Synergies among FC and ICE Hybrid Vehicles

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Abstract: The main objective of the ongoing EU project HySys is research and development on fuel cell and E-drive system components. One part of this work is the identification of possible synergies between conventional ICE hybrids and FC hybrids in general as well as between different specific types of FC hybrids in order to reduce development and production cost by the use of common drive train components.

Actually, common components with high synergy effects are electric motors, electric energy storages, inverters, electrically driven auxiliaries and coolant circuit components.

E.g. in view of the electric motor, one approach to reduce production cost and to keep scalability is the use of stators and rotors with different active length using the same iron lamina and diameter. These e-motors can be used in different vehicle classes starting from small passenger cars up to light delivery vehicles. Another solution could be the use of identical electric motors (same dimensions and power) in ICE and FC hybrids. The detailed effects of such common electric motors on the driving performance and the fuel consumption of a selected set of vehicle segments are analysed within this study.

Keywords: Electric drive trains, Fuel Cell Vehicles, Hybrid Vehicles, Simulation models.

1. Introduction

In order to find synergies between FC and ICE Hybrids a stepwise process was applied:

1. A literature research on respective OEM production, concept and research vehicles was executed. As result a detailed Vehicle and Component Specification Data Basis consisting of 15 FC hybrid vehicles and 16 ICE hybrid vehicles was built up.
2. Reference cases in different vehicle classes were defined and common components suitable for the pool of reference vehicles were selected.
3. Simulation models for ICE and FC hybrids were developed in order to analyse, optimize and compare the performance of the vehicles from the selected reference vehicle pool.

To illustrate this process and to comment upon the achieved results, three investigations will be presented:

4. The effects of using modular instead of standard power train components in ICE hybrids and the process of investigation and validation in respect to energy consumption and overall driving performance.
5. The analysis of a concept for extended usage of conventional components for light duty fuel cell vehicles.
6. The analysis of the effect of using e-motors with different active lengths using the same iron lamina.

By systematic and comprehensive optimisation of the drive trains it could be shown that the use of common components offers in addition to the potential of scale effects and cost reductions as well good opportunities for improvements in vehicular efficiency and driving performance.
In order to proof these simulation results, two demonstration vehicles will be built within the Hysys project in 2008/09.

2. Synergies and commonly used hybrid components

2.1 Vehicle and Component Specification Data Basis

A state of the art review of conventional ICE hybrids covers all kind of system layouts like serial, parallel and power split hybrids as well as the classification according to the degree of hybridization with

- Micro Hybrids allowing start-stop functionality for small cars with belt-driven electric motors, a power level of about 2-5 kW and an operating voltage of 14 V.

  Example: PSA C3
- Micro Hybrids allowing start-stop and regenerative braking functionality for all classes of cars with belt-driven or crank-shaft mounted electric motor, a power level of 4-8 kW and an operating voltage of 42 V

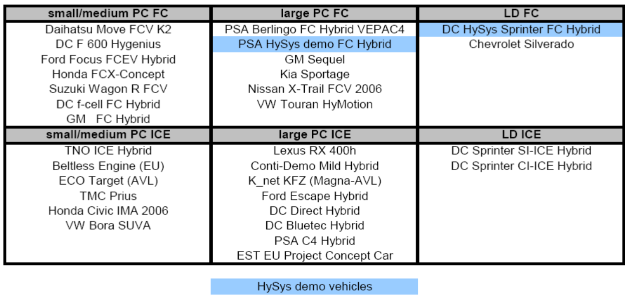
  Example: GM Silverado

- Moderate Hybrids with start-stop, regenerative braking and power assist functionality. The electric motor is crank-shaft mounted. The power range is about 12-30 kW with an operating voltage in the range of 40 to 150 V.

  Example: Honda Civic
- Full Hybrids (150– 600 V) with extended power assist and pure electric drive capability. Crank-shaft mounted electric motor 25-60 kW and an operating voltage in the range of 150 to 600 V.

  Example: Toyota Prius/ Escape

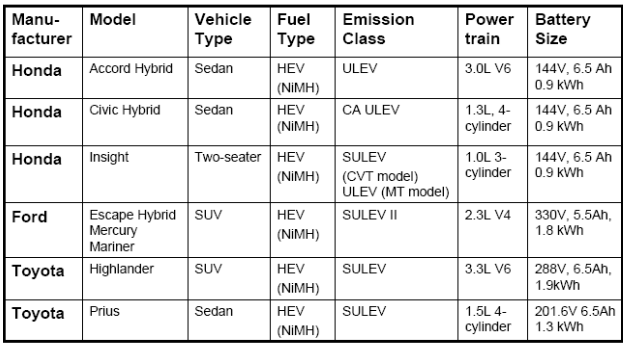
At the end a sample of 16 ICE Hybrids and 15 FC Hybrids were selected as basis for the detailed data collection in the component specifications process (Figure1).



small/medium PC FC	large PC FC	LD FC
Daihatsu Move FCV K2 DC F 600 Hygenius Ford Focus FCEV Hybrid Honda FCX-Concept Suzuki Wagon R FCV DC f-cell FC Hybrid GM FC Hybrid	PSA Berlingo FC Hybrid VEPAC4 PSA HySys demo FC Hybrid GM Sequel Kia Sportage Nissan X-Trail FCV 2006 VW Touran HyMotion	DC HySys Sprinter FC Hybrid Chevrolet Silverado
small/medium PC ICE	**large PC ICE**	**LD ICE**
TNO ICE Hybrid Beltless Engine (EU) ECO Target (AVL) TMC Prius Honda Civic IMA 2006 VW Bora SUVA	Lexus RX 400h Conti-Demo Mild Hybrid K_net KFZ (Magna-AVL) Ford Escape Hybrid DC Direct Hybrid DC Bluetec Hybrid PSA C4 Hybrid EST EU Project Concept Car	DC Sprinter SI-ICE Hybrid DC Sprinter CI-ICE Hybrid

