Evaluation and optimization of innovative hybrid drives

Introduction

The electrification of the powertrain is one of the most significant developments to reduce energy consumption and emissions. Hybrid drives will play an important role at reducing fuel consumption and local emissions in the near future.

Today's hybrid drives are usually extensions of existing, conventional powertrains (add-on solution). This is because the market share of hybrid drives is currently relatively low and thus the development of Dedicated Hybrid Transmissions (DHT) is not economical yet. However, with rising hybrid sales in the future, developments of DHT concepts are necessary because the full potential of hybrid technology can be achieved only with DHT. DHT can potentially improve fuel economy, lightweight, emissions and space requirements as well as costs comparing to existing add-on solutions.

Within this publication, therefore, a new DHT concept is presented and compared with a common P2 hybrid (add-on solution). The properties of both concepts in terms of performance and efficiency are analyzed and evaluated.

Powertrain synthesis

At the Institute of Automotive Engineering of the TU Braunschweig (IAE), a tool for synthesizing various vehicle transmissions was developed. Countershaft transmissions like manual transmissions (MT), dual clutch transmissions (DCT) and transmissions in planetary design such as automatic transmissions (AT) and Dedicated Hybrid Transmission (DHT) for conventional, hybrid and electric vehicles can be synthesized. Examples of identified and developed transmissions are shown in Figure 1.

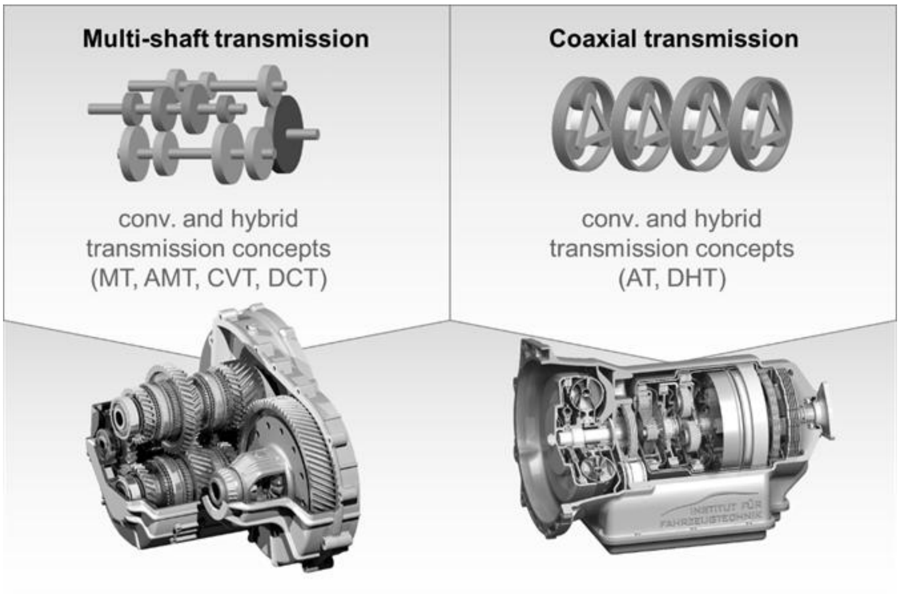

Figure 1: Transmission synthesis at the Institute of Automotive Engineering (IAE)

An essential part of the tool is the systematic evaluation of the determined transmissions. The evaluation and selection of the optimal transmissions are carried out on the one hand based on the transmission characteristics such as the gear ratio number, gear ratio, gear-set structure or loads in the transmission. On the other hand, the transmission will be considered and evaluated in the context of the entire vehicle. This is particularly important for hybrid transmissions, since the traditional evaluation methods can be only partially used for a hybrid transmission. Besides the transmission efficiency, the critical operating modes and points and other important properties are determined in the whole vehicle simulation. Given the intense development of hybridization at IAE, a lot of transmission concepts are analyzed to identify and design the optimal transmission for the hybrid powertrains.

In this paper a compact class car with a plug-in hybrid (PHEV) powertrain will be investigated. In total, more than 2,000 different DHT concepts were found and evaluated according to the number of necessary switching elements, realized gear ratios and driving modes. In this publication, the limit on the number of shift elements is set to four in order to meet package requirements. The concepts must offer at least three ICE solo modes (operation exclusively with the internal combustion engine), two EM-solo modes (drive exclusively with one or more electric motors) and an eCVT mode. If these criteria are not met, the concept will be rejected.

