32nd Electric Vehicle Symposium (EVS32)
Lyon, France, May 19 - 22, 2019

Mastering complexity of future dedicated hybrid powertrains

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Summary

This paper describes a way to right-size powertrain components (battery, e-motor(s), ICE, transmission) to fulfil today's customer requirements in a best possible way by using special IAV's tools for advanced development. Furthermore a new powerful hybrid concept will be derived which enables high performance vehicles with good driving performance and low fuel consumption.

The result of this investigation is a powertrain concept that bases on a gasoline engine combined with an electric motor that is connected to a 4-speed planetary automatic transmission. The target B-segment vehicle may accelerate in around 4 seconds from 0 to 100 kph and consume 4.0 l/100 km gasoline in a drive cycle.

Keywords: HEV (hybrid electric vehicle), parallel HEV, powertrain, energy consumption, vehicle performance

1 Objective of future hybrid drives

Plug-in hybrids offer great potential for meeting future fuel consumption and emission targets and satisfying growing mobility demands. They permit local pollution-free urban travel combined with dynamic performance as well as high driving comfort and range. At the same time, defining the powertrain architecture is getting increasingly complex [1].

In current scenario, the global focus is on drive systems where a hybrid derivative can be derived to the greatest possible extent as a modular, low-cost solution, based on a conventional transmission and using as many carry-over parts as possible. Particularly where high-powered full hybrids are concerned, ideal prerequisites are provided by integrating the electric motor (EM) at the input shaft to the internal combustion engine (ICE) with an additional disconnecting clutch (K0). Essential hybrid functions can be implemented with this kind of P2 arrangement as a parallel hybrid.

Free adaptability of the EM offers advantages compared to the electrically power-split continuously variable transmission (eCVT) with two EMs integrated in the transmission.

The size and output of the electric motor can be changed with minimum impact on the remaining transmission thanks to its structural position and design in the P2 hybrid at the input shaft. Furthermore, – in contrast to the eCVT – the EM power map does not have to correlate with the torque characteristics of the ICE. This warrants on the one hand more efficient use of the electric power for hybrid functions and, on the other hand, more flexible use for various vehicle/ICE combinations.

Pending emission legislations will demand much greater electrification of the vehicle fleet. This puts the motivation for a modular powertrain architecture as described before into perspective. Economies of scale will result in new dedicated hybrid transmissions (DHTs) as a technically and economically appropriate further development of currently available hybrid generations.

A major argument in favor of DHTs is the greater geometrical and functional integration of the EM in the transmission in order to generate further synergy effects in future.

Important aspects here include reducing the number of gears in the transmission, dispensing with the classic mechanical reverse gear and today's K0 clutch. The reduced complexity of the gear set compared to current systems with up to ten gears will help to reduce costs, weight and inertia. These development trends are currently investigated in various studies. [2, 3]

This paper describes the DHT potential as illustrated by a P2 hybrid for high-power applications. A major contribution comes from a new computer-based method for achieving high development safety when devising new technologies. Furthermore, the paper concludes by looking at the chances for future DHTs as P2.5 hybrids.

2 Determining application-optimized powertrains

The growing complexity of future powertrains is currently making engineers rethink conventional development processes that focused primarily on optimization of single powertrain components. Increasing significance is being attached to interaction between individual powertrain components, particularly in hybrid powertrains with high levels of electrification as well as conventional and all-electric systems.

FIGURE 1 shows the development process and illustrates how powertrain configurations are determined with a high overall benefit for implementing the technical and economic requirements. IAV's powertrain synthesis tool plays a central role in the process chain of advance and concept development [1]. This development methods permits systematic generation, analysis and evaluation of all technically suitable powertrain configurations. Every powertrain is based on parameters and maps for ICE, transmission, EM,

energy storage system and vehicle and is examined with regard to drive topology, operating strategy and driving cycles in terms of its properties such as emissions, performance and system costs. The final benefit analysis takes account of limit filters and weighting factors for all computed properties to produce a ranking of the most beneficial powertrain configurations with high overall benefit.