HySys demo vehicles

Figure 1: Selected ICE and FC Hybrid Vehicles for the Component Specification Data Basis



Manu-facturer	Model	Vehicle Type	Fuel Type	Emission Class	Power train	Battery Size
Honda	Accord Hybrid	Sedan	HEV (NiMH)	ULEV	3.0L V6	144V, 6.5 Ah 0.9 kWh
Honda	Civic Hybrid	Sedan	HEV (NiMH)	CA ULEV	1.3L, 4-cylinder	144V, 6.5 Ah 0.9 kWh
Honda	Insight	Two-seater	HEV (NiMH)	SULEV (CVT model) ULEV (MT model)	1.0L 3-cylinder	144V, 6.5 Ah 0.9 kWh
Ford	Escape Hybrid Mercury Mariner	SUV	HEV (NiMH)	SULEV II	2.3L V4	330V, 5.5Ah, 1.8 kWh
Toyota	Highlander	SUV	HEV (NiMH)	SULEV	3.3L V6	288V, 6.5Ah, 1.9kWh
Toyota	Prius	Sedan	HEV (NiMH)	SULEV	1.5L 4-cylinder	201.6V 6.5Ah 1.3 kWh

Figure 2: Example of an excerpt of the data collection sheet for the commercially available full hybrids in USA (Status Feb. 2006)

The whole Data Basis covered all information necessary for the simulation and comparison process:

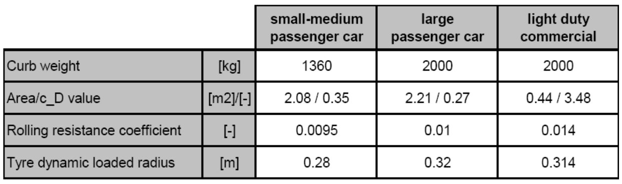
- Vehicular Design Parameter
- Vehicular Performance Data
- Driveline Components
- Auxiliaries
- E- Motors and Generators
- E- Converter
- Batteries and Fuel Cells
- Cooling System

2.2 Reference Cases and common components

All major performance figures for the vehicles and components were compared and clustered in reference cases with average values regarding the weight, power, performance etc.
In total a pool of 9 reference vehicle types defined:

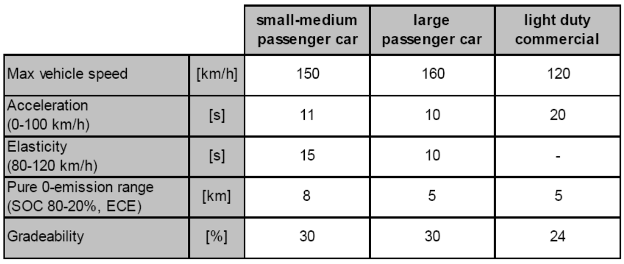
- Small- Medium Passenger Cars
    - FC Full Hybrid
    - ICE Mild Hybrid
    - ICE Full Hybrid
- Large Passenger Cars
    - FC Full Hybrid
    - FC Range Extender
    - ICE Mild Hybrid
    - ICE Full Hybrid
- Light Duty Commercial Vehicles
    - FC Full Hybrid
    - ICE Full Hybrid

Some of the characteristic vehicle data of the ICE categories and the performance requirements are shown in figure 3 and 4.



		small-medium passenger car	large passenger car	light duty commercial
Curb weight	[kg]	1360	2000	2000
Area/c_D value	[m2]/[-]	2.08 / 0.35	2.21 / 0.27	0.44 / 3.48
Rolling resistance coefficient	[-]	0.0095	0.01	0.014
Tyre dynamic loaded radius	[m]	0.28	0.32	0.314

Figure 3: Vehicle Data of ICE reference Vehicles



		small-medium passenger car	large passenger car	light duty commercial
Max vehicle speed	[km/h]	150	160	120
Acceleration (0-100 km/h)	[s]	11	10	20
Elasticity (80-120 km/h)	[s]	15	10	-
Pure 0-emission range (SOC 80-20%, ECE)	[km]	8	5	5
Gradeability	[%]	30	30	24

Figure 4: Performance requirements for the ICE reference vehicle categories.

The maximum vehicle speed must be possible continuously so it has to be reached only with the ICE without any electric boost power. For the 0-100 km/h acceleration and the elasticity 80-120 km/h a vehicle specific payload was considered. The pure zero-emission range refers only to the Full Hybrids at an SOC range from 80 to 20 %.

In order to define common components suitable for the pool of reference vehicles, the standard components were reduced to only a few modular components that cover the requirements of the reference vehicle pool.

Modular Components	Unit		Versions		
Electric motors	continuous power	[kW]	20	40	70
Batteries	nominal capacity	[kWh]	0.9	1.3	2.3
FC system	peak power	[kW]	1 x 25	3 x 25	
Transmission	-	[-]	Single-speed	5-gear AMT	6-gear DCT
Electric A/C	peak power	[kW]	4.0	6.0	
E-power steering	peak power	[kW]	1.0	1.2	
E-brake assistance	peak power	[kW]	0.2		

Figure 5: Common specifications of modular components

The same was done for the power demands of the auxiliaries in the respective categories

		small-medium passenger car	large passenger car	light duty commercial
Air condition (peak power)	kW	4	6	6
Power steering (peak power)	kW	1.0	1.2	1.2
Brake assistance (peak power)	kW	0.2	0.2	0.2
Load factor	%	10	10	10

Figure 6: Assumptions for the auxiliary power in the reference vehicle modules.

The average power for the auxiliary systems is given by multiplying the peak power by the load factor, which is a value, based on OEM experience.

2.3 Simulation

Simulation was done in Matlab/ Simulink using about four existing simulation programs, which were available within the Hysys team. This was done in order to compare results and to pool the experience of the whole team in order to achieve consistent and well adjusted results.

All the models were structured modular by resembling the layout of the physical system and thus allowing exchange of components and subsystems in an easy way. Links between the modules represent the physical variables that define the interactions between the components, such as torque, speed, current or voltage etc. In addition a driver model had to be implemented in order to allow the vehicle to follow a given drive cycle.

