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INMOVE –
Konzept eines autarken parallelen Hybridantriebs

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INMOVE – Konzept eines autarken parallelen Hybridantriebs

INMOVE - Concept of a charge-sustaining Parallel Hybrid Drive train

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Abstract

The R&D-project INMOVE has dealt with the development and realization of a hybrid drive system. The main objective of the project has been the definition of such a power train, the research on optimized technology and finally the prototyping of two demonstrators (Citroen Berlingo), in order to design and evaluate an appropriate hybrid driving strategy. To achieve a good fuel economy with a cost effective solution a parallel hybrid drive has been developed. The drive train is of the “single shaft” configuration, where the electric motor works on the input shaft of the manual gearbox. The clutch is electronically controlled and automated. The different components of the drive system are connected by a CAN-bus. The overall control, the drive system management and especially the driving strategy are realized by a vehicle management unit. With finishing the build up of the first prototype end of 1999 and the second prototype end of 2000, optimization and analysis under real conditions have been possible. Measurements of the fuel economy show comparatively low results and verify the overall functionality of the subsystems as well as the strategy.

Introduction

The project: “*Integrated Modular Electric Propulsion System for Parallel Hybrid Vehicles*” (abbreviation INMOVE), which had a duration from November 1997 to December 2000, was funded under the Industrial & Materials Technologies Programme (Brite-EuRam III) within the 4th Framework Programme of the European Community. The project objectives did include the research on a suitable system design and optimized component technologies as well as the prototyping of two demonstrators, in order to apply an appropriate hybrid driving strategy for final evaluation of the resulting performance [1].

The project has been a common effort between the project partners Mannesmann Sachs (coordinator), PSA Peugeot Citroen, ST Microelectronics, Aachen University of Technology - ika Institut für Kraftfahrwesen Aachen, The University of Sheffield – Department of Electronic and Electrical Engineering and Chambre de Commerce et Industrie de Marseille - ESIM Ecole Supérieure d’Ingénieurs de Marseille.

The basic requirements for an innovative vehicle concept, powered by a hybrid drive train, have been established by PSA Peugeot Citroen aligned to the requirements of the market.

This specification includes:

- Expected driving performance in terms of acceleration, top speed, cruising speed, hill climb ability, according to weight and load conditions.
- Economical and environmental objectives like reduced fuel consumption and compatibility to low emission standards expressed as a target value of 120 g CO_2 / km.
- Basic design objectives, i.e. cost effective solution, low complexity of system design without major modifications of the conventional drive train.
- Definition of user-friendly Hybrid operating modes with optimized dynamic torque splitting between alternative drives (combustion and electric)
- Zero Emission Operating Mode (ZEV), by pure electric powering.

Meantime this corporate effort of automotive and supplier companies supported by some Universities showed promising results. Two demonstrators have been completely equipped and therefore comparison between simulation and real test results, referencing the initial specification, could have been performed.

System design of Drive train

According to the fundamental objective to add electric drive components to a conventional, manually operated gearbox in order to establish a modular hybrid drive train, a "Single Shaft Configuration" has been selected [2]. This arrangement links the torque of the additional electric drive to the primary shaft of the gearbox and needs neither significant modifications on an existing drive train nor additional gear elements. Additionally this architecture supports a common type of operation in both operating modes (Hybrid, ZEV) allowing an usual handling for the typical driver. The "Single Shaft Configuration" in beneficial too for dimensioning to lower peak ratings of the electric motor and therefore results to lower weight and dimensions.

In parallel hybrid applications so far [3,4], the electric drive has been added as additional component between combustion engine and front end of the gearbox. This arrangement offers potential, i.e. by space tuned integration of clutch and electric drive, leading to an optimization of the often critical overall length of the complete drive train. But this approach typically needs major design modifications on both interfaces (engine and gearbox).

On INMOVE project an alternative integration towards the gear box rear end has been selected, as shown on Figure 1 and 2, in order to minimize design and prototyping expenditure. This approach appeared to be quite effective, because an interface normally used to mount the fifth gear extension unit could be applied for electric motor adaptation. This opportunity simultaneously supports the intention to reduce the number of shift steps of the gearbox from five to four with correspondingly spread transmission ratios.

The support of the electric drive on lower speed range allows this simplification, leading to a cost and weight compensating measure and driving comfort increase. With the same line of reasoning the reverse gear of the transmission may be omitted, because reverse driving will be possible with the first gear selected and operating the electric drive, in opposite turning direction. The limited range requirement will allow this option, offering additional comfort i.e. with button operated forward / reverse driving, especially helpful for maneuvering situations during car parking.

One fundamental disadvantage of the single shaft architecture, that already has been recognized early [5] has to be regarded. The additional rotor inertia of the electric motor causes problems during gear shifting of a manually operated gearbox. The basically provided synchromesh mechanism that shall accelerate or decelerate the gearbox input shaft is overtaxed by the additional rotor inertia. Therefore alternative system designs often apply a second clutch to separate the electric drive, but this requires additional automatic actuation and results in supplementary space requirements and costs.

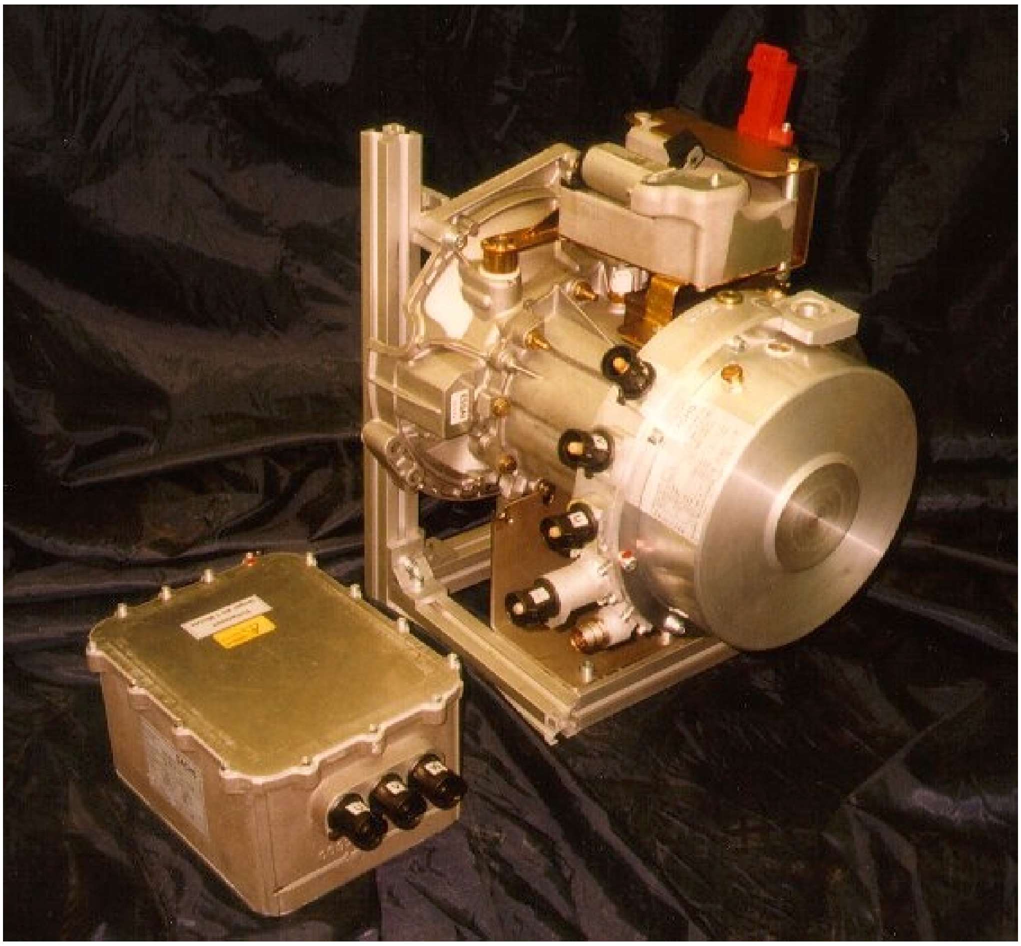

Figure 1
Realization of Single Shaft Parallel Hybrid Arrangement

With the former UNI-1-project [3,4], equipped with a single clutch only, it has been proven already, that an active synchronization supported by the electric motor during the gear shifting process is possible, but needs an automated shifted gearbox (ASG) in order to support the driver correspondingly.

