Energy efficiency of the Hydrid

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1 Serial hybrids

The torque, speed and power demands of automobiles are determined by the extreme conditions in which the vehicles have to perform: fast acceleration, hill climbing and high speed driving. The resulting installed engine capacity is however seldom needed. In most conditions, like driving in the city, the engine load is less than 30% of the maximum engine torque. Furthermore, at these operating points the engine has a very poor efficiency and energy is dissipated due to frequent braking and relatively long engine idle times.

A serial hybrid system could strongly reduce the fuel consumption –and the related CO_2-emissions– of a vehicle. In such a system, the engine is decoupled completely from the wheels. Instead the engine delivers its energy to a common grid with an energy storage device, and its operation can now be optimized for highest efficiency and lowest emissions.

In figure 1 two serial hybrids are presented, a full electric and a full hydraulic transmission. Both transmissions feature an in-wheel motor in all wheels. Aside from realizing a flexible all-wheel drive concept, the in-wheel motors completely eliminate the mechanical drive train, including all differentials and drive shafts. The removal of the mechanical drive results (in itself) in a reduction of the cost, weight and fuel consumption of the vehicle.

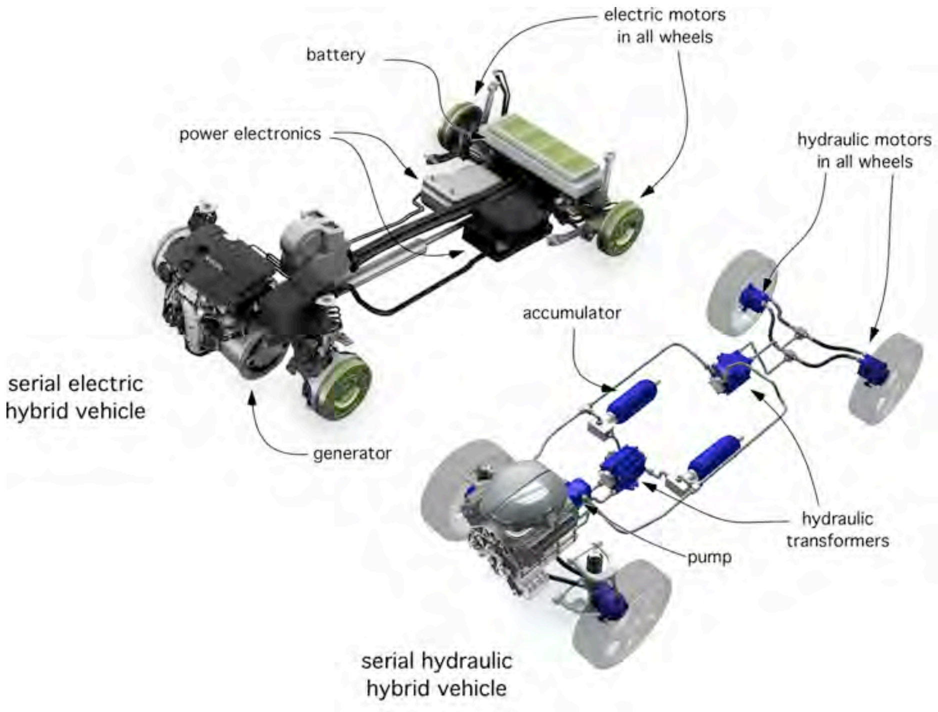


Figure 1: Electric and hydraulic serial hybrid drive trains with in-wheel motors

A serial hybrid however sets high demands for the main transmission components:

- High efficiency;
- High start-up torque;
- Smooth drive torque;
- Low cost;
- Low unsuspended wheel mass;
- Sufficient traction;
- High power performance in a wide temperature range;
- Robustness and reliability.