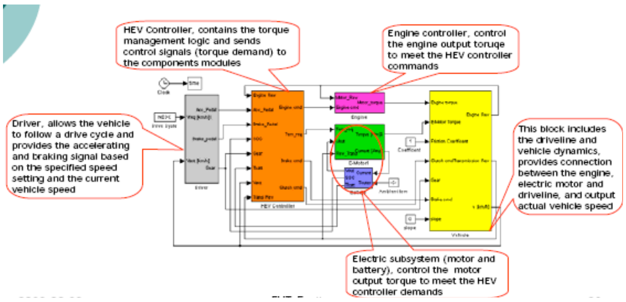


Figure 7: Structure of the Simulation Model for Hybrid Vehicles (Example: University of Applied Science Esslingen)

The Drive Cycles used were the New European Drive Cycle (NEDC) and the set of Artemis Drive cycles which requires the inclusion of auxiliaries.

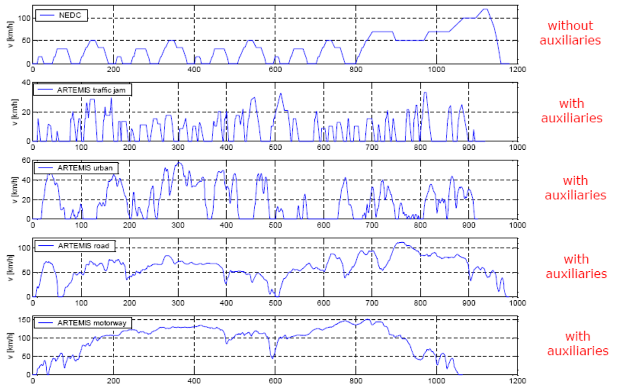


Figure 8: NEDC and Artemis driving cycles used in the Hysys simulation program.

The main objective of the simulation process was to reduce CO2 emission and consumption without loosing vehicle performance by optimizing the energy management algorithm and adjusting the size of the pre-selected components.

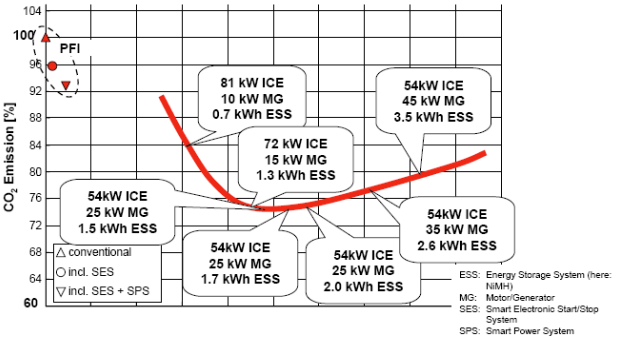


Figure 9: CO2 emissions versus size of battery and Internal Combustion Engine for a Compact Class Vehicle

For a Compact Class Car with 1350 kg, 1,8l Diesel ICE with 90 kW, manual transmission and a

Reference Port Fuel Injection (PFI) of 7,7 l/100 km = 185 gCO2/km the results of the simulation are shown in figure 9. Applying Smart Electronic Start/ Stop Systems (SES) or Smart Power Systems (SPS) CO2 emission reductions of about 4% respective 7% can be achieved. Full Hybrid approaches are going significantly beyond these values, showing a best fit in combining a 54 kW ICE with 25 kW E-Motor/ Generator and a 25 kW - Battery system with 1,5 kWh Energy content. With bigger batteries the increased weight of the vehicle is over compensating the benefits.

The simulation was based on the concept of keeping the same torque as the original reference vehicle and SOC (State of Charge) in respect to the stored energy in the batteries.

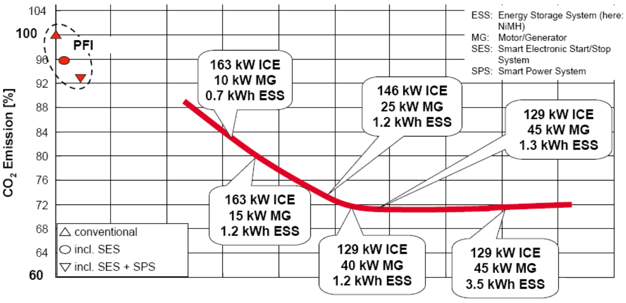


Figure 10: CO2 emissions versus size of battery and power of the Internal Combustion Engine for a Sport Utility Vehicle (SUV)

Similar results are achieved for a SUV Class Vehicle with 2300 kg, 4,0l Diesel ICE with 180 kW, Automatic Transmission with a Reference PFI of 14, 0 l/100 km = 336 g CO2 /km.

The optimized combination is here to use a downsized ICE with 129 kW together with a 40 kW Motor/ Generator and an energy content of the battery of about 1,2 kW. With bigger E- motors and batteries the weight and the costs are growing without further reducing CO2 and consumption.

2.4. Use of modular instead of standard power train components in ICE hybrids

The ICE hybrid pool of vehicles analysed in the simulation study consists of the five reference vehicles already mentioned before

- Small-medium passenger car with mild hybrid power train
- Small-medium passenger car with full hybrid power train
- Large passenger car with mild hybrid power train
- Large passenger car with full hybrid power train
- Light duty delivery van with full hybrid power train

A first step in the study was to analyse the effects by using modular instead of standard power train components. In order to demonstrate the opportunities concerning the power train layout and driving performance, the standard components were replaced by the modular ones which were recommended as common components for FC and ICE Hybrids without any other changes in a first step. This causes an improvement of the driving performance in general because the modular electric motors derived from the FC vehicles are in general bigger than the original ones. The second step was the adoption or scaling down of the combustion engine so that the minimum performance requirements are just reached. With this concept the losses of the combustion engine and with it the fuel consumption are reduced at least in urban traffic conditions.

