

## Development of a Post-Transmission Hybrid Powertrain

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### Abstract

Late 2006 Punch Powertrain started the development of a hybrid powertrain. To meet the next generation of hybrids head on Punch Powertrain defined ambitious targets with respect to fuel saving, total cost and vehicle implications. To supply hybrid powertrains to OEMs a minimal impact on the vehicle side is required.

This paper focuses on the chosen parallel topology, the general system optimisation strategy, the technology and components selection and the control system development. Simulations for different target vehicles are performed with detailed component maps. The fuel consumption target is well within reach. Actual hardware tests are planned for 2009.

*Keywords: parallel HEV, powertrain, transmission, switching reluctance motor, lithium battery*

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### Used Abbreviations

BCU	Brake control unit
CO <sub>2</sub>	Carbon dioxide
CVT	Continuous variable transmission
DoE	Design of experiments
ECU	Engine control unit
EMG	Electric motor/generator
EV	Electric vehicle
HCU	Hybrid control unit
LiFePO <sub>4</sub>	Lithium iron phosphate
ICE	Internal combustion engine
MCU	Motor control unit
NEDC	New European drive cycle
NiMH	Nickel metal hydride
OEM	Original equipment manufacturer
SoC	State of charge
SR	Switched reluctance
TCU	Transmission control unit

## 1 Introduction

In 2006 Punch International took over the Belgian CVT transmission plant from ZF with a clear goal: the development of hybrid

powertrains for small and medium passenger cars. The company was renamed Punch Powertrain. The newly developed hybrid powertrain would have to be competitive with the products from competitors at the time of introduction and maintain a competitive level for several years. To assure the hybrid powertrain meets head on these hybrids from the competitors Punch defined ambitious targets.

This paper focuses on the chosen topology, the system optimisation strategy, the technology and components selection and the control system development. Simulations for different target vehicles are performed with detailed component maps. The fuel consumption target is well within reach. Actual hardware tests are planned for 2009.

## 2 Strategic View

The strategic view of Punch Powertrain is to develop a next generation hybrid powertrain. This powertrain will need to lower the barriers for OEMs to offer hybrid versions of their vehicles. Ambitious targets were set to fulfil the strategy.

## 2.1 Fuel Saving

The main target is a fuel saving of minimum 25%/15% on the NEDC drive cycle with gasoline/diesel cars while achieving similar savings in real world drive cycles. These savings need to be realised by the powertrain only. Especially for the gasoline hybrid powertrain the target is high compared to the theoretically maximum saving of nearly 40% that can be attained [1]. Additional measures at the vehicle level like engine efficiency improvement, mass reduction and streamlining allow realising further fuel consumption reduction. The similar savings of greenhouse gases can help to meet the CO<sub>2</sub> emission target of 130 g/km set forward by the European Commission.

## 2.2 EV-Range

An EV-range of at least 13 km at city traffic speeds fits into policies of some major European cities to reduce harmful emissions in cities. It allows emission free driving into and out of most city centres. When benefits from incentives can be gained or taxes (e.g. the congestion tax in London) can be avoided the cost premium for the hybrid powertrain can be partially or totally compensated.

## 2.3 Compatibility

As Punch Powertrain intends to supply the hybrid powertrain to OEM's which will integrate it in vehicles that are also marketed with conventional powertrains, the hybrid powertrain should be compatible with a conventional vehicle architecture. Moreover, the total impact of the hybridisation on vehicle packaging, functionality and user comfort should be minimal.

## 2.4 Target Segments

Punch Powertrain targets the most popular vehicle segments of small and medium passenger cars and small vans in Europe. Both Toyota and Honda have proven that in these segments a considerable number of hybrid vehicles can be sold [2].

## 2.5 Cost Target

Punch Powertrain has set strict cost targets to lower the barrier for OEMs and their customers to buy vehicles with this powertrain. Buyers in these target segments are very cost sensitive. Therefore the cost premium for the hybrid must clearly allow a high return on investment.



Figure 1: Hybrid Powertrain by Punch

## 3 Hybrid Strategy Development

To meet the fuel saving target as well as the EV-range only a full parallel hybrid configuration is within the scope. Because Punch Powertrain intended to develop a dedicated hybrid transmission, two configurations were possible.

### 3.1 Hybrid Configuration

When developing a hybrid powertrain various system architectures are possible, each with advantages and disadvantages. The selection of the optimal system architecture is a compromise between cost, performance (efficiency) and vehicle packaging constraints.

Punch Powertrain aims at a segment of front wheel driven vehicles, where the conventional layout consists of a transverse positioned four cylinder engine directly connected to a transmission which incorporates a differential.

When developing a CVT based hybrid, there are basically two options within the system architecture. The first option is to link the electric motor/generator with the powertrain before the CVT variator. Although the motor/generator can be located elsewhere a configuration similar to some other hybrid powertrains with a flywheel motor/generator is quite common. At Punch Powertrain this is called the "PRE" configuration. The other configuration, hence called the "POST" configuration, links the electric motor/generator behind the variator.

For both configurations a physical simulation model of the powertrain including system optimisation strategy was developed. A first step in

this strategy development is to create a holistic view on the optimisation principles. To reach the ambitious fuel reduction targets a system optimisation rather than a component optimisation [3] is required. The optimisation principles were cast into newly developed mathematical models to derive the operating areas for the different hybrid modes.