Within INMOVE project it has been demonstrated, that an electronic clutch system (ECS) will be sufficient to support the driver at lower additional costs. The automatic clutch operation delays the reengagement of the clutch until synchronous speed is achieved, and the driver is relieved from the task to learn the correct clutch operation timing. This allows an easy handling and control of the vehicle for the driver, despite the increased functionality of two alternative driving modes and without increased load interruption, if compared to an experienced driver's shifting performance.

In contrary to the basic considerations for selection of the most suitable drive train architecture, the electrical control system layout is simply driven by functional considerations as shown in Figure 2.

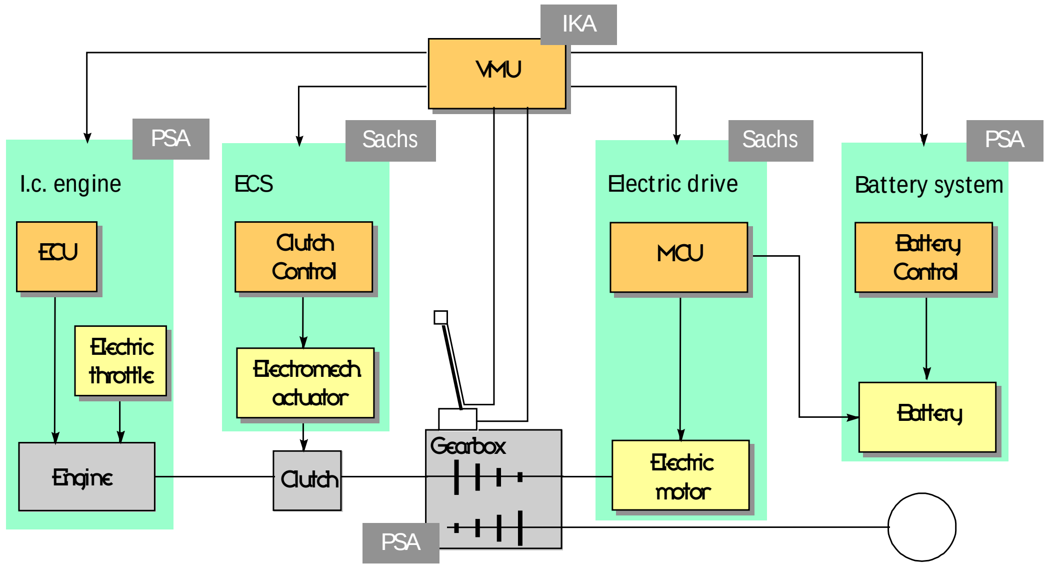

Figure 2
INMOVE Parallel Hybrid System Design

A central Vehicle Management Unit (VMU) connected via CAN-Bus interface to all other subsystems handles the following basic tasks:

- Detection of drivers basic intentions i.e. start, accelerate, decelerate, gear shifting, braking.
- Parallel control "by wire" of both traction drives, based on a sophisticated torque splitting strategy that regards the most efficient operating areas of each drive according to the actual speed and load situation.
- Control of active synchronization process during gear shifting.

The functions of the applied clutch control system have been reduced to basic speed-dependant clutch engagement, because during pure electric driving mode, with constantly disengaged clutch the complete shifting procedure has to be performed by the VMU by means of synchronization.

New Drive train Components

The electrical portion of the hybrid drive train was subject of thorough investigations during the project. Research and prototyping mainly targeted efficiency increase and cost optimization of these components. At the same time basic automotive requirements like low volume and weight, high reliability and lifetime expectations have been taken into consideration. According to the different state of technology, individual topics for improvement have been targeted on the main components: electric motor and power inverter.

Electric Motor (EM)

A particular type of permanent magnet synchronous motor (PSM) has been improved for automotive applications and in terms of low cost volume production at Mannesmann Sachs since some years. The basic features of this motor like high power density of up to 2 kW/kg and its ideal proportions (high diameter, short active length) enable most suitable automotive integration. On the other hand typical disadvantages, known from standard PSM, are strongly reduced. Mainly its unusual field weakening capability, typically said as advantage of induction motors, is rather high and theoretically unlimited due to an increased inductivity. Another critical issue addressed on PSM, especially if operated in field weakening range, may occur by the loss or failure of control, due to its inherent and possibly excessive voltages. This safety problem meantime has been covered by redundant hardware circuitry (patents pending), implemented to the power inverter, that automatically short circuits the motor, in cause of critical voltages. The remaining braking torque as well as torque transients are quite uncritical on this type of PSM.

Due to the high pole number that requires a fundamental current excitation of increased frequency (up to 2 kHz) iron losses, especially in the upper speed range, are not to be neglected. But by sophisticated magnetic circuit design and in conjunction with the application of new metal sheet materials with improved magnetic properties an optimization of this PSM is possible. The individual approach is always targeting a main operating area (MOA), where frequent operation is expected and therefore an efficiency optimization is advisable.

During INMOVE hybrid system design phase this MOA has been defined, in accordance to the desired operating strategy, for a speed range of 2000 to 4000 rpm and a torque bandwidth of 30% to 70% of the rated motor torque. A gradual application of design measures has been pursued, in order to adapt an existing computer based motor design tool, by the results of real measurements for improvement of prediction quality:

- With the first prototype an optimization of the magnetic circuit design has been performed, based on a plugable stator tooth design (see Figure 3), that leads to lower production costs on the winding process and additionally allows an increased copper density resulting to reduced copper losses. This process is performed by FEM simulations of gradually modified magnetic circuit designs, leading to an optimized guidance of the magnetic flux.

- The second motor design focused on the influence of metal sheet properties. After evaluation of most suitable materials and based on iron loss measurements of samples this motor has been prototyped. The selected material promised and already verified an reduction of iron losses up to 35%.

- Finally a third motor has been designed and prototyped regarding cost optimizations. For that purpose high volume production aspects have been followed, i.e. the punching of a complete motor intersection with one tool. Therefore the benefit of improved metal sheet for stator teeth carrying high flux density in contrary to low cost material for stator and rotor yoke had to be dropped. The loss of advantageous material properties partly may be compensated by corresponding tooth geometry adoptions.

The electric motor ratings have been specified at the beginning of the project according to the required vehicle dynamics (see column: Specification in Table 1). From an existing type of line a motor diameter (outer housing dimension) of 260 mm has been selected and an active length of 55 mm has been derived by the existing motor design tool. These dimensions have been kept constant during the above mentioned steps of innovation. Therefore the results of each step may be compared against each other (see Table 1)

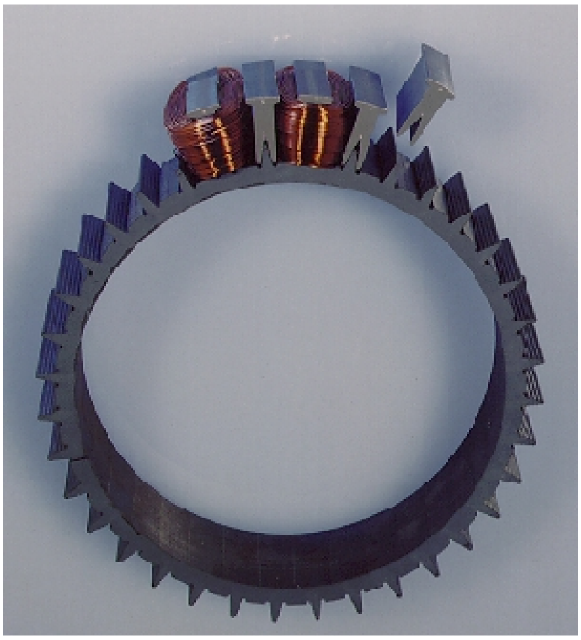

Figure 3
Stator design with plugable teeth

Table 1
Specified versus Measured Ratings of Electric Drive

INMOVE Motor	Target Specification	Test results Motor 1	Test results Motor 2	Remarks
Peak power	30 kW	30,5 kW	31 kW	2700 rpm, Ud=130V
Continuous power	22 kW	25 kW	25 kW	S2 (2 min)
Peak torque	130 Nm	150 Nm	140 Nm	at 100 rpm
Continuos Torque	95 Nm	120 Nm	120 Nm	at 100 rpm
Peak efficiency	>90%	89,5%	90,5%	motor & inverter
MOA efficiency	Opt.	86%	> 88%	motor & inverter
Weight	25 kg	24,3 kg	24,3 kg	

The efficiency increase of the second motor (see Figure 4) in the main operating area, but as well in the upper speed range, is quite significant. But it has to be admitted, that this improvement must be paid by more expensive metal sheet material. Therefore simulation and real vehicle tests of fuel consumption benefit may show if this expenditure is justified.