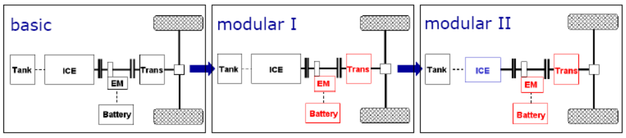
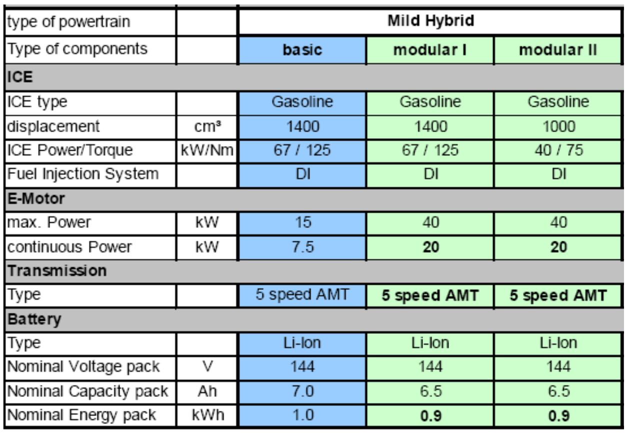


Figure 11: Generation of the modular reference ICE hybrid vehicles.
Modular I step: the standard components are replaced by the modular components without any other changes.
Modular II step: the ICEs are adopted or scaled down so that the performance requirements are just reached.

2.4.1 Mild Hybrid for Small – Medium Reference Passenger Car



type of powertrain		Mild Hybrid		
Type of components		**basic**	**modular I**	**modular II**
ICE				
ICE type		Gasoline	Gasoline	Gasoline
displacement	cm³	1400	1400	1000
ICE Power/Torque	kW/Nm	67 / 125	67 / 125	40 / 75
Fuel Injection System		DI	DI	DI
E-Motor				
max. Power	kW	15	40	40
continuous Power	kW	7.5	**20**	**20**
Transmission				
Type		5 speed AMT	**5 speed AMT**	**5 speed AMT**
Battery				
Type		Li-Ion	Li-Ion	Li-Ion
Nominal Voltage pack	V	144	144	144
Nominal Capacity pack	Ah	7.0	6.5	6.5
Nominal Energy pack	kWh	1.0	**0.9**	**0.9**

Figure 12: Layout of the Mild Hybrid basic versions and the modular I and II approaches for the small – medium ICE reference vehicle.

As example for the applied optimization process the results for the Small – Medium Reference Passenger

Car are will be shown, starting with the Mild Hybrid Version.

The basic version is equipped with an 7, 5 kW continuous power electric engine, a 1 kWh battery and an internal combustion engine of 67 kW/ 125 Nm. The step to the modular I version is to apply modules from the defined common set (Figure 5).

The lowest power version from the common set is one with a 20 kW electric engine and a 0, 9 kWh battery. With this amount of electric power, the internal combustion engine can be downsized significantly to 40 kW/ 75 Nm. This lead to the modular II version.

For the assessment of the simulation results the energy consumption is plotted versus the driving performance for the different vehicle configurations.

The driving performance is represented by the **Performance Index** which is defined as:

PI = Time to cover 1000m @ vmax [s] + acceleration time 0-100 km/h [s] + elasticity 60-100 km/h [s] + elasticity 80-120 km/h [s].

The lower the Performance Index the better the validated performance.

type of powertrain			Mild Hybrid		
Type of components		req.	basic	modular I	modular II
Vehicle mass	kg		1360	1360	1360
Area/c_D value	m2/-		2.08 / 0.35	2.08 / 0.35	2.08 / 0.35
Rolling resistance coefficient	-		0.0095	0.0095	0.0095
Tyre dynamic loaded radius	m		0.28	0.28	0.28
Max vehicle speed	km/h	150	183	183	150
Acceleration (0-100 km/h) (@ 200 kg payload)	s	11	11.0	7.5	9.8
Elasticity (60-100 km/h) (@ 200 kg payload)	s		10.8	7.0	8.4
Elasticity (80-120 km/h) (@ 200 kg payload)	s	15	12.4	7.7	10.1
1000 m @ v_max	s		19.7	19.7	24.0
Pure 0-emission range (SOC 80-20%, ECE)	km	8	0	5.1	5.1
Gradeability	%	30	> 30	> 30	> 30
Fuel consumption					
NEDC (**without** auxiliaries)	l//100km		4.2	4.2	3.9
ARTEMIS traffic jam (**with** auxiliaries)	l//100km		10.0	8.5	7.8
ARTEMIS urban (**with** auxiliaries)	l//100km		6.8	6.6	6.6
ARTEMIS road (**with** auxiliaries)	l//100km		4.7	5.0	4.8
ARTEMIS motorway (**with** auxiliaries)	l//100km		6.6	6.8	6.5

Figure 13: Simulation results of the small-medium passenger ICE Mild Hybrid.

The simulations were done in the selected driving cycles (NEDC + Artemis motorway, road, urban).

Regarding the modular I -Mild Hybrid with standard ICE and modular components, the NEDC fuel consumption is about the same compared to the basic version which is the result of the bigger electric motor with higher losses on the one hand and the opportunity of pure electric propulsion on the other hand.

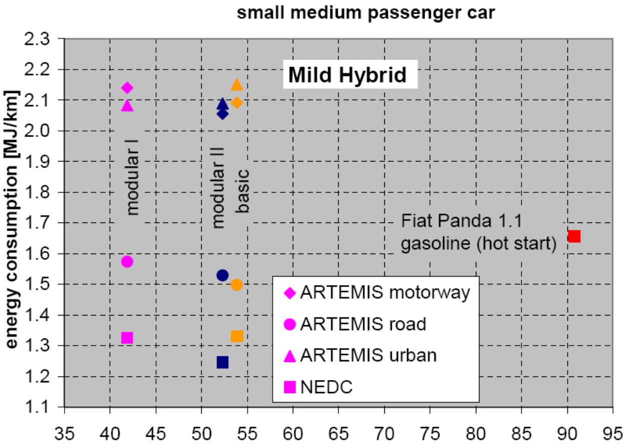


Figure 14: Graphic of simulation results of the small-medium passenger ICE Mild Hybrid.