In turn, the determined preferential properties for individual powertrain components form the input values for downstream processes, such as IAV's combustion engine synthesis, transmission synthesis [4] and electric motor synthesis [5], FIGURE 1. On completing the computations, preferred variations are suggested for specific technological implementation of the respective components, which then have to be put into detail in the ongoing development process.

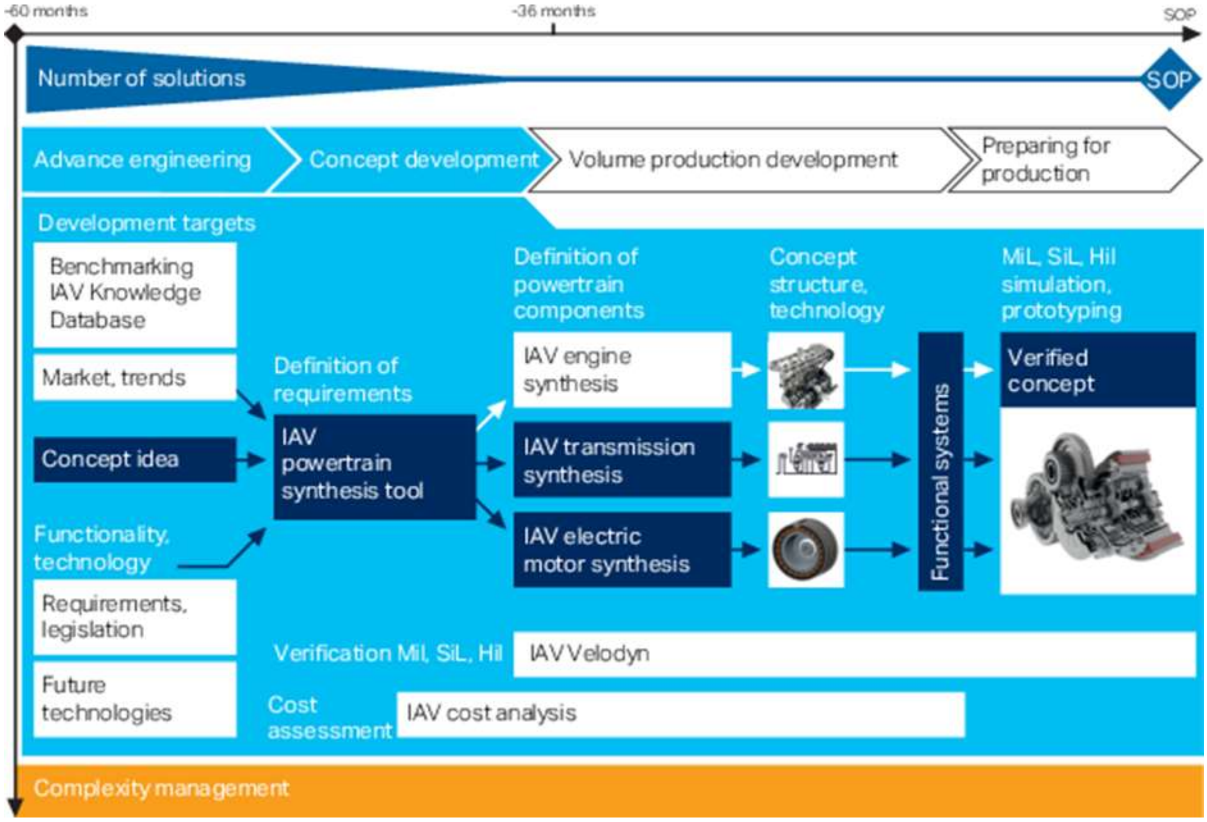


Figure1: Process for determining application-optimized powertrain configurations – dark blue development path as a development process

3 Generation of an efficient plug-in hybrid powertrain

The following looks at the potential and efficiency of this development process as illustrated by a new plug-in hybrid by way of example, as it is shown in FIGURE 1, with the dark blue development path. The study is based on a B-segment vehicle weighing 1.4 t in combination with a powerful 2-l turbo gasoline engine with 213 kW power and maximum torque of 400 Nm. The powertrain is to be designed as a front-transverse architecture with a four-wheel drive option.