The DHT concept which will be investigated in this paper is schematically illustrated in Figure 2.

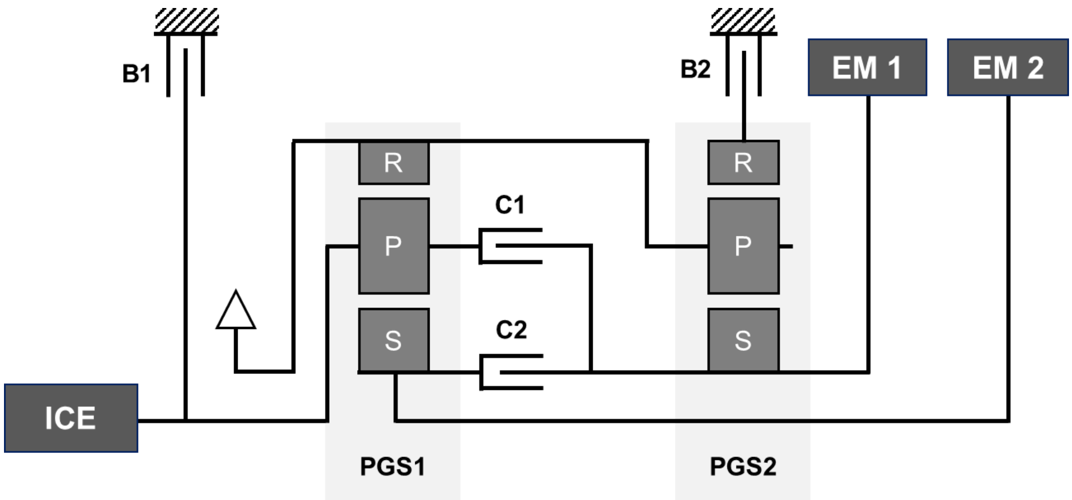

Figure 2: DHT transmission with two planetary gear-sets, four shift elements and two electric motors

The transmission consists of two planetary gear-sets and a total of four shift elements, including two disc clutches C1 and C2 and two disc brakes B1 and B2. Two electric motors (EM1 and EM2) are each coupled to a sun gear. The internal combustion engine (ICE) is connected without a clutch to the carrier of the first planetary gear-set.

Compared to common P2 hybrid transmissions the DHT concept offers significantly more operating modes and flexibility. Overall, with the transmission structure shown in Figure 2, three parallel hybrid and three EM-solo modes and an eCVT mode were realized. Thus, the illustrated transmission has seven modes ("gears"). The following basic parameters of the DHT concept were chosen:

Table 1: Basic parameters of DHT concept

		EM1	EM2	ICE
Max. speed	[1/min]	12,000	12,000	6,000
Max. torque	[Nm]	168	305	160
Max. power	[kW]	48	87	75

In the first step, the coverage of the vehicle demand map is investigated by calculating the delivery maps for each driving mode. The following vehicle parameters were chosen:

Table 2: Vehicle parameters

Compact size hybrid vehicle		
m	[kg]	1,400
c_D x A	[m²]	0.59
$\lambda_{average}$	[-]	1.03
F_{Fric}	[N]	45
f_R	[-]	$8 \cdot 10^{-3}$

The achievable driving range in each operation mode is shown in Figure 3 separately for the EM-solo (above) and the parallel hybrid as well as eCVT (below) modes. In "EV-1" mode, the vehicle is propelled with EM1 and EM2. Thus, high traction forces can be achieved up to speeds of 170 km/h. In the mode "EV-2", the vehicle is driven exclusively by EM2, which can also reach a speed of 170 km/h, but with lower traction forces compared to "EV-1". The demand map is completely covered up to 170 km/h with these two modes. In mode "EV-3" the vehicle is driven exclusively by EM1. Theoretically, the vehicle can reach in this mode very high speeds but with low traction forces.

In pure internal combustion engine modes (without EM support) a speed range from 20 to 200 km/h can be covered. Above 50 km/h a satisfactory coverage of demand map is given but below 50 km/h no high traction forces can be generated. However, through the combined operation with EM2 high traction forces and a complete coverage of the demand map can be achieved.

In eCVT mode, all three drive machines are working together. EM1 is used to vary the speed of the ICE continuously so at any vehicle speed the ICE speed can be adjusted with high flexibility. The driving experience is comparable to a conventional CVT. Simultaneously, the EM2 can support depending on driver's wish in order to boost performance or charge the battery by load point shift (LPS).