The downscaling of the ICE in the next step (modular II) causes a reduction of the fuel consumption, because of the improvement of the ICE part-load efficiency whereas the driving performance declines slightly.

In summary, there are achieved:

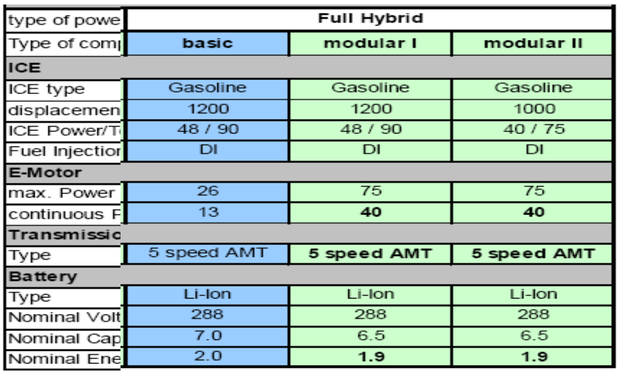
- Strong improvement of energy consumption as well as driving performance with all hybrid configurations
- Further improved driving performance with modular components
- Possibility of scaling down the ICE without loosing driving performance and keeping similar energy consumption

For small to medium vehicles the application of common components with fuel cell vehicles will transform mild into moderate hybrids with electric drive capabilities. This may change the whole electric architecture of the vehicle and of cause the costs as well and has to be studied carefully more in depth before considering such a modification.

2.4.2 Full Hybrid for Small – Medium Reference Passenger

For the Full Hybrid Version of the small-medium passenger car, the basic version is already equipped with a smaller internal combustion engine of 48 kW and 90 kW due to the installed power of 13 kW continuous and 26 kW peak of the electric motor. Modular I is equipped with an even bigger electric motor of 40/ 75 kW and a slightly reduced battery power pack. In modular II the downsizing is rather smooth with about 20 % for torque and power.

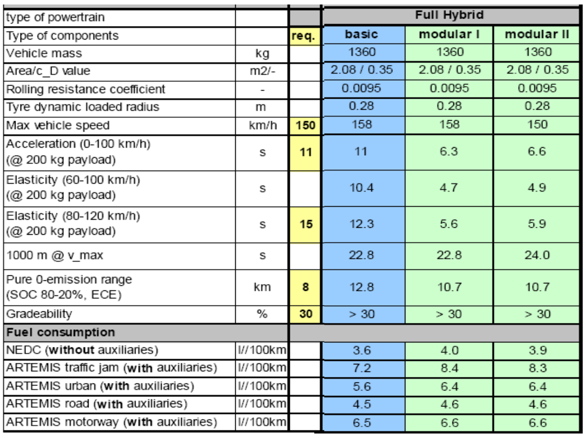
With the bigger electric motor in modular I +II the performance of the car can be improved significantly



type of powe	Full Hybrid		
Type of comp	**basic**	**modular I**	**modular II**
ICE			
ICE type	Gasoline	Gasoline	Gasoline
displacemen	1200	1200	1000
ICE Power/T	48 / 90	48 / 90	40 / 75
Fuel Injectior	DI	DI	DI
E-Motor			
max. Power	26	75	75
continuous F	13	**40**	**40**
Transmissio			
Type	5 speed AMT	**5 speed AMT**	**5 speed AMT**
Battery			
Type	Li-Ion	Li-Ion	Li-Ion
Nominal Volt	288	288	288
Nominal Cap	7.0	6.5	6.5
Nominal Ene	2.0	**1.9**	**1.9**

Figure 15: Components of the Full Hybrid Small-Medium ICE reference vehicles

but the consumption is slightly increased because of the weight penalty. The downscaling effect is slightly improving the efficiency but performance is getting worse. (Figures 16 and 17)



type of powertrain			Full Hybrid		
Type of components		**req.**	**basic**	**modular I**	**modular II**
Vehicle mass	kg		1360	1360	1360
Area/c_D value	m2/-		2.08 / 0.35	2.08 / 0.35	2.08 / 0.35
Rolling resistance coefficient	-		0.0095	0.0095	0.0095
Tyre dynamic loaded radius	m		0.28	0.28	0.28
Max vehicle speed	km/h	**150**	158	158	150
Acceleration (0-100 km/h) (@ 200 kg payload)	s	**11**	11	6.3	6.6
Elasticity (60-100 km/h) (@ 200 kg payload)	s		10.4	4.7	4.9
Elasticity (80-120 km/h) (@ 200 kg payload)	s	**15**	12.3	5.6	5.9
1000 m @ v_max	s		22.8	22.8	24.0
Pure 0-emission range (SOC 80-20%, ECE)	km	**8**	12.8	10.7	10.7
Gradeability	%	**30**	> 30	> 30	> 30
Fuel consumption					
NEDC (**without** auxiliaries)	l//100km		3.6	4.0	3.9
ARTEMIS traffic jam (**with** auxiliaries)	l//100km		7.2	8.4	8.3
ARTEMIS urban (**with** auxiliaries)	l//100km		5.6	6.4	6.4
ARTEMIS road (**with** auxiliaries)	l//100km		4.5	4.6	4.6
ARTEMIS motorway (**with** auxiliaries)	l//100km		6.5	6.6	6.6

Figure 16 Simulation results of the small- medium passenger ICE Full Hybrid

The conceptual approach of using an electric drive motor from a pure electric fuel cell vehicle in a full hybrid ICE version offers the possibility of an extensive use from this opportunity by adapting the operation strategy adequately. This was done in the optimisation processes within the Hysys program with results as illustrated in Figure 18. The interaction between ICE and e-motor in the Artemis Urban Drive Cycle is dominated by the electric motor in the speed range of up to 50 km/h and helps to improve the energy efficiency significantly.