The aim is to determine a DHT concept in P2 configuration allowing for vehicle-specific packages. A target vehicle should offer very sporty performance with acceleration to 100 km/h in less than 4 s. On the other hand, fuel consumption rates are to be dramatically reduced compared to commercially available non-hybrid vehicles with comparable performance levels. Other boundary conditions include acceleration in electric mode to 100 km/h in less than 10 s to gather with electric and hybrid maximum speeds of at least 160 km/h and 270 km/h respectively. The electric cruising range is stipulated as 60 km with a battery of 12 kWh energy content and an effective State of Charge (SoC) range of 75 %.

The following results of the powertrain synthesis feature transmissions with 3 to 7 gears, spreads of 3.0 to 9.0, starting ratios from 8 to 16 and transmission ratio series with differing progressions. There are 6,508 transmission variants in this search space. Another 790 electric motor configurations result from incrementing maximum output and maximum torque between 60 and 120 kW respectively 200 Nm and 350 Nm for different variations in efficiency maps. The combination of all parameter variants and maps generates altogether 5.1 million powertrain configurations. FIGURE 2 shows example sensitivities for these studies in the context of cycle consumption and driving performance.

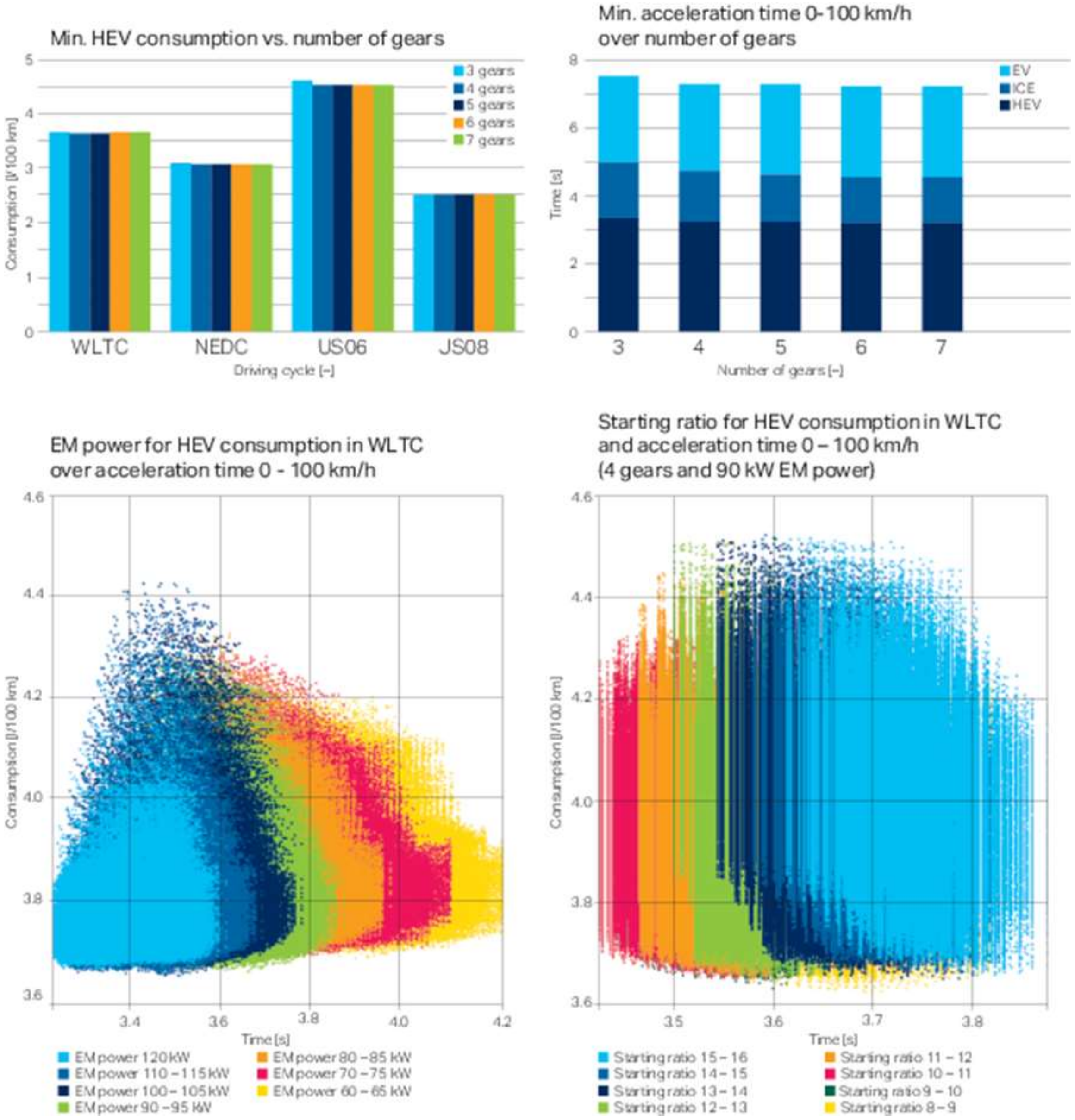


Figure2: Results of the powertrain synthesis – sensitivities in the context of cycle consumptions and driving performances