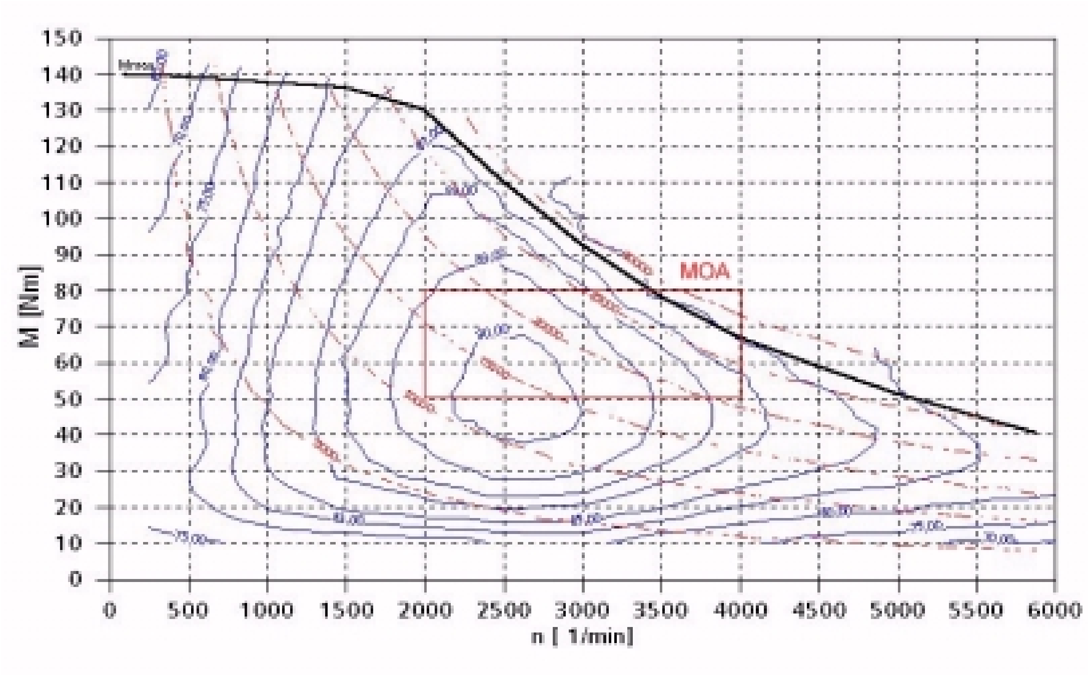

Figure 4
Efficiency Map of motor 2 (Ud = 130V)

Motor Control Unit (MCU)

The Motor Control Unit (MCU) consists of a power inverter with micro controller based, rotor-oriented control algorithm. The technology of this component is well experienced since many years in automotive drive train applications.

One major part of that unit consists of electric power switches, preferably packaged as Half Bridge Modules including IGBT semiconductors. As the cost share of these elements amounts to almost 50% of the complete unit price, there should exist some potential for cost improvement. Additionally the reliability, according to the automotive application, shall meet the extreme load cycle requirements caused by acceleration and recuperation periods that result to increased thermal stress.

Some sophisticated approaches on silicon optimization and semiconductor packaging have been researched during this project by the partners ESIM (Ecole Superieure d´Ingenieurs de Marseille) and ST Microelectronics.

One new approach has been selected to build such power modules by application of multiple IGBTs, including optimized silicon design, but in conventional, low-cost transistor packages as i.e. MAX247. The arrangement of this switching elements has been performed on insulated metal substrate (IMS). After a design phase mainly dealing with investigations on the parallelisation and suitable layout, first prototype samples have been made available and have been under intensive tests (see Figure 5 and 6).

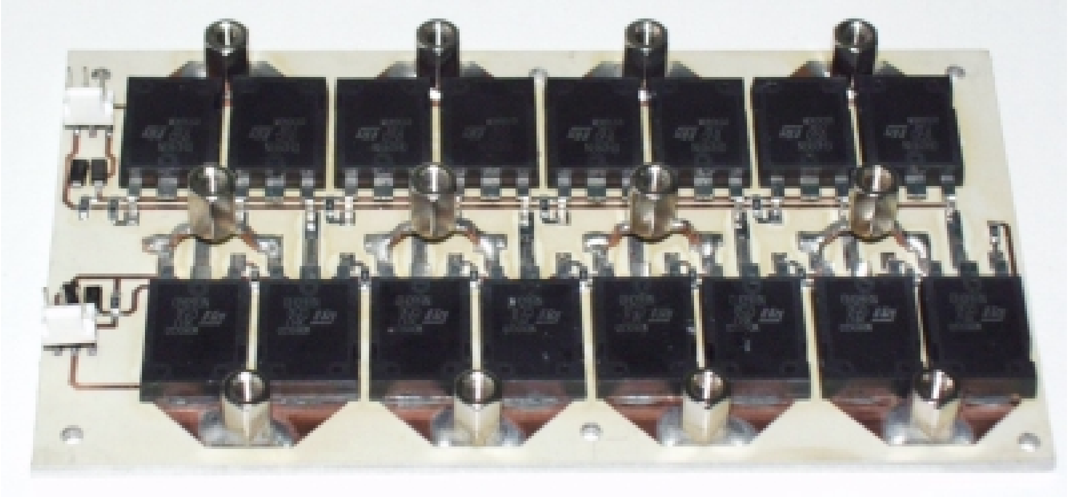

Figure 5
IGBT Module (400A Half Bridge), prototyped by ST Microelectronics

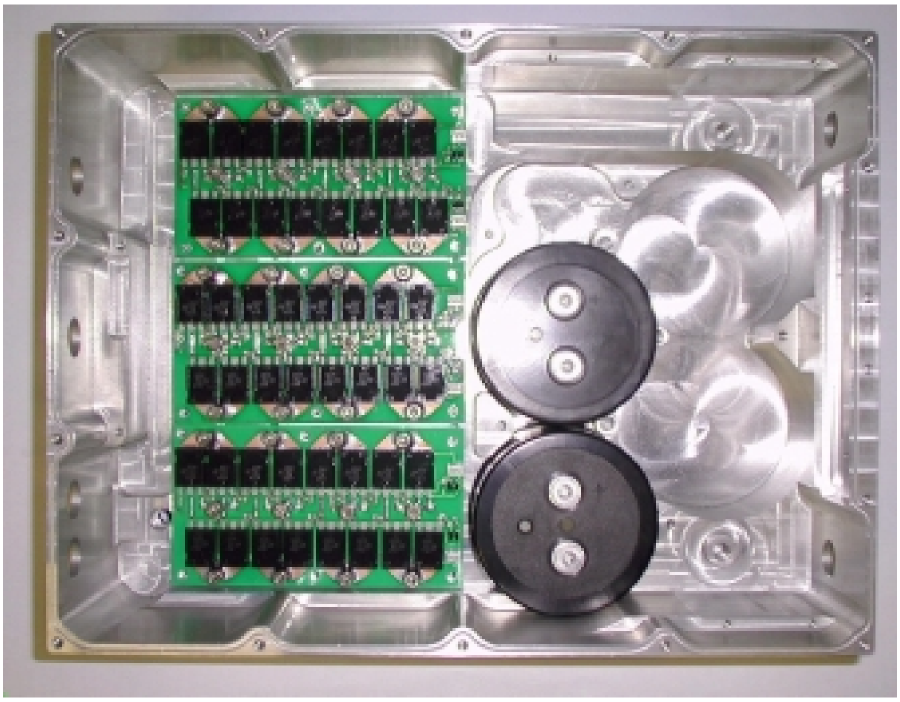

Figure 6
Prototype Inverter with IGBT Modules prototyped by ST Microelectronics

Vehicle Management Unit (VMU)

The VMU used in the first prototype vehicle consists of the „smart167"-system which has been especially designed by ika to fit to prototype car applications. The system consists of different modules using a self-stacking bus (PC/104 standard) and can be expanded with different controller boards (i.e. PowerPC, Pentium, ...) and application boards (i.e. GSM, GPS, ..) easily. For this hybrid vehicle application the system consisted of one power supply, a Siemens SAB/C167 based microcontroller with bus transceivers and CAN-driver and a digital and analog I/O-board (Figure 7).