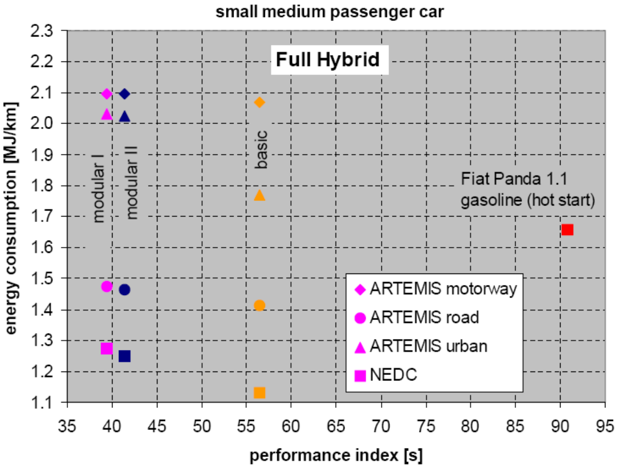


Figure 17: Graphic of simulation results of the small-medium passenger ICE Full Hybrid.

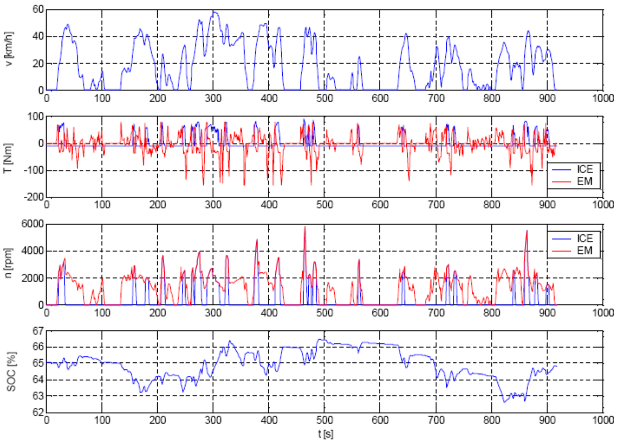


Figure 18: Example of the ICE Full Hybrid operation strategy in the Artemis urban cycle.

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2.5 Analysis of a concept for extended usage of conventional components for Light Duty Fuel Cell Vehicles.

As long as Fuel Cell and ICE Hybrids are produced in small quantities, it is advisable to use as many components of the conventional car as possible in order to reduce development and product costs. This was done for instance by Daimler when developing the Full Hybrid Sprinter for a Prototype Demonstration Program phase with total 6 vehicles for customer applications in USA and Europe. The objective within the Hysys program was to analyse whether this approach could serve as platform for an FC Hybrid delivery van as well.

Figure 19: The Daimler Full ICE Hybrid Sprinter

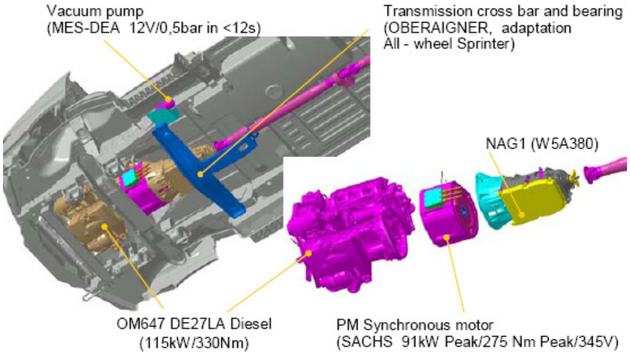


Figure 20: The Drive Train of the Daimler Full ICE Hybrid Sprinter

The applied packaging concept of the drive train for the Daimler Full ICE Hybrid Sprinter required only a slight reduction of the length of the cardan axis and a new positioning of one bearing element at the transmission side.

The 91 kW peak power and 275 Nm electric motor is placed between the four cylinder diesel engine and the automatic transmission. An integrated clutch is positioned between the engine and E-motor in order to allow pure electric driving.

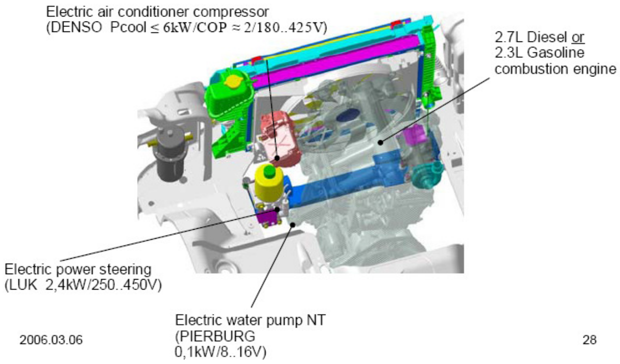


Figure 21: Auxiliary elements of the Daimler Full ICE Hybrid Sprinter delivery van

A Hybrid ICE Vehicle with the capability of pure electric drive performance needs all auxiliaries in electric mode operation as well. Therefore components like electric power steering, electric water pumps, electric air conditioning compressors are candidates for common use in both FC and ICE hybrid applications.
In respect to the performance, test driving measurements of the ICE-Hybrid Sprinter were available and served as basis for the validation of the simulation program.

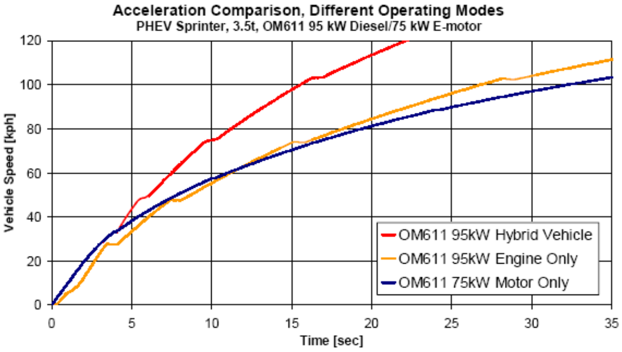


Figure 22: Acceleration curves for pure engine mode, pure E-motor mode and boost mode with engine and E-motor in operation.