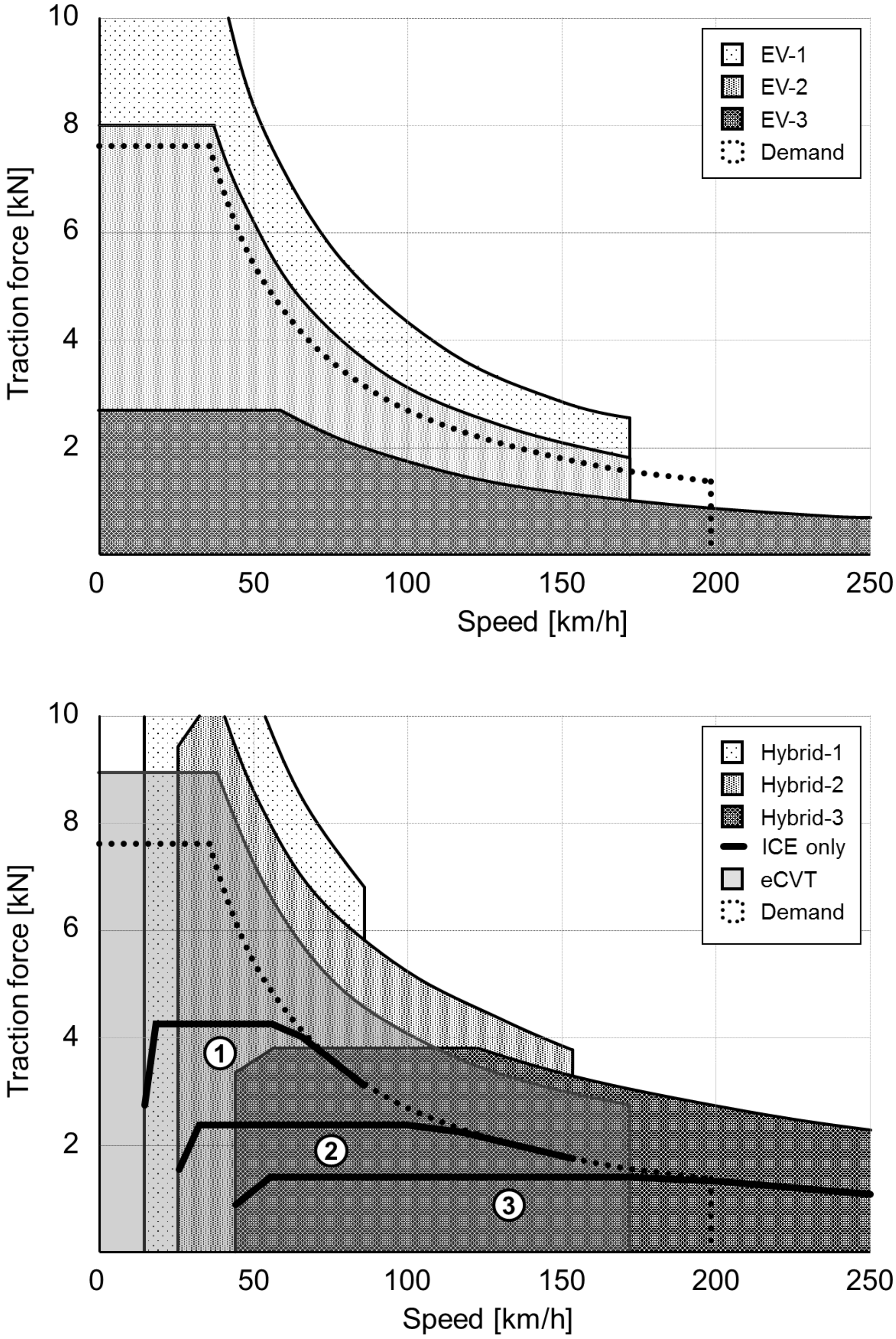

Figure 3: Operation modes and delivery maps of DHT transmission

By utilizing the realized DHT driving modes, a full coverage of the demand map is achieved. At the same time, in most driving situations all three driving modes (ICE, EV, eCVT) are available, so the best operating point can be selected at each of the propulsion machines with the help of the operation strategy. This leads to a reduction in energy / fuel consumption and improved drivability at the same time.

