual, AWD) and the new Hydrid drive train

plicated than in a regular transmission without recuperation. **Figure 8** shows the aggregated energy flows as calculated for the New European Driving Cycle (NEDC). The transmission losses of the mechanical drive train are almost negligible and are for certain much lower than of the hydraulic drive train. The energy loss of the hydraulic drive train is partly due to the limited energy storage capacity of the accumulator. With the hydraulic drive train, all brake actions are performed by the hydraulic wheel motors, which are then acting as hydraulic pumps. The brake energy is stored as much as possible in the hydraulic accumulator, but as soon as the high pressure accumulator has reached its maximum value, the rest of the brake energy is dissipated in a pressure relief valve. Of the 1.9 MJ calculated hydraulic transmission losses, 0.5 MJ is dissipated in the pressure relief valve. In the end 55 % (NEDC) to 76 % (FTP75) of the energy supplied back by the hydraulic transformers is effectively stored in the accumulator. All hydraulic losses are converted into heat. During the cycle the average required hydraulic cooling capacity for both cycles is around 1.6 kW. An advantage of hydraulic components is that the hydraulic oil transports the heat away from the transmission components. Unlike electric components there is no extra cooling system needed.

The amount of energy that needs to be supplied by the internal combustion engine is almost equal for both transmissions: the higher losses of the hydraulic transmission are offset by the brake losses of the mechanical drive train. Yet, there is a large difference in the fuel consumption of both drive trains, which is entirely due to the way the engine is operated and the effect this has on the engine efficiency. In the Hydrid configuration the engine is switched on and off and is only in operation during 10 % of the NEDC-time. But when it is in operation, it is always running at high loads, between 170 and 350 Nm, **Figure 9**. Operation at low load conditions, as is often the case with the mechanical transmission, is avoided completely. As a result, the specific fuel consumption is reduced from 6.6 l/100km for the reference vehicle to 3.1 l/100km for the Hydrid. The specific CO_2-emission is reduced from 174 to 82 g/km. The on-off operation of the engine and the shift of operating conditions will have an effect on the emission of particulates, NO_x and other legislated exhaust gas emissions. However, this is a concern for all hybrid vehicles in which the engine is shutdown whenever this is possible and the engine is operated in different operating points. Eventually it is to be expected that the engine control, and maybe even its design will be changed to adapt and optimise the new operating regime of the engine for the hybrid drive train.

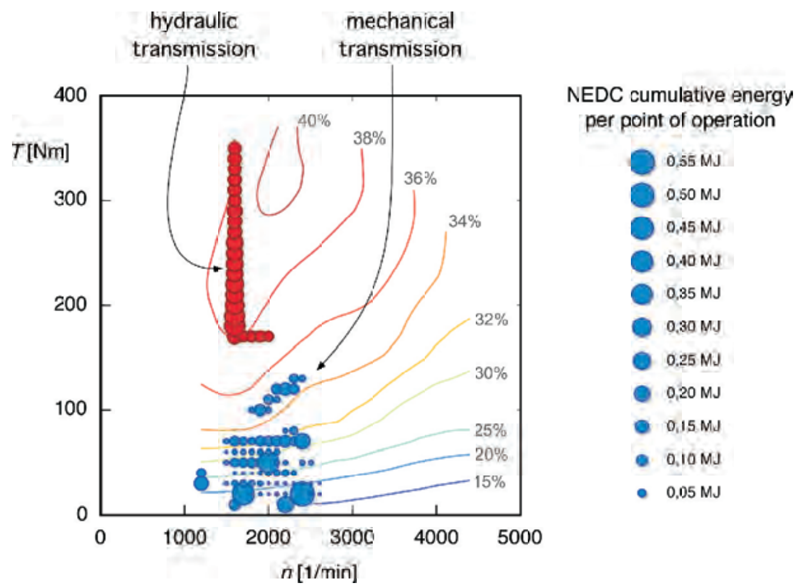

Figure 9: NEDC-operating points of the engine of a conventional vehicle with a mechanical transmission and of a vehicle with a Hydrid transmission, plotted on the efficiency map of the diesel engine. The size of the bubble indicates the amount of energy the engine produces at that point

7 Conclusion

Two new technologies, the floating cup principle and a new hydraulic transformer, enable the entire replacement of the mechanical transmission in passenger cars by a series hydraulic hybrid transmission. This new Hydrid transmission reduces the specific fuel consumption of a mid-sized sedan by more than 50 %, without compromising the cost, weight, acceleration performance or gradability of the vehicle. The CO_2-emission is reduced to 82 g/km, far below the limits set by the European legislation for the year 2012 (120 g/km). These reductions are mainly realised by forcing the engine to operate at high loads only and shutting it down when whenever the accumulator is charged. Essential for the low fuel consumption of the Hydrid are the high part load efficiencies of the new hydraulic components. The same series drive line lay-out may be realised with electric or conventional hydraulic units, but these lose a very large part of the reduction potential because of their rather poor part load efficiencies. The new Hydrid transmission also facilitates the application of electric batteries, which can be used for their strength (energy density) without letting their weakness (power density) lead to compromises regarding cost, weight or performance of the vehicle.

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