This paper will investigate the feasibility of the hydraulic hybrid, further refered to as 'Hydrid' /1, 2/. Hydraulic transmissions are applied for many years in construction equipment and earthmoving machines, a domain which is more demanding than on-road applications and much more demanding than the generally stationary applications of electric transmissions. Also, the power and torque density of hydraulic pumps and motors is much higher than of electric machines. Key to the Hydrid is the development of the floating cup principle /3, 4/ for hydraulic pumps, motors and transformers /5, 6/. Based on this principle, motors can have a smooth torque output with minimal torque losses, especially at start-up conditions. Also, efficiency measurements have proven the high efficiency /7/ and the low noise and pulsation levels of the floating cup machines.

The idea behind the Hydrid is to reduce the fuel consumption of a vehicle by:

- Stopping the engine whenever this is possible, thereby eliminating idle losses;
- Recuperating the kinetic energy of the vehicle during braking;
- Improving the average efficiency of the engine by running it at high loads only.

Start-stop control of the engine and energy recuperation can also be achieved with parallel hybrid systems. But serial hybrid systems are much better in power and energy management. In order to investigate these effects on the fuel consumption of a vehicle, a simulation model of a mid-class Volkswagen Passat sedan with a Hydrid transmission has been built by the German Institute for Fluid Power Drives and Controls (IFAS) at RWTH Aachen University. This paper describes the results of the study.

2 Vehicle and drive cycle

In Europe, the New European Driving Cycle (NEDC; see the top diagram of Figure 3) is generally used for specifying the specific fuel consumption and CO_2-emission of vehicles. The NEDC is also used for evaluating the Hydrid. This allows a direct comparison with the data for a conventional vehicle, as given by the car manufacturer. The results of the simulations are compared to the specific fuel consumption and CO_2-emissions of a Volkswagen Passat sedan with a range of drive train options (see appendix A). The Hydrid transmission was laid out to fulfil the same demands and requirements as the average drive train in the Volkswagen Passat range:

empty curb weight:	m = 1450 kg
maximum traction:	F_{tr} = 4400 N
frontal area:	A_{fr} = 2,26 m^2
drag coefficient:	c_w = 0,26
dynamic wheel diameter:	D = 0,63 m
rolling resistance coefficient:	f_r = 0,008
maximum vehicle speed:	v_{max} = 190 km/h

Table 1: Hydrid car parameters

The maximum traction of the vehicle follows from the requirement that a fully loaded vehicle (including the maximum trailer load) must be able to climb a slope of 12% (from standstill). Although the maximum braking force can be significantly higher than the maximum driving force, it is assumed that the vehicle will still have foundation brakes and will use these for emergency stops i.e. extreme brake forces. The maximum drive torque that the in-wheel motors of the Hydrid transmission have to deliver can then be calculated to 1408 Nm.

The average installed engine power in the reference vehicle is 100 kW, which is much more than the wheel power required for the NEDC, which uses a maximum of 32,5 kW (during propulsion). During 80% of the cycle the engine needs to deliver less than 10 kW. The strongly reduced engine efficiency at these operating conditions is the most important reason why a vehicle has a high fuel consumption while driving in the city. Especially at this point, the Hydrid aims to improve the fuel economy of the vehicle.

3 Size of the transmission components

Figure 2 shows the simplified hydraulic circuit of the Hydrid transmission, depicting the most important components.