The E-motor operates the van at low speeds and because of its excellent torque characteristic it is as well adequate for all acceleration requirements below 40 km/h. Beyond this speed the Diesel engine might be switched on as support. Depending on the energy management concept of the vehicle, the diesel engine might be operated with higher power than required, thus allowing to charge the batteries as shown in the example of figure 23. When braking, the energy will be recuperated. The automatic transmission allows to keep the revolution of the E-motor at low level, contributing in this way to a good noise performance of the vehicle.

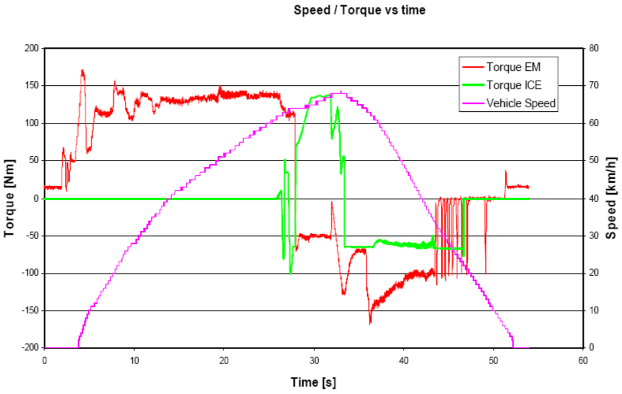


Figure 23: Example of the dynamic behaviour of the Daimler Full ICE Hybrid Sprinter

The objective of the simulation analysis was to investigate the performance of three types of hybrid sprinter vehicles:

1. ICE hybrid sprinter with 5-speed transmission, and then make comparisons based on the simulation results.
2. Fuel cell hybrid sprinter with 5-speed transmission and
3. Fuel Cell hybrid sprinter with one-step transmission.

Version 1 is the built version of the Sprinter. In the second version the ICE is substituted by a 70 kW Fuel Cell system using the existing basic design of the drive train of the conventional vehicle including the 5-speed- transmission. In the third version the 5-speed- transmission is substituted by a one-step transmission which is sufficient for the applied electric drive train because of its good torque characteristic.

The second version is using in an extended way conventional components accepting thus the weight penalties (5-speed- transmission, cardan, differential) while the third version allows a taylor made concept for a fuel cell drive train with for instance the e-motor/transmission unit integrated in the rear axel area.

As can be seen from figure 24, the fuel consumption of the fuel cell versions is significantly lower than the one of the ICE Hybrid due to the much better efficiency of the fuel cell system compared to the diesel engine. The application of the 5- speed-transmission in combination with an optimized switch strategy is over compensating the influence of the higher weight on the overall consumption.

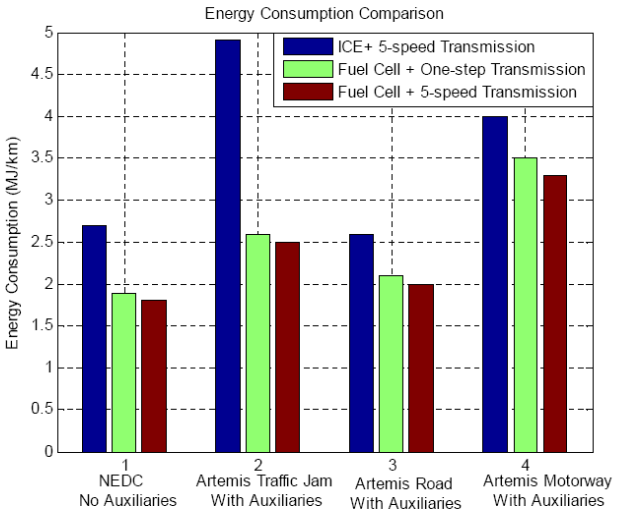


Figure 24: Energy consumption of the selected versions of the Full Hybrid ICE and FC Sprinter Drive Trains

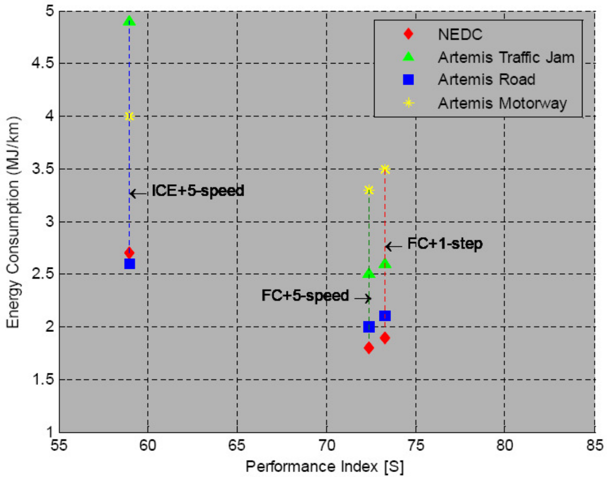


Figure 25: Energy consumption versus performance of the selected versions of the Full Hybrid ICE and FC Sprinter Drive Trains.

On the other side, the performance of the Diesel version with more than 20 kW higher power and about 700 kg lower weight is by far better than those of the fuel cell versions. The 5-speed transmission is offering a slightly better adaptation of the drive train to the performance and efficiency requirements in all the analysed drive cycles.

To illustrate this, the operating points of the drive trains are plotted in the torque/speed/efficiency diagram of the electric motor.