Modular Simulation Model

For the evaluation of powertrains in terms of efficiency and performance, a modular simulation model for all kinds of powertrain concepts and topologies (conventional, electrical and parallel hybrid) was developed. It was designed to evaluate and optimize results out of the powertrain or transmission synthesis.

The model is basically a reverse simulation. The module "wheel" includes vehicle parameters and the driving cycle. From these boundary conditions, the driving resistances can be calculated, which define the output torque and the output speed of the transmission module. The transmission module includes the mathematical description of the transmission including mechanical connections, defined shift elements and the transmission operating modes. In addition, the transmissions efficiency is modeled by loss maps. This is determined in advance by means of a transmission loss calculation and then integrated into the whole vehicle model. Furthermore, the transmission module can include up to nine integrated electric motors, so not only conventional but also hybrid transmissions such as dedicated hybrid transmissions (DHT) can be simulated. In the transmission module all possible operating point combinations are calculated for each driving mode. This results in the required speeds and torques of the transmission input which defines the output of the launch element module, which is directly connected to the transmission module. The launch element can be a disc clutch, a torque converter or a direct connection. The input conditions of the launch element are finally the boundary conditions for any parallel combination of ICE and another EM (conventional, electric, parallel hybrid). The efficiency behavior of the EMs and the ICE are also modeled using static loss maps. Figure 4 shows the structure of the simulation model schematically.

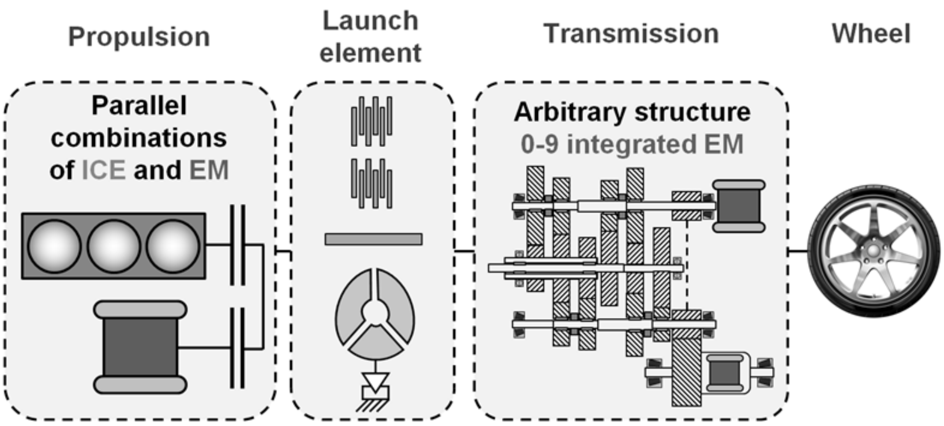

Figure 1: Modular simulation model

The selection of the best operation point is performed by the operation strategy. In order to realize a modular solution and achieve a very good fuel economy for all concepts, the equivalent consumption minimization strategy (ECMS) is used. This strategy also includes an SOC neutral operation by iterative adjustment in the driving cycle. The idea behind the ECMS is to minimize an equivalent fuel consumption, which is composed by the petrochemical (E_{Tank}) and electrochemical ($E_{Battery}$) energy. In order to ensure a SOC neutral operation, the electric energy must be originally converted from fuel. Therefore, the energy from the battery is weighted by an equivalence factor. The matching ratio is achieved by iterations of the cycle simulation. To increase the reliability of a SOC neutral solution, the SOC deviation is included in the weighting of the two energies. Basically, the following equation can be applied:

$$E_{Equivalent} = E_{Tank} + (k_{E1} + k_{E2} \cdot \Delta SOC) \cdot E_{Battery}$$

The ECMS was extended by additional criteria to meet limitations of operation mode selections. For example, minimum running durations for the ICE or time restrictions for operation modes can be considered. Moreover, constraints can be set to prevent or to enforce certain state changes. For example, in order to chance the transmission mode, a maximum of two shifting elements may be operated simultaneously. Additionally, there are comfort criteria for ICE speed gradients. The parameterization of the ECMS is realized both globally and concept-specific. This means that there are general, global rules that apply for all considered concepts. In addition, concept-specific constraints may also be defined, which are specifically determined for the characteristics of the powertrain concept.

Simulation parameters

In the following the simulation parameters which are used in this paper will be described. Here, a compact vehicle is simulated, with the parameters listed in table 2 and used for the static analysis of the demand and delivery maps.