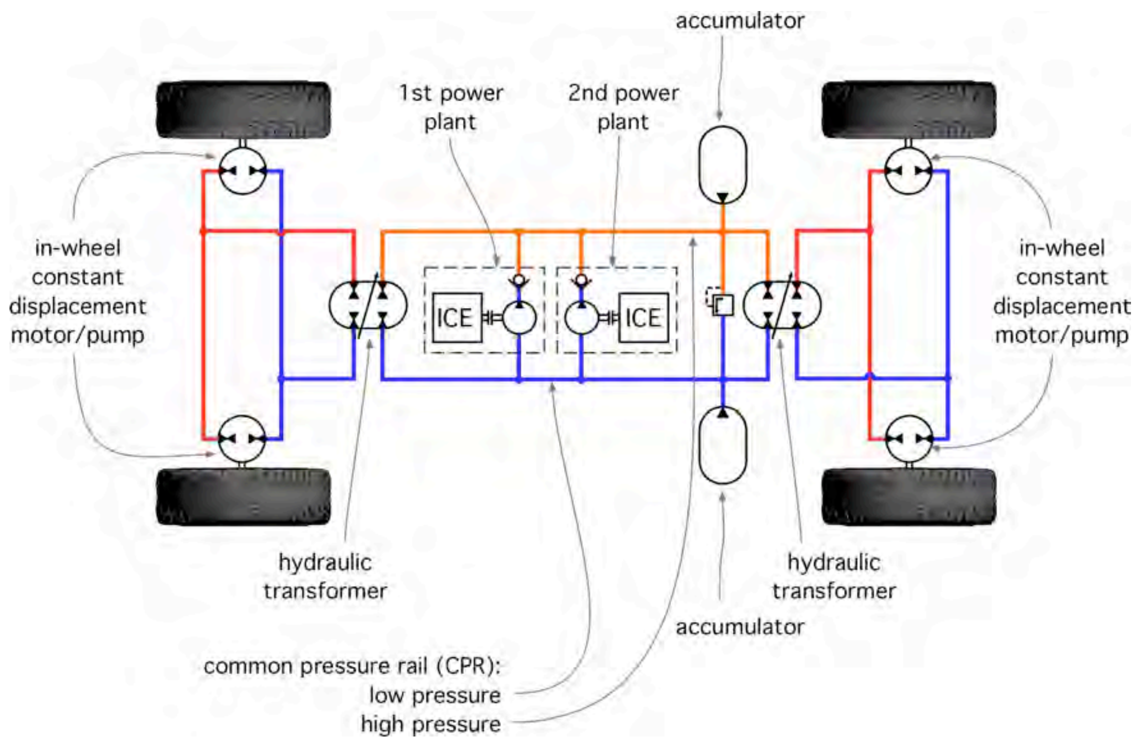


Figure 2: Hydraulic diagram of the Hydrid

The vehicle has two equal internal combustion engines, each having its own constant displacement pump. Both engines have an installed power of 50 kW and a maximum torque of 185 Nm. The complete NEDC can now be performed with only one of the two engine-pump-combinations. The second unit is only needed for situations in which the power demand exceeds the installed power of a single engine-pump-combination. Likewise, it is possible to have all four wheel motors in operation in case the maximum torque is needed, or –during city driving– to switch one of the drive axis off. Furthermore, the in-wheel motors and the transformers do not necessarily need to be equally sized. This analysis will only take one of the many possible configurations of the Hydrid. Table 2 gives the most important dimensions and characteristics of the chosen components.

	pump	**hydraulic transformers**	**in-wheel motors**
quantity	2	2	4
size of each unit	28 cc/rev	60 cc/rev	45 cc/rev
maximum Δp	400 bar	CPR-side: 420 bar motor-side: 500 bar	500 bar
maximum rotational speed	4500 rpm	3000 rpm	1600 rpm

Table 2: Dimensions and characteristics of the hydrostatic components of the Hydrid