For the second demonstrator vehicle an even more sophisticated, smaller new version of this VMU prototype system has been developed and used (Figure 8). [6]

Figure 7
Vehicle Management Unit (first prototype vehicle)

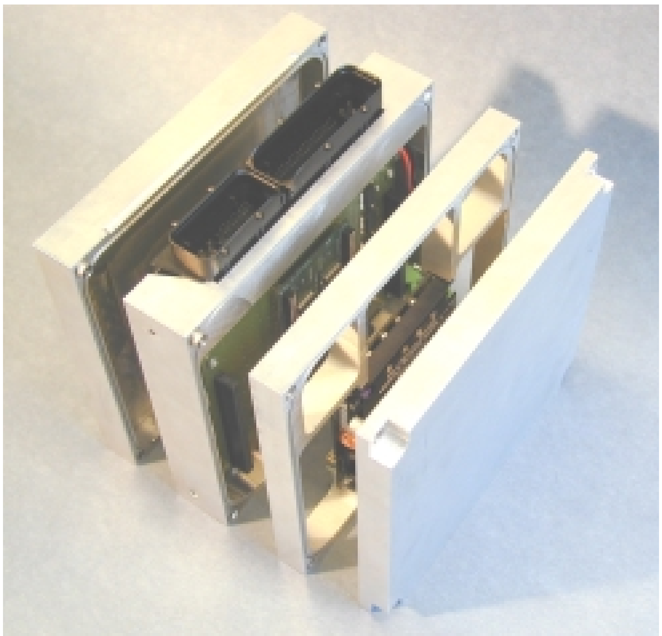

Figure 8
Vehicle Management Unit (second prototype vehicle)

Functional Design

The combination of the IC-engine with an electric motor of nearly the same torque capacity as the combustion engine, permits a very flexible operating strategy. The aim of this strategy, which provides a torque split of the demanded torque to both of the motors, is to optimise the overall efficiency and to allow the self-sufficient operation of the vehicle, independent from external recharging.

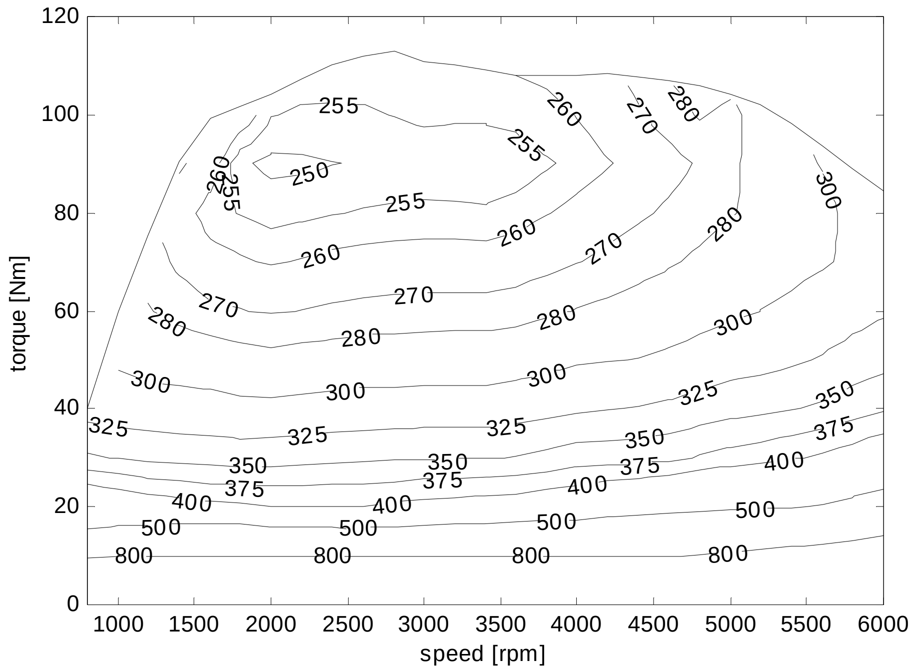

Figure 9
Efficiency Map of ICE [g/kWh]

As can be seen from Figure 9 the fuel efficiency of the IC-engine declines especially at low torque below about 40 Nm. Thus the operation of the combustion engine in this area should be avoided. In consequence, the electric motor should operate the vehicle at this low torque demand and the combustion engine should be started only at higher torque demand. To achieve a battery sustaining operation of the vehicle, a mechanism to charge the battery while driving with the IC-engine must be provided by the strategy. Figure 10 and Figure 11 show two basic maps, which realize such an operating strategy. Figure 10 explains the torque split. The red line shows the ICE-torque over the demanded torque and the green one is the torque of the electric motor. Beginning with the ICE off and a state of charge of about 67.5 %, the IC-engine starts, if the torque demand rises over 30 Nm. Once started, the ICE operates with 40 Nm, producing 10 Nm more than the demand by the driver. This difference is absorbed by the electric motor, which acts as a generator and recharges the batteries.

The limits to start and stop the ICE change in dependence of the state-of-charge (SOC) of the battery (Figure 11). With rising state-of-charge, the torque limit to stop the ICE (green line in Figure 11) also rises. If the drivers torque demand is constantly 30 Nm, the ICE will be stopped, if the state of charge reaches 82.7 %. Under normal traffic conditions the driver will eventually lower the torque demand to stop the car and the ICE will switched off for example at a torque demand of 10 Nm as shown in Figure 10.

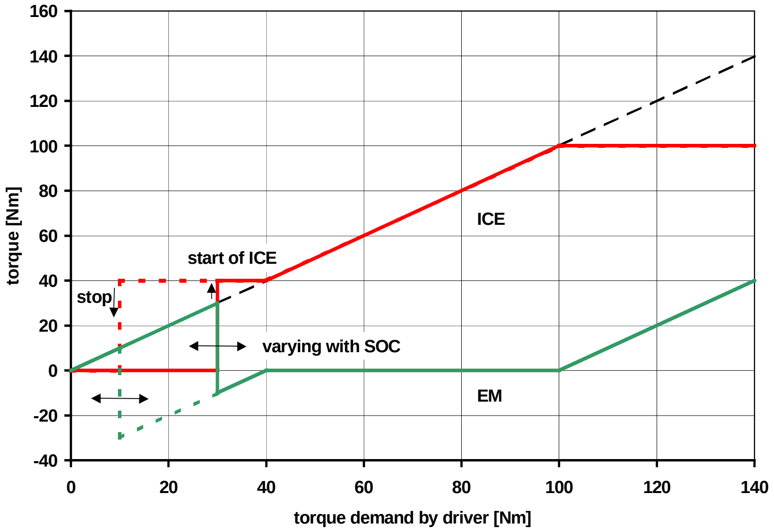

Figure 10
Torque Split Between ICE and Electric Motor

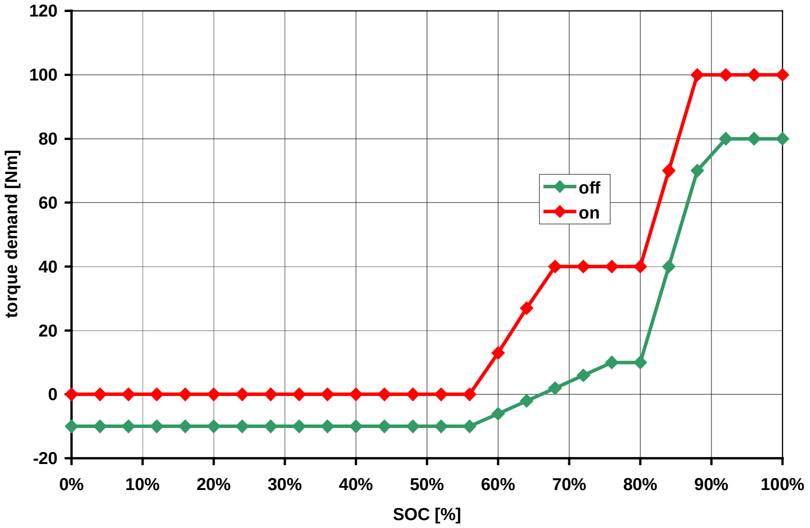

Figure 11
Torque Limits for Starting / Stopping the ICE versus SOC

With the variation of the torque limits for starting and stopping the ICE depending on the state-of-charge of the battery, the SOC stays in a middle area between 60 and 80%. If the batteries have a low SOC, the limit to start the ICE is very low. The ICE will then be started very soon and also the charging torque of the electric motor is very high, leading to a fast recharge of the batteries. On the other hand, at very high state of charges, the vehicle will operate mostly electric discharging the battery to lower SOC, because the start limit for the ICE is very high and only reached under full load conditions. At a demand higher than 100 Nm, the electric motor also boosts the vehicle by adding additional torque to the power train (Figure 10).

As a second measure to avoid further discharge of the batteries, an offset is added to the torque demand of the ICE at low SOC. Thus the ICE torque is higher than the original torque demand of the driver and the electric motor compensate this additional offset torque operating as a generator and charging the batteries.