For the following studies the DHT concept is compared to an common P2 topology with an 8-speed DCT. The basic parameters of the P2 concept are listed below:

Table 3: Basic parameters of the P2 hybrid

		EM	**VKM**
Max. speed	[1/min]	6.000	6.000
Max. torque	[Nm]	350	160
Max. power	[kW]	50	75

For the selection of the optimal drive concept full factorial parameter variations are done, whereby the basic parameters differ in both concepts. For the P2 hybrid the transmission spread will be varied while maintaining the ratio of the 1st gear and the same progression factor. In addition, the final drive ratio is also varied. The speed range of the EM was assumed congruent to the ICE, so only the torque of the EM was scaled.

For the DHT concept the ratios of both planetary gear-sets (PGS) are varied. In addition, there is a variation of the EM maps in terms of speed and torque ranges. This is necessary because the EM are connected with different ratios to the transmission and their speed range is also important in eCVT mode. Additionally, the final drive ratio is adjusted. Overall, for the specified basic parameter variations, the DHT leads to significantly more parameters configurations compared to the P2 hybrid. Table 4 shows the varied basic parameters including their limits of variation for both concepts.

Table 4: Basic parameters variation of hybrid concepts

P2 Topologie		DHT Konzept	
EM torque	100-240%	EM1-speed	80-120%
Spread	100-130%	EM1-torque	80-120%
Final drive ratio	80-120%	EM2-speed	80-120%
		EM2-torque	80-120%
		PGS ratio 1	80-120%
		PGS ratio 2	80-120%
		Final drive ratio	80-120%

To determine the optimal concept legal cycles were not used because these do reflect real customer operation inadequately. With the 3D methodology (**D**river, **D**riven vehicle and **D**riving environ) developed at the Institute of Automotive Engineering, customers operation can be collected and characterized systematically. Further, representative cycles will be generated for the design of the powertrain. For this paper a mixed customer cycle based on urban, extra-urban and highway operation of an average driver was generated and used. Figure 5 shows the speed profile.

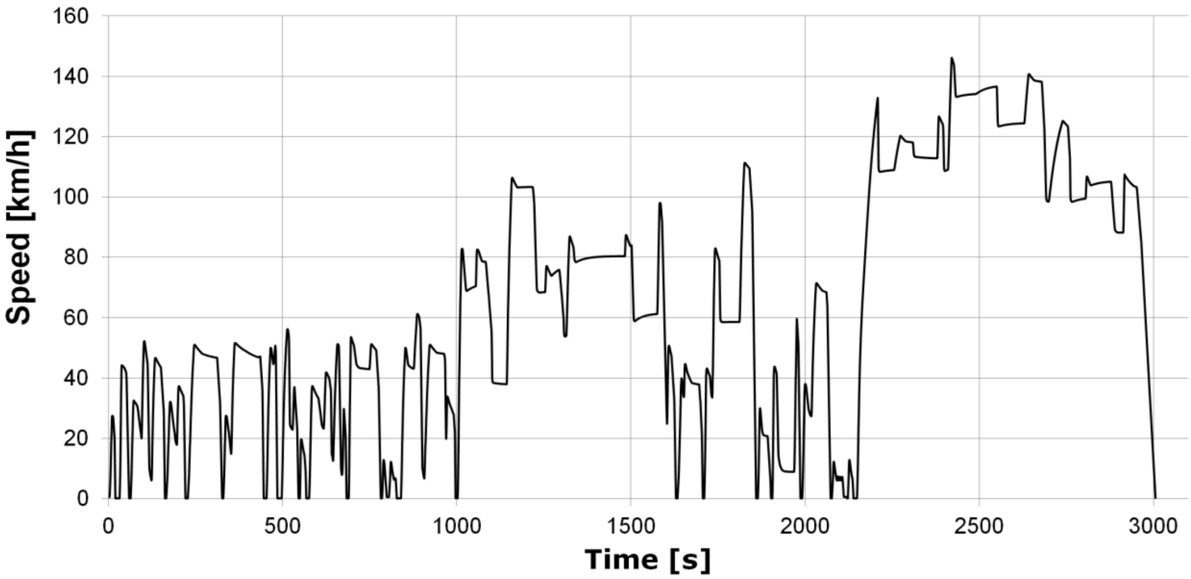

Figure 5: Customer Cycle

The cycle parameters comparing to WLTP are shown in Table 5.