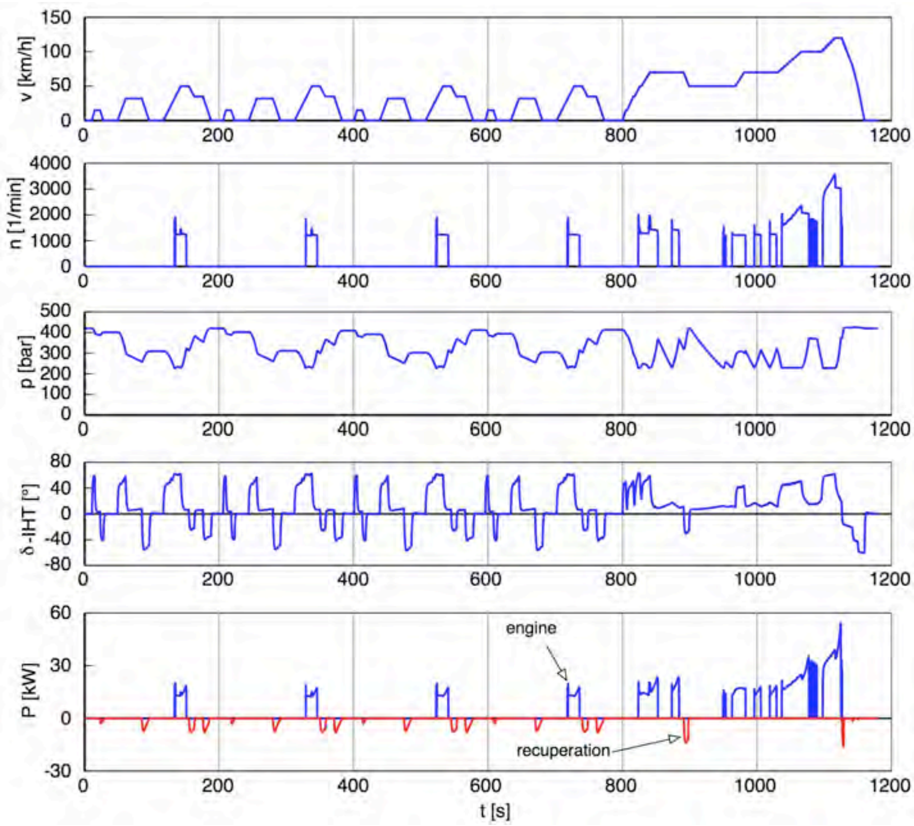
The in-wheel motors directly drive the wheels, without any gear transmission. The maximum pressure level of the in-wheel motors is assumed to be 500 bar. With all four motors having a displacement of 45 cc/rev, the maximum theoretical torque is 1432 Nm. Normally, hydraulic motors suffer severely from stiction, which strongly reduces the torque at brake-away conditions. Furthermore, most motors have a limited number of pistons (or other displacement volumes). This results in a large variation of the drive torque of these motors. The floating cup principle however has 24 pistons and therefore a torque variation of only 1,4%. Floating cup machines also have hardly any coulomb friction, and the torque delivered by the floating cup motors is almost equal to the theoretical torque.

Several simulations have been run, investigating the influence of the size of the accumulators, the number of axis driven (2-wheel drive or 4-wheel drive) and various sizes of the hydrostatic components. In the following paragraphs, the vehicle is driven by a single axis having one of the hydraulic transformers completely shut off.

Furthermore, only one engine-pump-combination is in operation. This is enough for driving the NEDC. The cycle simulation is performed with a 20 litre accumulator, which can be charged to a maximum pressure of 420 bar. In the simulation, the compression and expansion of the nitrogen volume in the accumulators is assumed to be adiabatic. Flow losses are however accounted for.

4 Cycle analysis

The simulation starts and ends with a completely charged accumulator (figure 3; see the third diagram). During the first 134 seconds, the vehicle can run completely on the stored energy in the high-pressure accumulator. As soon as the pressure level in the accumulator drops below a certain value, the engine is started and supplies energy to the vehicle until the point where the vehicle decelerates again and the brake energy is recuperated, thereby charging the accumulator again.