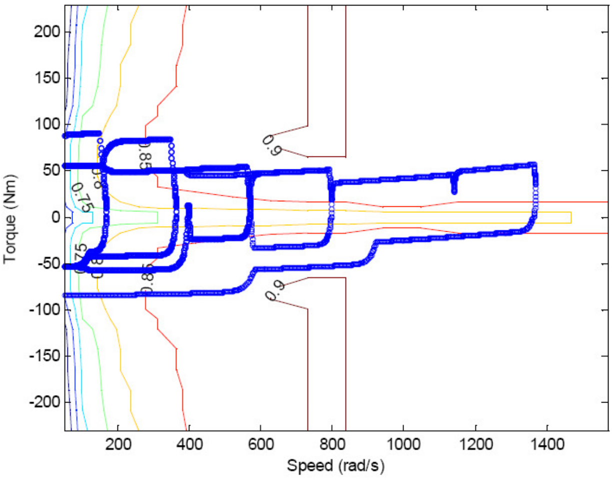


Figure 26: Motor operating points of the Fuel Cell Drive train with one-step transmission

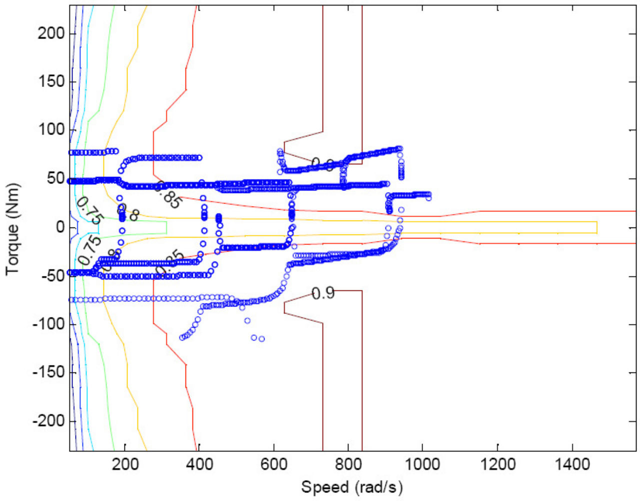


Figure 27: Motor operating points of the Fuel Cell Drive train with the 5-speed transmission in the efficiency dependent version

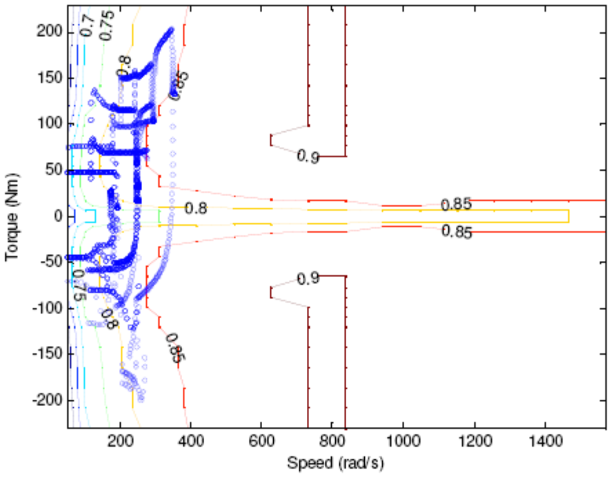


Figure 28: Operating points of the Fuel Cell Drive train with the 5-speed transmission with speed-dependent shift strategy

The application of an optimized one-step transmission results in a broad use of the engine speed, covering areas with high efficiency but as well those of lower efficiencies. Using the 5- gear-transmission in the speed – dependent shift mode as shown in figure 28 reduces the speed range but is keeping it in an area of low efficiency. With an efficiency optimized shift strategy as shown in figure 27, the amount of operating points in the low efficient area could be reduced and an even better overall efficiency than with the optimized one step transmission could be achieved.

2.6 Analysis of the effects by using e-motors with different length using the same iron lamina.

Synergies between components can be classified according to the following definition:

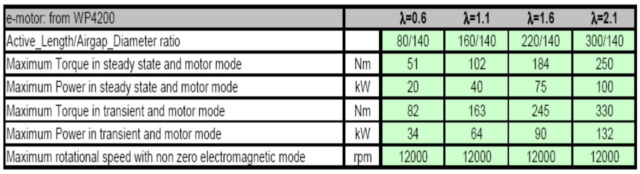
- Level one: common (identical) subsystem
- Level two: common components
- Level three: common materials and production processes

As an example for the level two approach, studies were done by starting from well defined e-motor iron sheet designs, different form factors (lambda = ratio rotor length to rotor diameter) were analysed keeping the diameter constant and varying the rotor and stator length.

This was applied in the design phase of e-motors for the two Hysys demo vehicles (see figure 1):

- PSA Hysys Demo FC Hybrid
- Daimler Hysys Demo Hybrid Sprinter

It was studied the application of an AC three phases synchronous Interior Permanent Magnet (IPM) Motor from ATB with 230 mm outer active stator diameter for both demo vehicles with different form factors.



e-motor: from WP4200		λ=0.6	λ=1.1	λ=1.6	λ=2.1
Active_Length/Airgap_Diameter ratio		80/140	160/140	220/140	300/140
Maximum Torque in steady state and motor mode	Nm	51	102	184	250
Maximum Power in steady state and motor mode	kW	20	40	75	100
Maximum Torque in transient and motor mode	Nm	82	163	245	330
Maximum Power in transient and motor mode	kW	34	64	90	132
Maximum rotational speed with non zero electromagnetic mode	rpm	12000	12000	12000	12000

Figure 29: E-motor parameters at different form factors lambda for the ATB IPM synchronous motor

The result achieved was that all performance requirements of both vehicles could be fulfilled with Form factors 1,-1 for the PSA e-motor and 1,6 for the Daimler e-motor.

3. Conclusions

The use of **same electric motors in ICE and FC hybrids** is one way to increase the production volume and reduce costs. In this case the electric drive power increases in the ICE hybrids, which means an **improvement of the driving performance** and an **slight increase of the fuel consumption** basically due to the higher losses.

One approach to reduce production cost is the **use of e-motor** with **different active length** using the **same iron lamina**. These e-motors can be used in different vehicle classes containing small passenger cars up to light duty vehicles.

In terms of an **extended usage of conventional components in light duty FC vehicle** it is also possible to use a conventional **5-speed transmission** in a FC vehicle. With an e-motor optimized shifting strategy the **energy consumption can be reduced slightly** compared to a FC vehicle with a fixed transmission.

4. Acknowledgement

The authors acknowledge the contribution of all colleagues from the whole Hysys team to this work.

5. References

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