For the four computed driving cycles WLTC, NEDC, US06 and JC08, minimum consumption in hybrid mode (HEV mode), FIGURE 2 (top left), and acceleration times to 100 km/h in various operating modes, FIGURE 2 (top right), are practically independent of the number of gears. The only slight improvements to be seen are when changing from 3 to 4 gears.

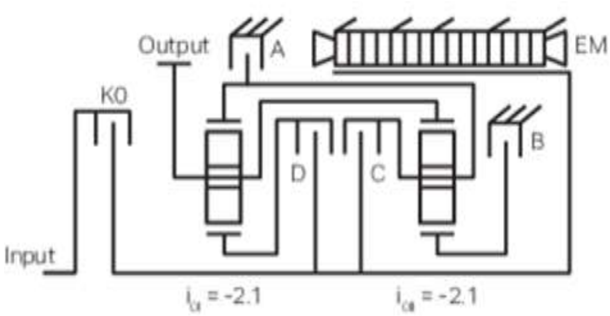
The variation in EM output, FIGURE 2 (bottom left), shows that there are scarcely any further consumption advantages in the WLTC and improvements in acceleration at least to 100 km/h once electric output exceeds 90 kW.

This defines the initial boundary conditions for the new hybrid transmission. Four gears and electric output of 90 kW are necessary to fulfil the requirements. Suitable starting ratios are between10 and 12, FIGURE 2 (bottom right). The benefit analysis results also provide preferred spreads in the gear set of between 4 and 5 with minimum progression impact on the transmission ratio series. Furthermore, electric motors with maximum torques of 250 Nm to 300 Nm and efficiency maps of permanent magnet synchronous machines are shown to be altogether beneficial.

4 Next steps: Transmission synthesis and electric motor synthesis

In the next computation step – the transmission synthesis – the ascertained requirements for the transmission form the input values for systematic, computer-based generation and assessment of new transmission structures for various technologies. The following investigations are limited to planetary automatic transmissions (AT). Concepts with two planetary gear sets and four or five shift elements are appropriate to implement the required functionality, resulting in about 475,000 possible solutions.