- Vehicle velocity v
- Rotational speed n of the engine and the pump
- Pressure level p in the high-pressure accumulator
- Control angle δ of the hydraulic transformer
- Engine power and hydraulic power during recuperation

Figure 3: Simulation results of the Hydrid during the NEDC

During the entire NEDC, the engine is in operation for only 19% of the time. The rest of the time it is shut off. Only at the end of the cycle, the full installed power of one of the engine-pump-combinations is needed (see the last curve of figure 3). In the Hydrid, the speed control of the vehicle is shifted from the engine to the transformer. The fourth curve in figure 3 shows the angular position of the port plate of the hydraulic transformer, relative to the top dead center. A positive value of the control angle results in the propulsion mode of the in-wheel motors. With negative control angles of the transformer, the pressure differential across the motor becomes negative and the in-wheel motors start working as pumps, thereby supplying power back to the high-pressure accumulator while braking the speed of the vehicle. As in all serial hybrid transmissions, the energy storage has to follow the power transients of the vehicle. More than a need for storing energy, there is the need for handling power. Hydraulic accumulators are much better at this than batteries.

5 Fuel consumption and CO_2-emissions

For the entire NEDC the Hydrid vehicle has a total fuel consumption of 0,338 litres. At a total travelled distance of 11,02 km this amounts to a specific fuel consumption of 3,1 l/100 km (Table 3).

	Fuel consumption:	CO2-emission:
city	1,8 l/100km	49,2 g/km
highway	3,8 l/100km	102,2 g/km
combined	3,1 l/100km	82,7 g/km

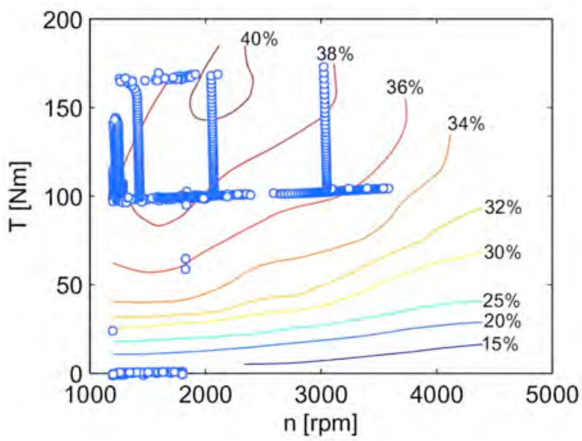
Table 3: Specific fuel consumption and CO_2-emission of the Hydrid during the NEDC

Contrary to conventional drive trains, the city cycle does not result in a higher fuel consumption per 100 km than the highway driving. On the contrary, driving in the city now results in a lower fuel consumption. This is to be expected from any efficient vehicle drive train since the higher velocity at highway driving results in more drag losses. The good fuel economy of the Hydrid is achieved in several ways:

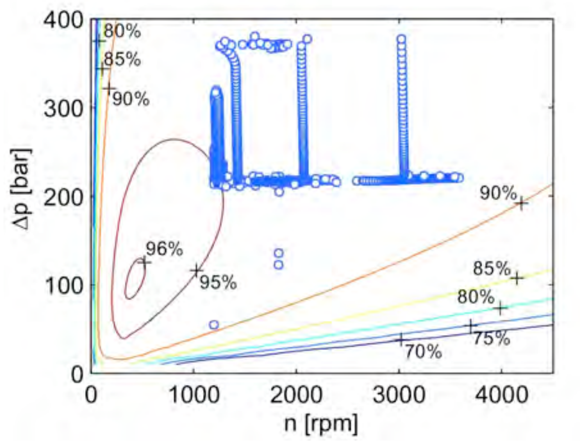
- Shutting the engine off when idling (81% of the time)
- Recuperating brake energy (about half of the energy that can be recuperated during the NEDC is stored in the high-pressure accumulator)
- Forcing the engine to run at high efficiency

Furthermore, the efficiencies of the transmission components (pump, accumulators, transformers and in-wheel motors) are higher than of their electric equivalents. The high power and torque density of the hydraulic components and the elimination of the mechanical drive train keep the vehicle weight low.