The offset is activated at 68 % SOC with a value of 10 Nm. If the SOC still decreases, the offset begins to increase at 56 % and reaches maximal 20 Nm at 44 %. If the SOC increases, the offset is switched of at 76 %. Offsets between 0 and 10 Nm do not occur. So the areas of low efficiency of the electric motor in generator mode are avoided.

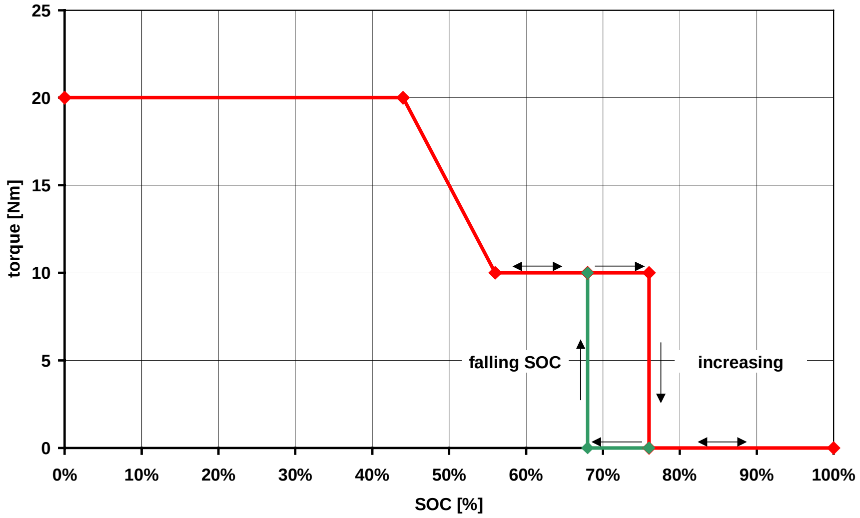

Figure 12
Torque offset versus SOC

Another aspect of this operating strategy is the effect on the fuel efficiency of the vehicle. As explained, with the given strategy, the vehicle will operate at low torque demands first with the ICE running and afterwards only running on the electric motor. The energy which is charged to the batteries in the first phase is used to drive the vehicle in the second phase.

Instead of operating the ICE at low efficiency for the whole time, the ICE operates at higher efficiency with higher absolute fuel flow, but for a shorter time and afterwards the ICE is switched off while the vehicle is driven by the electric motor, using the energy which is charged in to the batteries in the first phase.

To calculate the energy, which is available for the electric motor to drive the vehicle , the efficiency chain of the electric motor acting as a generator, the efficiency of the batteries being charged and discharged and the efficiency of the electric motor acting as a motor must be considered. This overall efficiency determines the ratio between the ICE-on-time and the ICE-off-time. The fuel consumption of the ICE is then related to the whole operating time, as the sum of ICE-on- and -off-time.

With the given map of the electric motor and the efficiency map of the ICE the resulting specific fuel efficiency can be calculated, which is done in Figure 13 for an operating torque of 40 Nm for the ICE. The red curves show the original fuel efficiency and the blue ones the resulting overall fuel efficiency with this load levelling strategy.

For example at a speed of about 2000 rpm and a torque of about 20 Nm, which must be delivered to the drive train, the original fuel efficiency of the ICE is about 400 g/kWh. With the given strategy, the motor operates at 40 Nm and 2000 rpm with a fuel efficiency only for the ICE of about 310 g/kWh but for a shorter time. The blue curves show the overall efficiency, regarding the shorter operating time and the losses in the electric components, which is about 360 g/kWh for a torque demand of 20 Nm. So the improvement a this point (20 Nm, 2000 rpm) is about 10 %. Especially at lower torque the efficiency advantage rises.

As a result of this strategy the fuel efficiency is better in mostly the complete area below 40 Nm. The improvement in the fuel efficiency and the shorter operating time of the ICE overcompensate the losses in the electric components.

This torque split-strategy has been iteratively developed using a longitudinal simulation model, programmed in Matlab/Simulink.

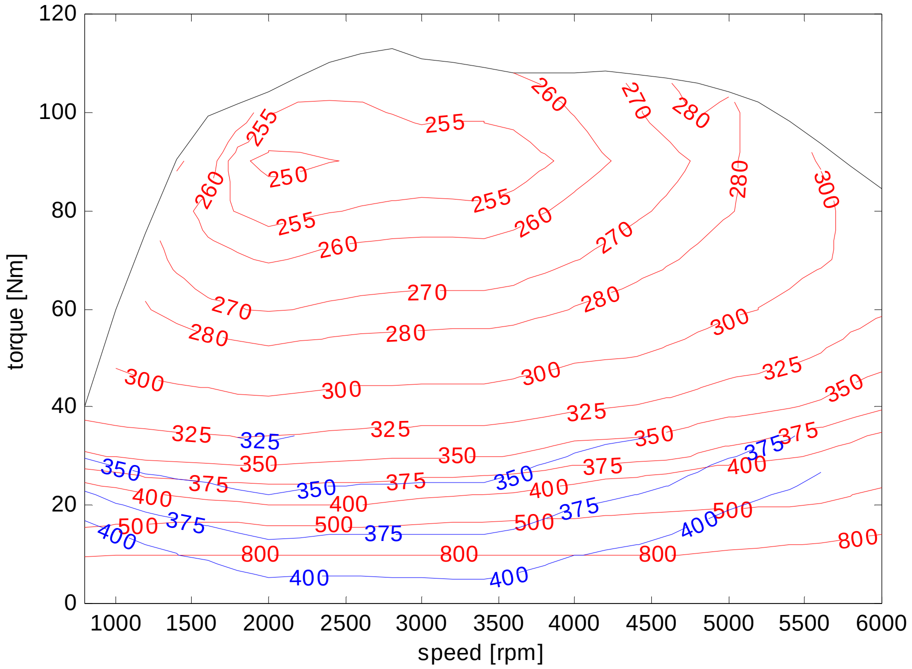

Figure 13
Specific Fuel Efficiency Map with 40 Nm Operating Torque for the ICE [g/kWh]

Shifting

Beside the torque split, the process of shifting the gear is one fundamental functionality, which must be handled by the strategy. Based on the structure of the drive train, where the electric motor is permanently joined to the input shaft of the gearbox, the electric motor has to actively synchronize the gears. The additional rotor inertia of the electric motor is too high for shifting of a manually operated gearbox. Because of the inertia of the electric motor mounted on the input shaft of the gearbox, the synchronisation is not able to appropriate de- or accelerate the input shaft together with the electric motor during shifting. So the electric motor has to perform an active synchronisation by controlling its speed accordingly to the target speed, which results from the vehicle speed and the intended gear after the gear change.

The detailed shifting process is explained in Figure 14, which shows a schematic time plot of the speeds and the several limits within the strategy.