The preferred variant shown in FIGURE 3 with two planetary gear sets and four shift elements A to D, two of which are expediently designed as brakes, offers high torque density at comparatively low engine speeds and high gearing efficiency. Stationary gear ratio of -2.1 in each case offer the potential for a radial, compact design and supply a progressive ratio series with starting ratio in the gear set of 3.1 and a spread of 4.6. The additional drive-side clutch K0 permits decoupling of the ICE in electric mode. Thus obviates the need for a conventional reverse gear.



	Brake		Clutch			
Gear	A	B	C	D	i	φ
1	●			●	3.10	1.85
2		●		●	1.68	1.68
3			●	●	1.00	1.47
4		●	●		0.68	

Figure3: Four-gear automatic transmission of the IAV PowerHybrid with two planetary gear sets – transmission structure (left) and shift logic

Similarly, the results of powertrain synthesis can be used in combination with EM synthesis to generate a preferred variant for the permanent magnetized synchronous motors. Comprehensive computation is necessary to maximize torque density without impairing efficiency, torque ripple, power factor or other characteristics. The stipulated package reduces the search space to a few ten thousand geometry variants. The 4,372 benefit analysis solutions shown in FIGURE 4 all fulfil the required general geometrical and technical conditions using typical materials. The preferred variant for design implementation consists of a suitable compromise between total losses, material costs and other characteristics.

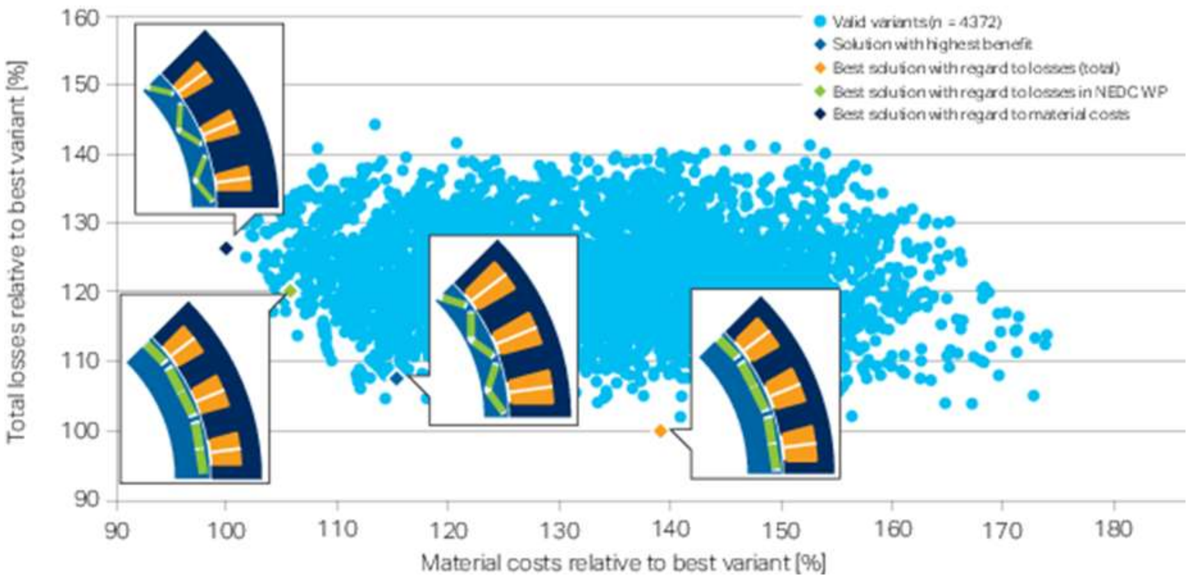


Figure3: Results of the EM synthesis – comparison based on material costs and total losses relative to best variant

These results act as the basis for 3-D design implementation of the IAV PowerHybrid, FIGURE 5, for input torques up to 700 Nm (ICE and EM) and input speeds of up to 7000 rpm. An axle ratio of 3.5 results in a maximum total ratio of approximately 11.