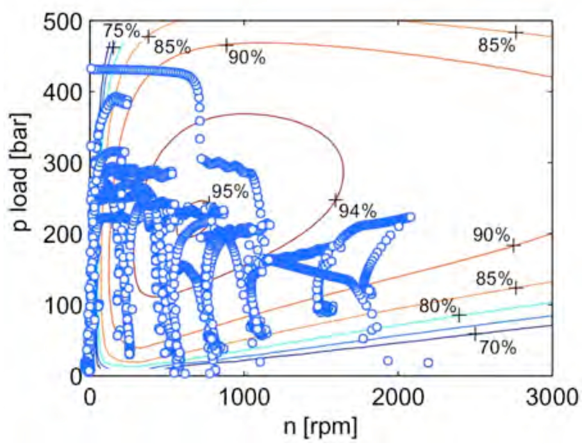
The high efficiencies of the engine and the main transmission components are shown in Figure 4. The contour plots also show the points of operation during the NEDC with a time interval of 0,2 seconds. The engine efficiency is derived from the data of the OM 639 diesel engine of the Mercedes Benz A-class [8]. In the Hydrid, the engine is in principle always forced to run at a high load (figure 4a). For this engine, this results in an average engine efficiency of around 37%.



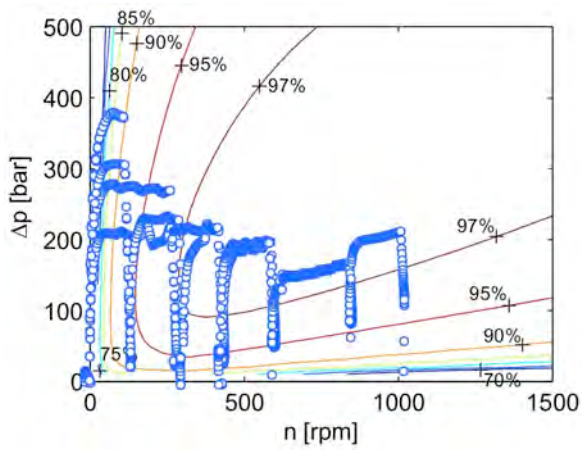
4a: internal combustion engine



4b: main pump



4c: hydraulic Transformer



4d: in-wheel motor (propulsion mode)

Figure 4: Efficiency maps and points of operation during the NEDC

The efficiency maps of the hydrostatic components are derived from the efficiency measurements on a 28 cc floating cup pump /7/. The average cycle efficiencies can be found in Table 4. As with the engine, the pump is only in operation when this is needed for charging the accumulator. For the transformer and the in-wheel motors the average efficiency is differentiated for propulsion and braking modes. During propulsion, the total transmission (pump, transformer and motors) has an average efficiency of 82,6%. While braking, the combined average efficiency of the motors and transformers is 87,2%. Compared to the amount of energy which is delivered by the engine, 15% is recuperated to the high-pressure accumulator during braking. Theoretically, this amount could be doubled if more energy could be stored in the accumulator, for instance by means of changing the control algorithm for charging the high-pressure accumulator.

Component	Mode	Efficiency
pump	Non-idling	94,0%
hydraulic transformer	propulsion	91,2%
	braking	92,7%
in-wheel motors	propulsion	96,3%
	braking	94,0%

Table 4: Average NEDC-efficiency

The simulation does not take the energy consumption for starting the engine into account. Also the energy needed for controlling the hydraulic transformers, as well as the power consumption for auxiliaries are not taken into account. Furthermore, some of the auxiliaries, like cooling fans, will increase the fuel consumption. But there will also be secondary beneficial effects of the hydraulic transmission that will reduce the fuel consumption, for instance switching from an open centre to a closed centre power steering system. Finally, the control of the engine i.e. of the pressure level in the high-pressure accumulator is not yet optimized.