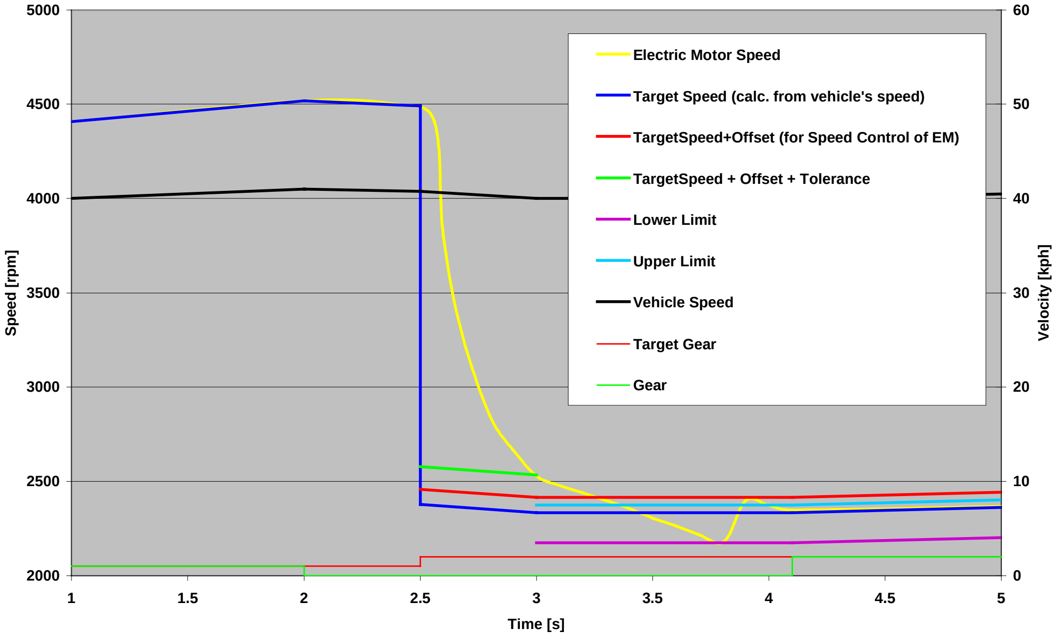

Figure 14
Shifting from 1st to 2nd gear

Figure 14 shows an up-shift from first to second gear at a vehicle speed of about 40 km/h (black line). At t = 2 s, the driver puts out the first gear and begins to move the shift lever. At t = 2.5 s, the shift position detection algorithm detects the second gear as the target gear (red line at the bottom of the diagram). The blue line shows the target speed, which is derived from the vehicles speed and the target gear. The yellow line shows the speed of the electric motor. With the detection of the new target gear, the target speed also changes from about 4500 rpm to 2400 rpm. The electric motor (yellow line) is in a speed controlled mode and decelerates until at t = 3 s the green line is reached. At this moment, the electric motor is switched to a torque controlled mode with a torque command of zero. Thus, the input shaft coasts down, decelerated by the losses in the gear box and electric motor and the additional torque, produced by the synchronization clutch. As a result, the speed of the electric motor, matches at t=3.4 s. If the driver does not put in the gear, the electric motor and decelerates further, until the violet limit is reached. At this point, the electric motor is switched to speed mode with the red line as the speed command. After reaching the light blue limit, it is switched off again, and the motor coasts down. At t = 4.1 s the speeds matches again and the gear gets in. A direct synchronization with the electric motor to the target speed does not work because of the following reasons. The target speed has to be calculated from the vehicles speed. The limited accuracy of the measurement leads to an inaccurate calculation of the target speed. In case the calculated speed does not match the desired speed, for example the electric motor operates at a target speed above the real needed speed, the synchronization clutch has to decelerate the electric motor, which is in speed mode. Thus decelerating the electric motor to a speed below the commanded target speed would result in the speed controller of the electric motor to increase the torque in order to hold the commanded speed. As a result, the torques of the synchronisation clutch works against the electric motor torque, and the conditions to get the gear in, that the differential speed at the synchronisation clutch and the transferred torque are zero is never fulfilled.

Gear identification

Another element of the strategy, is the identification of the actual and intended gear. The gear identification is based on a two dimensional potentiometer, which is mounted directly on the gearbox gearshift shaft. It detects the angular motion (forward and backwards movement of the shift lever) and the sideways linear motion (sideways linear motion of the shift lever). The sensor is connected to a reference voltage of 5 V and produces to voltages to identify the position of the shift lever (see Figure 15).

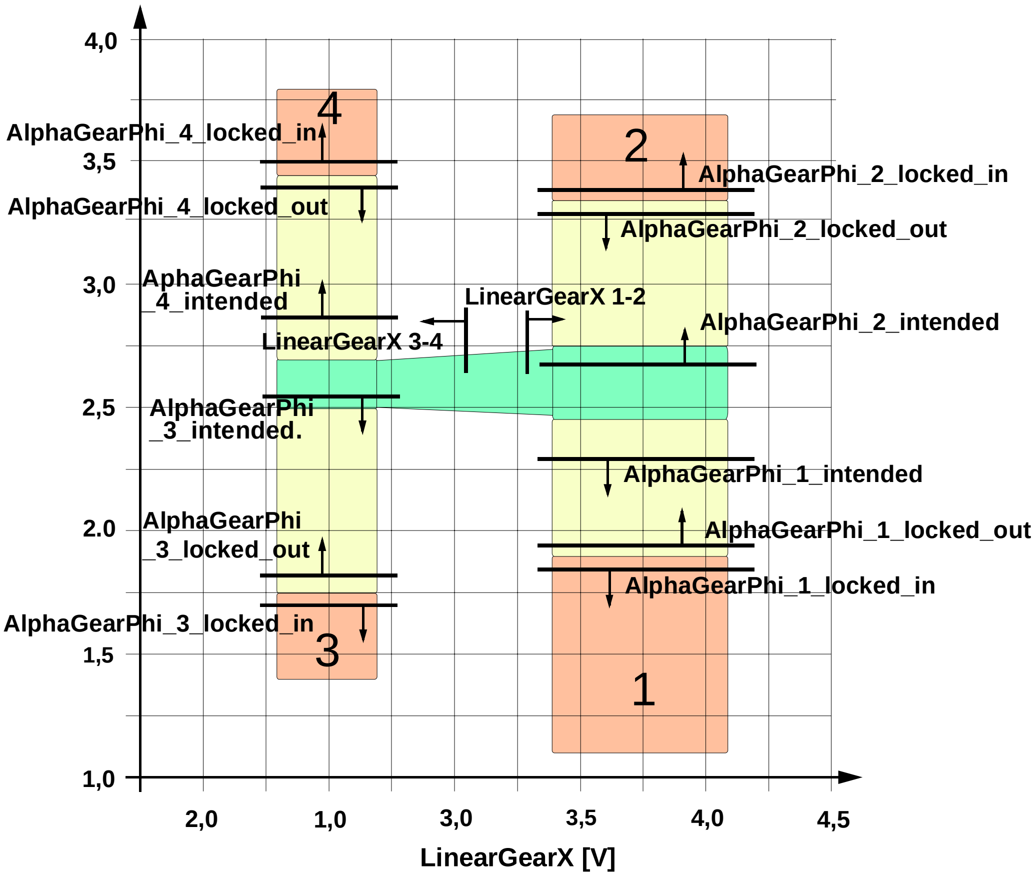

Figure 15
Voltage of potentiometers for detection of shift lever position

The state machine, which uses the limits shown in Figure 15 to identify the actual and the target gear is shown in Figure 16.

Besides the information of the position of the shift lever, the state machine makes use of two additionally signals, the force in the shift lever and the signal” sync ready”. A small sensor integrated into the shift lever measures the force in the shift lever in forward/backwards direction, measuring not only the force but also the direction. With this information, the drivers intention to put out a gear is detected. Additionally if the shifting force increase while a gear is shifted in, it shows that the synchronisation clutches are right now in contact. The information “sync ready” is derived from the speeds. If the difference between the target speed and the actual speed of the input shaft falls below a specific limit. The signal “sync ready” becomes true.