Table 5: Comparison of customer cycle and WLTP

		Customer Cycle		WLTP	
		Traction	Thrust	Traction	Thrust
Total distance	[km]	45.8	7.2	18.3	4.9
Duration	[s]	2,303	613	1,113	461
Distance share	[%]	86	14	79	21
Average acceleration	[m/s²]	0.12	-0.73	0.16	-0.6
Effective speed	[m/s]	27.3	21.5	23.9	17.4
Standstill duration	[s]	91		225	

If the customer cycle is used as a basis for the optimization, an optimal fuel consumption for customer operations is achieved. Nevertheless, a high priority is still on the consumption in legal cycles, since these are relevant for taxilation and the basis for customer comparison. Furthermore, the electric power consumption in legal cycles is relevant, since this affects the electric range and thus the combined CO_2 emissions arising under the legislation. Therefore, the parametric studies are done with the customer cycle and optimal concepts will be selected for further investigations with WLTP.

Comparison of powertrain concepts

The evaluation of the drive concepts are based on the acceleration of 0-100 km/h and fuel consumption in customer operation. Figure 6 shows the results for all calculated configurations that have resulted from the full factorial parameter variations of Table 4.

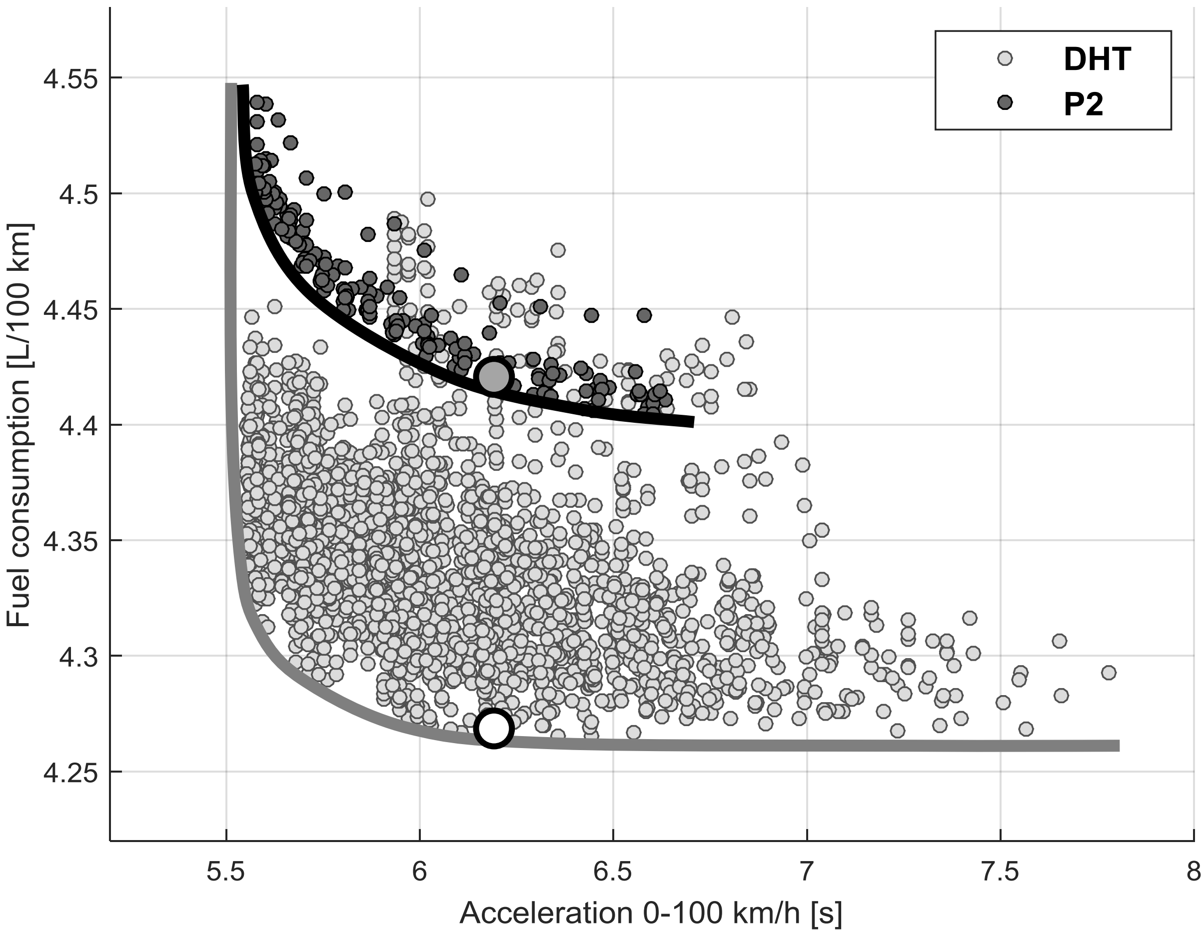

Figure 6: Full factorial parameter variation of DHT und P2

Two pareto fronts can be identified among the results in Figure 6. These fronts describe the best compromise between these two characteristic parameters. It can be seen that the DHT concept offers a better compromise between acceleration and efficiency than the P2 concept.

For further investigations two optimal concepts are selected (along the pareto front), where the EM2 of the DHT has the same power as the EM in the P2 concept. In each case, the same ICE and the optimal transmission parameters, which were determined in the customer cycle, are used. The two concepts are presented in the following table:

Table 6: Simulation results optimal concepts

		DHT		P2	
		EM1	**EM2**	**EM**	
Max. speed	[1/min]	12,000	12,000	6,000	
Max. torque	[Nm]	134	244	525	
Max. power	[kW]	38	70	70	
		Efficiency			**Δ [%]**
$B_{S,Kundenzyklus}$	[l/100km]	4.27		4.42	- 3.4
		Performance*)			**Δ [s]**
$t_{acc\ 0\text{-}100km/h,\ hybrid}$	[s]	6.2		6.1	+ 0.1
$t_{acc\ 0\text{-}100km/h,\ ICE\ only}$	[s]	10.8		10.3	+ 0.5
$t_{acc\ 0\text{-}100km/h,\ electric}$	[s]	7.3		10.1	- 2.8

*) No limit by battery power

These results are valid in case the battery power is sufficient to supply both EM in the DHT. Given the current state of the technology, this is not necessarily the case. However, the potential of the DHT concept can be recognized if there is enough battery power available. In particular, the electric performance is improved significantly by the second EM, which enables DHT to accelerate 2.8 s quicker than the P2. In hybrid mode, the additional EM is used to adjust the ICE speed, thus the mechanical complexity of the transmission and therefore the transmission losses are reduced.