6 Conclusion

The fuel consumption and CO_2-emission has been calculated for a mid-sized car, based on the Volkswagen Passat sedan. The figure below shows the fuel consumption and specific CO_2-emission of the petrol and diesel versions of the Passat, compared to the specific fuel consumption and CO_2-emission of the vehicle with the Hydrid transmission. It can be concluded that, with state-of-the-art hydraulic components, a very efficient serial hybrid transmission and drive train for on-road vehicles can be achieved. The simulation shows that the fuel consumption (and the related CO_2-emission) is reduced during the city part as well as during the highway part of the NEDC.

The European Commission has recently announced CO_2-emission limits for new passenger cars /9/. The proposal sets mandatory targets from 2012 onwards to an average maximum level of 130 g/km. The European Parliament also insisted on the second step to be taken in view of the longer-term target: the average new car fleet should reach 95 g CO_2/km by 2020 and possibly 70 g CO_2/km by 2025 subject to a confirmation or review by the Commission no later than 2016.

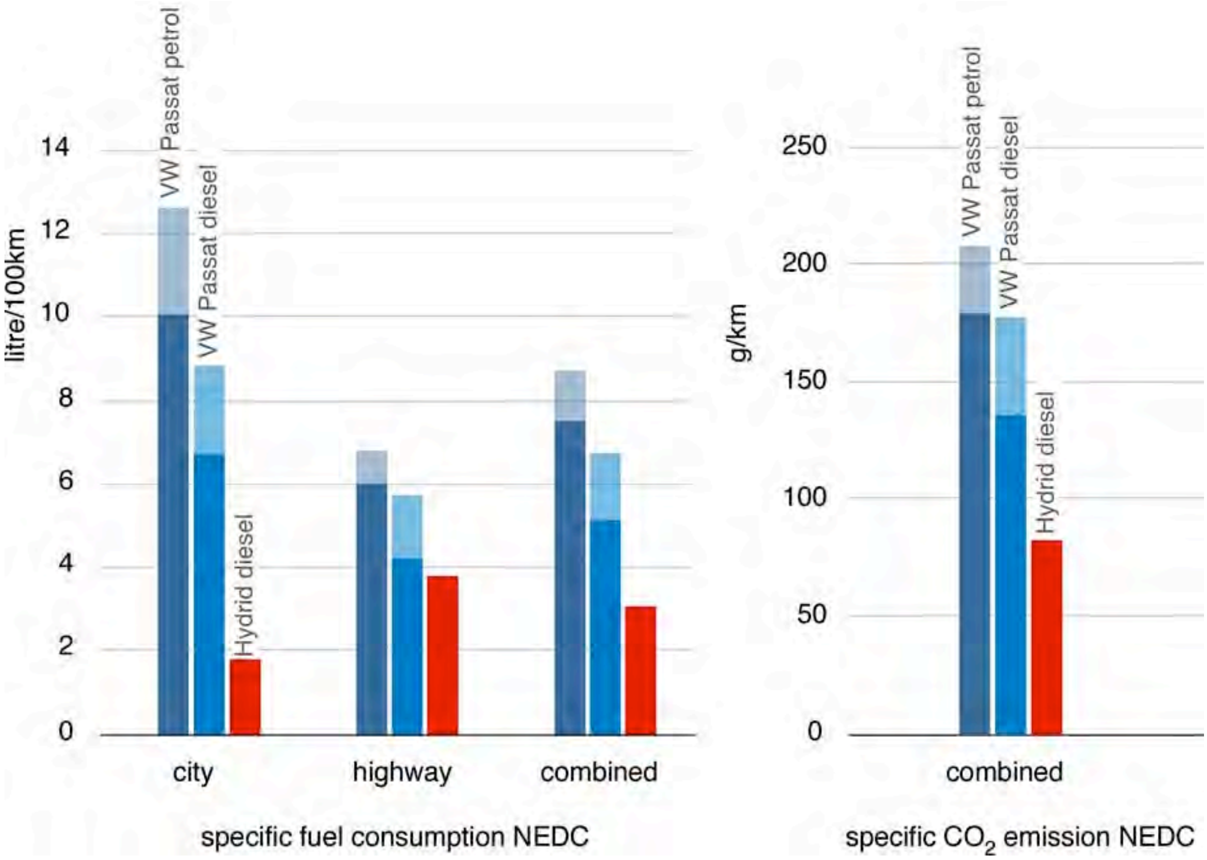


Figure 5: The specific fuel consumption and CO_2-emission of a vehicle with a Hydrid transmission compared to a vehicle with a range of conventional drive trains.