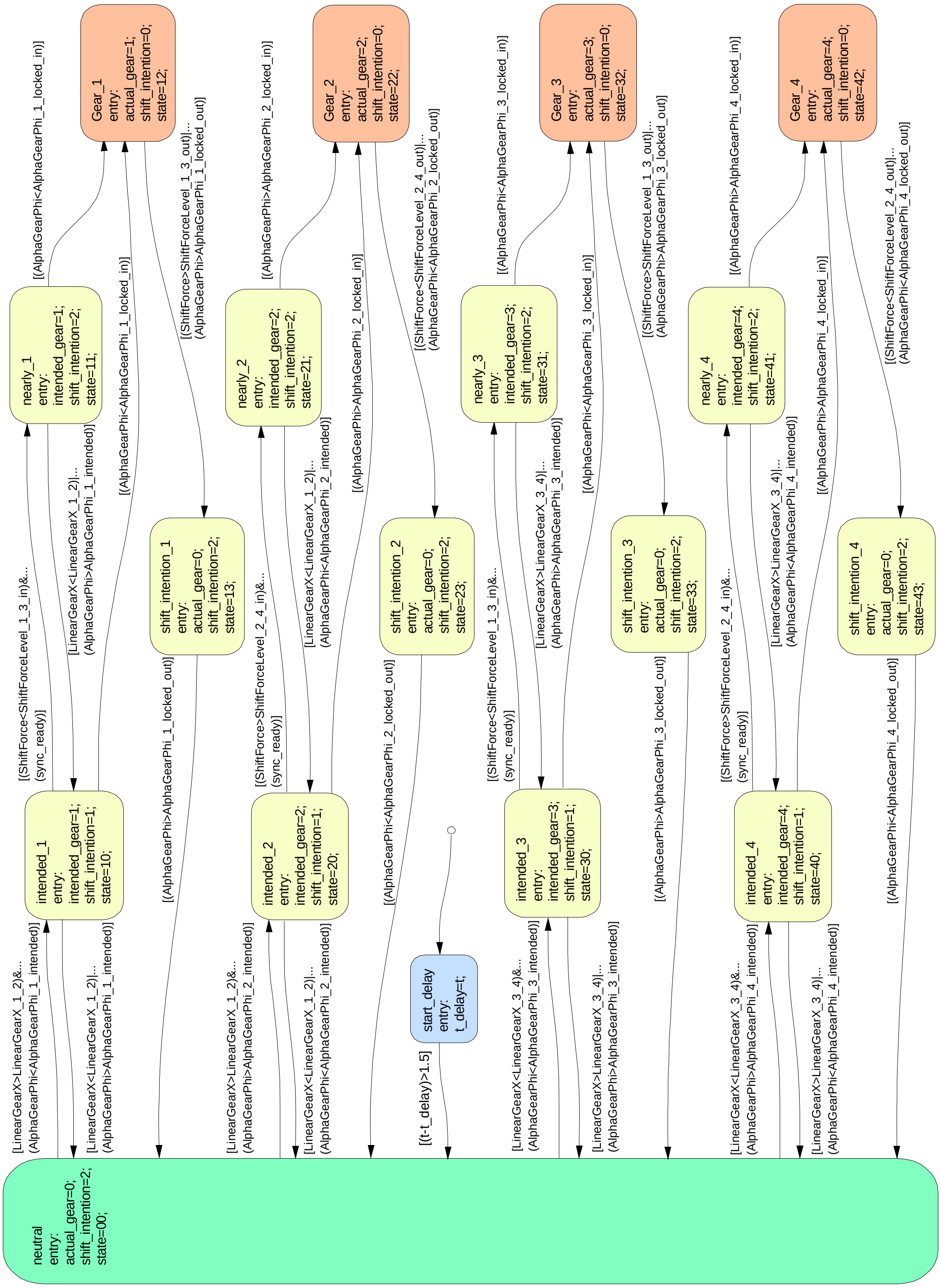

Figure 16
State machine for the gear identification

Simulation of the power train

The simulation model consists of several modules representing the mechanical components, as well as a system for the driving strategy and the driver. The driver model, which intends to follow the cycle, acts on the drive train by producing a driving or braking demand. The strategy converts this into appropriate torques and speeds of the electric motor and the combustion engine. These moments were converted – regarding the correspondent losses- in the gearbox and the final drive and transferred to the vehicle model. In the vehicle subsystem the velocity is calculated by integrating the acceleration. The acceleration itself results from the equilibrium of driving resistances, driving forces of the engines and the inertia forces of the vehicle mass and reduced rotating inertias.

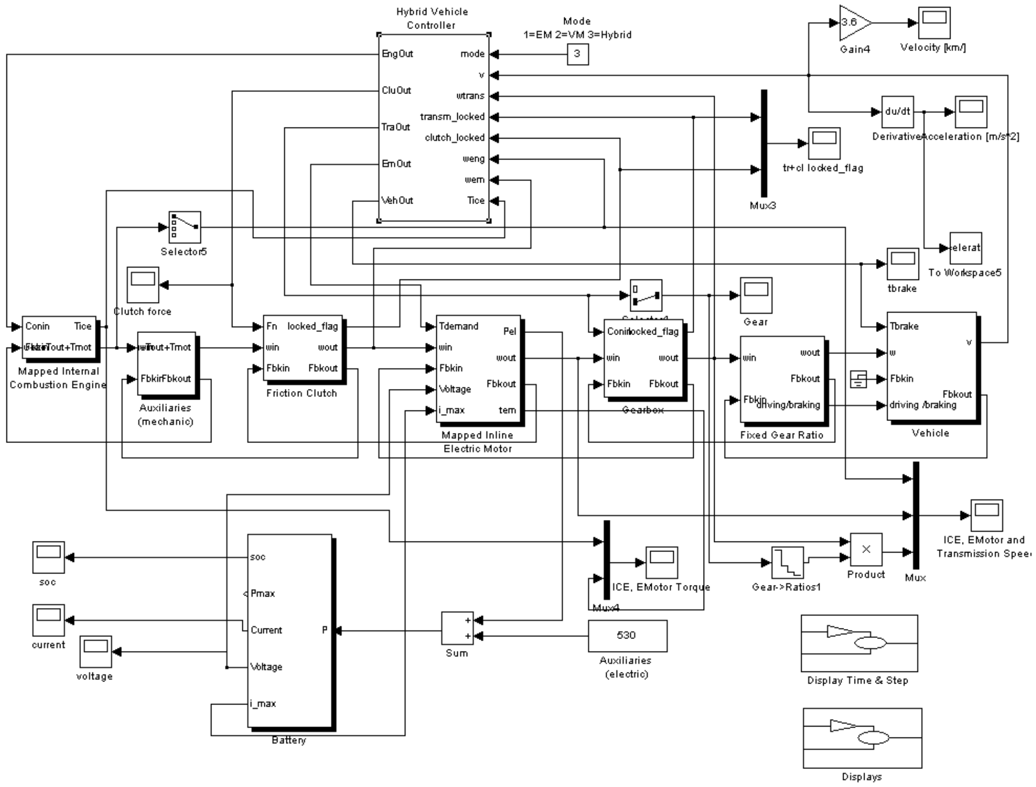

Figure 17
Simulation Model for the Hybrid Vehicle

The modules to simulate the drive train are taken from an internal ika library of already existing modules. The fuel rate of the internal combustion engine, the efficiencies of the electrical machine and gearbox are stored in maps.

A detailed model of the clutch, gearbox with synchronisation clutches and electric motor arrangement enables refined analysis of the gear change and is necessary to analyse the active synchronisation by the electrical motor. The battery model is based on two look up tables, which represents the behaviour of the internal resistance and the open circuit voltage versus the state of charge of the battery.

With this longitudinal simulation model of the INMOVE vehicle different aspects have been analysed. The aspects analysed are the shifting process, the driving performance, the fuel consumption and the start up of the ICE. The analysis of the shifting process indicates, that the time needed for active synchronisation is in the worst-case 0.4 s leading to an overall shifting time below one second. The simulations of the hybrid vehicle’s performance showed, that all targets can be achieved. On hybrid-mode in particular the initial operating strategy has to be improved to achieve an optimised overall system efficiency. The resulting simulated fuel consumption in the NEDC in hot mode is 5.72 l/100 km.

Additionally, a strategy to tow start the ICE by closing the clutch has been designed and the feasibility has been proven.

During the development process of the software for the hybrid vehicle controller autocode tools were used successfully in different steps. In a first step, RCP-tools were used to transfer strategies from the simulation of the complete vehicle. In a second step automatic code generation has been used to implement several sub functions of the operating strategy. [6]

Demonstrator Vehicles

All the components described above are installed in two prototype vehicles (evaluation prototypes), to evaluate the concept of this design in real live under driving conditions. The figures 18, 19 and 20 show the prototype(s) and the package of the engine compartment.

Figure 18
Prototype hybrid vehicle

Vehicle data:

Curb weight:	1380 kg (for evaluation prototype, goal 1300 kg)
Acceleration:	0-100 km/h 14 s
Top speed:	150 km/h
Power train:	ICE 1.4 l Otto engine, 55kW @5300 rpm, 112 Nm @2800 rpm permanent synchronous motor 25/30 kW (nom./peak) 4 speed manual gearbox, automated clutch

Figure 19
Engine compartment (1^{st} Prototype)

Figure 20
Engine compartment (2^{nd} Prototype)

With the prototype vehicles functional tests and measurements of the fuel consumption and exhaust emissions have been performed.

One specific event, which has been analyzed in detail, was the shifting process, where the electric motor synchronizes the speed of the input shaft of the gearbox. The following figures show the operation of the electric motor and combustion engine during a part of the ECE cycle. The vehicle starts electric, then an up shift from first to second gear occurs and afterwards the internal combustion engine is activated. During the shift process, the electric motor has to decelerate itself and the input shaft of the gearbox. As a result, the electric motor operates for a short time (t = 102 s) in regenerative mode with negative torque.