The transmission structure allows high integration of the gear set elements within the EMs rotor with many carry-over parts for reducing costs. The permanent magnet synchronous machine has an active length of 100 mm and a total length of 130 mm. A transmission length of only 360 mm is possible despite the high input torque, and a weight of just about 110 kg including electric motor without operating fluids.

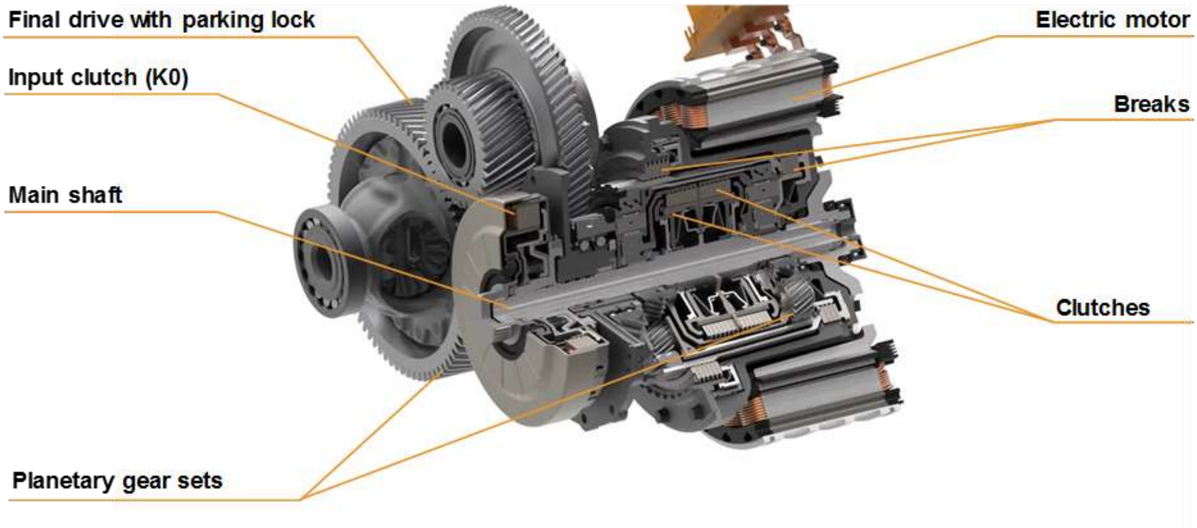


Figure1: 3-D design of the IAV PowerHybrid – despite the high input torque, a drive length of only

5 Conclusion and outlook

The development of future powertrains will have to take account of interaction between the powertrain components as a prerequisite for competitive solutions. IAV's method of powertrain synthesis fulfils the demands made of the individual components for new powertrains like DHTs. Subsequent synthesis programs take these results as the basis for detailed technical implementation of the components for the ICE, transmission and EM.

The development process is demonstrated by a new powerful plug-in hybrid with P2 architecture that offers very sporty performance and low fuel consumption rates.

Further potential for future DHTs consists of connecting the EM to a gear set internal shaft. Such P2.5 hybrid solutions offer additional advantages such as larger transmission ratios between EM, ICE and transmission output. As a result, it is quicker and easier to restart the ICE with the vehicle both stationary and moving, while enhancing traction power in electric mode as well as the boost and recuperation capability with somewhat lower maximum torques at the EM. Rating the electric motor therefore focuses more on its efficiency at cycle-relevant operating points with high time shares instead of maximum torque. This also reduces the package demand of the EM.

For the first time a DHT can be used in P2.5 arrangement with continuously variable transmission ratio between ICE and transmission output with just one electric motor by adding the speeds of both drives with planetary gear sets. This new hybrid function helps,

for example, to improve efficiency when tapping into the primary energy. It is also suitable for flexible drive strategies and new driving modes, including wear free, highly efficient start with the ICE – without a separate start-up element also with minimum SoC of the traction battery – or comfort-focused continuously variable driving as demonstrated by current eCVTs.

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