The simulations have shown that the targets set for the year 2012 can easily be achieved with the proposed hydraulic serial hybrid system. It even seems possible to stay below the long-term target limits of the European Parliament. Contrary to the current parallel hybrid electric drive trains, the Hydrid does not add a system to the mechanical drive train. Instead the complete mechanical transmission is replaced, and the total weight and cost of the system is not expected to exceed the weight and cost of a four-wheel drive mechanical transmission. Finally, the Hydrid does not compromise the performance or characteristics of the vehicle but offers an automatic transmission with an all-wheel drive having a variable traction control between the front and rear axis.

7 References

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Appendix A: Data Volkswagen Passat Sedan 2007

Volkswagen Passat sedan 2007	P kW	T_{max} Nm	m kg	v_{max} km/h	fuel consumption city l/100km	highway l/100km	comb. l/100km	CO_2 g/km
P 1.6L 75 kW 5-MT 2WD	75	148	1343	190	10.5	6	7.6	179
P 1.6L FSI 85 kW 6-MT 2WD	85	155	1348	200	10	6.1	7.5	179
P 1.6L FSI 85 kW 6-AT 2WD	85	155	1386	195	10.5	6.2	7.7	184
P 2.0L FSI 110 kW 6-MT 2WD	110	200	1389	213	11.2	6.3	8.1	193
P 2.0L FSI 110 kW 6-MT 4WD	110	200	1492	209	12	6.8	8.7	208
P 2.0L FSI 110 kW 6-AT 2WD	110	200	1418	208	12.6	6.4	8.7	206
D 1.9L TDI-DPF (BlueMotion) 77 kW 5-MT 2WD	77	250	1422	193	6.7	4.2	5.1	136
D 1.9L TDI 77 kW 5-MT 2WD	77	250	1422	188	7.2	4.7	5.6	148
D 1.9L TDI-DPF 77 kW 5-MT 2WD	77	250	1422	188	7.3	4.8	5.7	151
D 2.0L TDI 103 kW 6-MT 2WD	103	320	1454	209	7.8	4.8	5.8	153
D 2.0L TDI-DPF 103 kW 6-MT 2WD	103	320	1454	209	7.9	4.9	5.9	156
D 2.0L TDI 103 kW 6-MT 4WD	103	320	1554	204	8.7	5.5	6.6	174
D 2.0L TDI 103 kW DSG 2WD	103	320	1476	206	8.7	5.3	6.5	172
D 2.0L TDI-DPF 103 kW 6-MT 4WD	103	320	1554	204	8.7	5.7	6.7	177
D 2.0L TDI-DPF 103 kW DSG 2WD	103	320	1476	206	8.8	5.4	6.6	175
D 2.0L TDI-DPF 125 kW 6-MT 2WD	125	350	1457	223	7.9	5.2	6.1	160
D 2.0L TDI-DPF 125 kW DSG 2WD	125	350	1479	220	8.5	5.4	6.5	172

two-wheel drive (2WD) or all-wheel drive (4WD)

transmission: MT = manual transmission
AT = automatic transmission
DSG = direct shift or dual-clutch gearbox

engine power [kW]

engine type: FSI = Fuel Stratified Injection
TDI = Turbocharged Direct Injection
DPF = Diesel Particulate Filter

engine displacement volume (liter)

fuel: P = petrol
D = diesel