When considering the acceleration times without battery support (ICE only), it is clear that the speed and torque conversion of the DHT is slightly worse than the P2 hybrid with eight different gear ratios. However, battery boost is available most of the time in a PHEV so this disadvantage is acceptable.

In order to check how the concepts compare in WLTP, additional simulations were done. The results of the energy consumption in hybrid and electric mode are shown in table 6 below.

Table 6: Optimal concepts in WLTP

Parameter	DHT	P2	Δ [%]
$B_{S,WLTP}$ [l/100km]	3.75	3.90	- 3.8
$E_{S,WLTP}$ [kWh/100km]	12.47	13.57	- 8.1

It turns out that the DHT achieves better efficiency in WLTP than the P2 concept. This applies both to the hybrid as well as the electrical energy consumption. The better efficiency in electrical operation is justified because the two electric motors may be used as needed. In certain load ranges the smaller EM offers efficiency advantages over the larger EM. Further, the transmission losses of the DHT are lower than the 8-speed DCT of the P2 hybrid.

Summary and Outlook

In this publication, a method was presented which combines the synthesis of new transmission concepts with a whole vehicle simulation including operation strategy.

It has introduced a new concept DHT, which consists of two sets of planetary gear-sets, four shifting elements and two electric motors. This was compared to a common P2 topology in form of an add-on hybrid.

In order to perform the comparison, full factorial parameter studies were carried out and the pareto fronts of both concepts for hybrid operation were generated. To evaluate the concepts, the acceleration from 0 to 100 km/h and the fuel consumption were analyzed. The parameter studies were not carried out with a usual legal but customer cycle, which was generated using the 3D method. As result, the DHT concept can achieve a better compromise between performance and efficiency. In particular the electric performance was significantly better because of the additional electric motor. In hybrid mode, this EM allows to reduce the mechanical complexity of the transmission, which in turn results in lower transmission losses.

Finally, a P2 and a DHT concept with similar performance along their respective pareto fronts were selected. Both concepts were investigated in terms of fuel and energy consumption in WLTP. The DHT offers better efficiency particularly in electric operation with an advantage of approximately 8% over the P2. The results show that DHT should be preferred over a P2 topology, especially with an increasing degree of electrification.