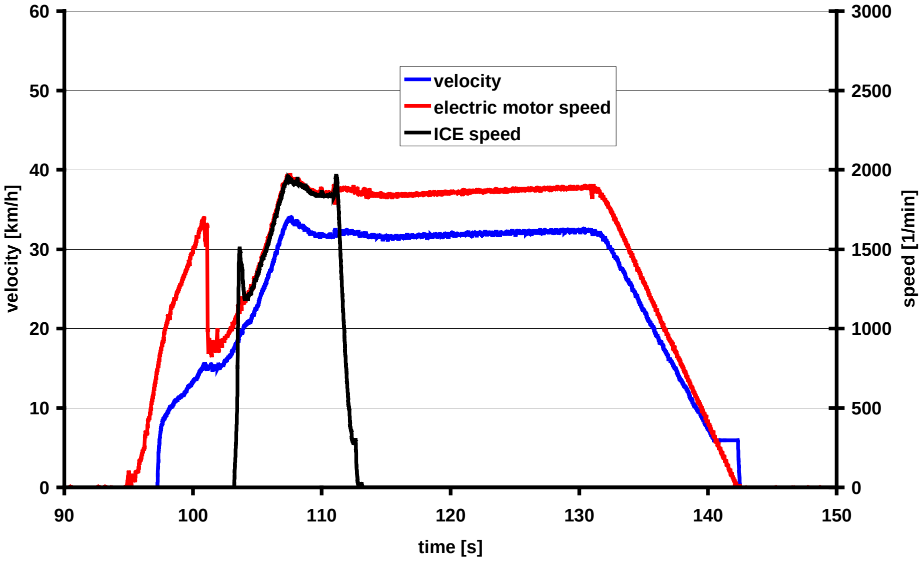

Figure 21
ICE and electric motor speed

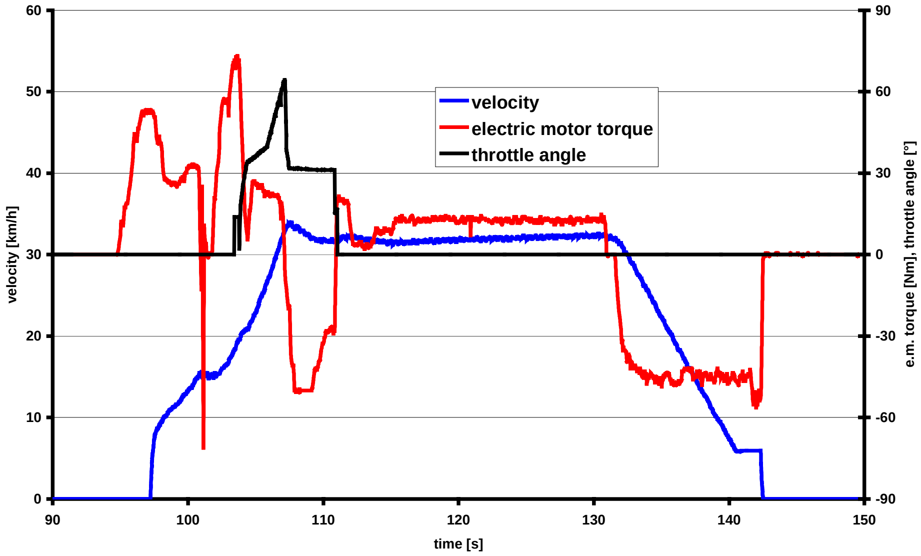

Figure 22
ICE throttle angle and electric motor torque

A second phase of regenerative operation of the electric motor occurs between t =107 s and t = 111 s. In this phase, the torque demand is nearly zero to compensate the overshoot in velocity and so it is lower than the minimal allowed torque of the ICE. Therefore the ICE stays at 40 Nm with a throttle angle of about 32°, whereas the electric motor operates with negative torque of about –40 Nm. The negative torque demand by the driver triggers also the cut off of the ICE, and after a delay, the engine stops.

For the consumption measurements, the vehicle was loaded up to 1600 kg, which reflects the weight of a typical driver of 75 kg plus 145 kg payload. For calculating the fuel consumption, the influence of the change in the state of charge of the battery has to be considered.

Figure 23 shows the result of three test runs in the European driving cycle (City and Extra Urban Driving Cycle) in hot mode.

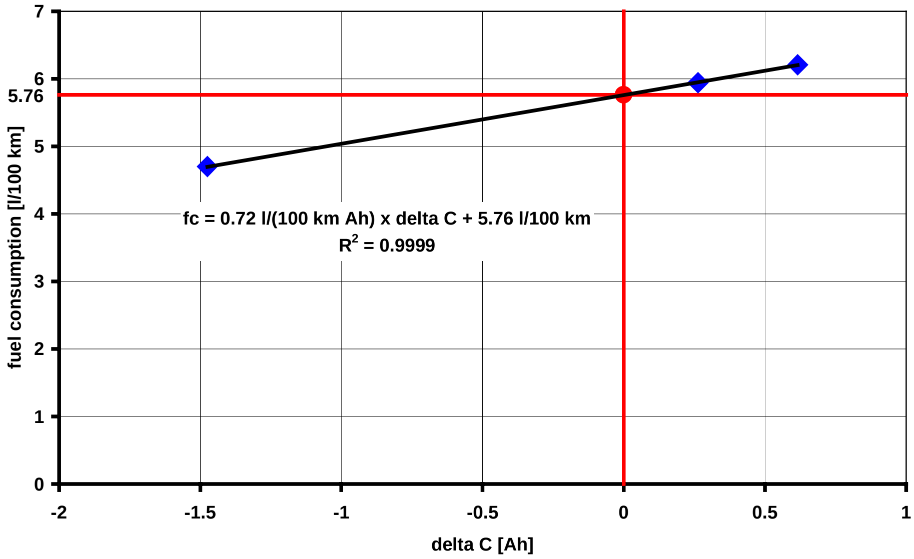

Figure 23
Regression of Ah-balanced fuel consumption in the EUDC
(total vehicle weight 1600 kg)

As the strategy of the vehicle tries to keep the state of charge within 50 and 80 %, only relatively small changes in the state of charge occur, here represented by the capacity [Ah] going in and out of the batteries.

The results of fuel consumption measurements (Ah balanced) in cold and hot mode are summarized in Table 2.

Table 2
Fuel Consumption Measurements

Consumption	(l/100 km)
Urban (ECE)	6,9
Extra Urban (EUDC)	5,9
Global	6,2
Global (hot start)	5,7
90 km/h	5,8
120 km/h	8,1

The resulting fuel consumption of 6.2 l/100 km for delta C equal to zero is -compared to a conventional vehicle of this size- remarkable low. (The conventional vehicle with the same engine is rated at 8.6 l/ 100 km with a correspondent test weight of 1245 kg)

Performances (Table 3) have been measured with different battery state of charges. It could be recognized that the performances are more or less identical independent of the battery SOC. Maximum speed is achieved using the electrical motor additionally. Thus this speed can't be maintained during a long time, since the operating strategy doesn't allow a complete discharge of the battery.

Table 3
Performance Measurements

Maximum speed (km/h)		133 without using battery 148 using battery
Accelerations (s) from stop		
0 to 400 m		20,5
0 to 1000 m		37,5
0 to 100 km/h		15,2
Acceleration (s)		
2nd Gear from 14 to 40 km/h		4,3
3rd Gear from 30 to 60 km/h		7,9
4th Gear	from 60 km/h on 400 m	17,8
	from 60 km/h on 1000 m	36,9
	from 60 to 90 km/h	12,8
	from 80 to 120 km/h	22,4

Conclusion

It seems quite obvious that the introduced Parallel Hybrid Concept will demand an increased vehicle system price, caused by the additional components and increased system complexity, although the most simple system design has been selected. This additional costs might be balanced by reduced fuel consumption over the lifetime, but the experience of the automotive market shows, that such line of reasoning often will not appropriately considered by the final consumer.

Therefore basically the design of each new component has been aligned to cost reduction. Additionally it appeared during system design phase, that the modification of conventional drive train components may be utilized for cost reduction too. The combustion engine may be downsized, leading to reduced fuel consumption too, and peak torque ratings may be balanced by the electric drive. Also the gearbox may be simplified by dropping fifth and reverse gear as indicated. Finally the starter might be eliminated and substituted by an engine start employing the electric drive motor or by clutch operation during driving.

But it is well known that one main point for success of innovations is an increase of value - in terms of performance, functionality or comfort - in relation to the effective additional costs. The introduced Parallel Hybrid offers several promising features, that will support this strategy:

The driving performance, according to the established requirements, has been completely met or even surpassed. Especially the property of the electric drive, offering a peak torque at the low speed range results to an efficient support of the combustion engine. The boost operation, achieved by torque addition of both drives, show remarkable acceleration and the driving comfort will be increased, because a "lazy shift behavior" will be enabled.

The drive train automation supports the driver at a high level. He starts to drive by the electric motor only and the combustion engine is activated automatically if hybrid mode is pre-selected. The combustion engine may be stalled again during longer periods of floating operation.

Pure electric driving ability will allow missions in critical surroundings (e.g. inner cities).

The already introduced environmental benefits by reduced fuel consumption shall conclude this enumeration and have been confirmed by real measurements on the demonstrators.

The commonly participating companies on this project are quite confident, that not only an innovative drive train with environmental benefits and improvements regarding the driving comfort will arise, but also the commercial requirements to enable market introduction will be successfully met.

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