The key advantage of the POST configuration is a higher system efficiency. Additionally, the higher efficiency of the POST configuration allows a substantially increased EV-range compared to the PRE-configuration when using the same battery capacity.

An advantage of the PRE-configuration is the fact that the electric motor/generator with lower torque specification can be used due to the torque multiplication through the CVT transmission.

### 3.2 Basic Simulations

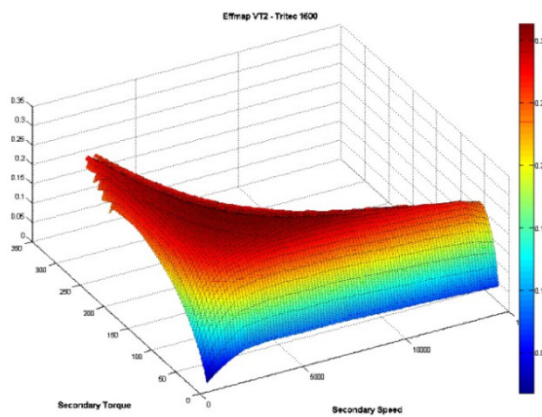


Figure 2: Combined Efficiency of Engine with CVT

Initially, a backwards [4] calculation scheme in spreadsheet was used to implement and refine the strategies. This scheme was first based on simple component characteristics as a first validation of the optimisation principles. The required torque at the wheels is calculated backwards to engine and motor torque. Gradually, the calculation scheme was extended with more complex component maps. This required a migration from a spreadsheet based tool to a Matlab® based application. Eventually, the calculation scheme contained very detailed component maps and yielded realistic fuel consumption results for non-hybrid vehicles.

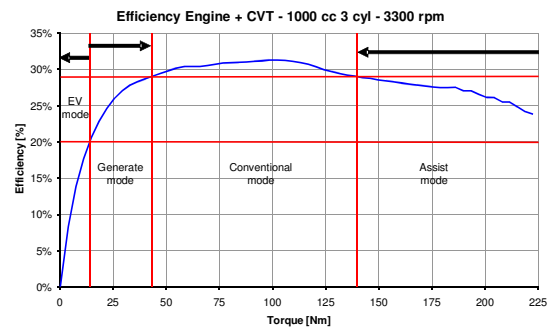
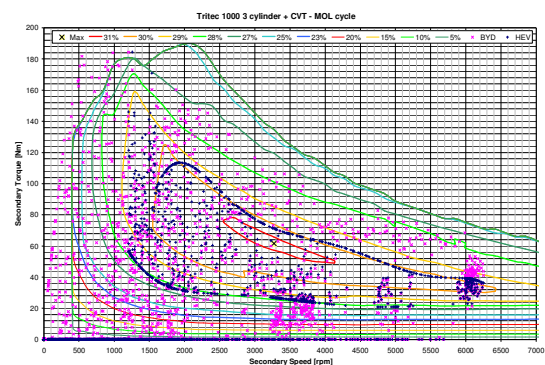


Figure 3: Use of the Hybrid Modes depending on Torque Levels at a Given Speed

The calculation scheme allowed comparing both the PRE and POST configuration. Overall the POST configuration resulted in higher fuel savings on both type approval drive cycles and real world drive cycles. The PRE configuration demonstrated a higher launch acceleration from stand still due to the torque multiplication by the variator. Due to the higher fuel saving potential Punch Powertrain opted for the POST configuration although this requires a more powerful electric motor/generator.

### 3.3 High-end, Dynamic Simulations

In parallel with the calculation scheme, a highly detailed and dynamic hybrid powertrain simulation was developed in Matlab®/Simulink® by using the SimDriveLine® toolbox. The POST configuration strategy was carried over from the calculation scheme and further refined. The powertrain simulation tool uses a forward approach, i.e. driver action causes vehicle acceleration. Furthermore, the inertia of all powertrain components as well as highly detailed component models are included. This allows fully simulating the transient behaviour inside the powertrain and adopting the strategy to obtain a good driveability (low jerk level).



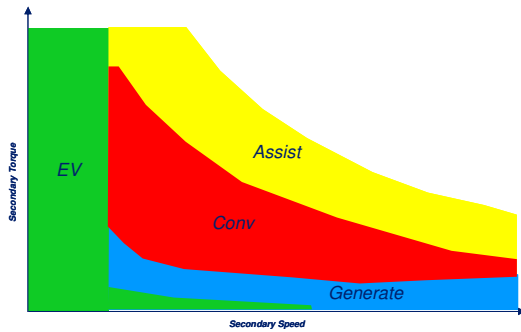


Figure 4: Operating Points and Actual Modes during a Real World Cycle

Figure 4 shows the results for a certain C-segment vehicle. The upper graph shows the non-hybrid (magenta) as well as the hybrid operating points of engine+transmission. This allows dividing the complete speed-torque maps into different areas with different operating modes of the hybrid powertrain as shown in the lower graph of Figure 4.

### 3.4 Optimisation by Design-of-Experiments

The simulation tool was used to perform a DoE to find the optimal components sizing. For the electric motor and the battery system three levels of components were used. Two engines were used, one was the standard engine and the other one was largely downsized. To assess the robustness of the strategy the simulations were performed for two vehicle types and on two cycles.

Table 1: DoE Variables and Levels

Electric motors (number is lamination diameter)	SR157 SR210 SR246
Battery systems	CAEC 9.5 Ah K2 10.0Ah K2 12.5Ah
Engines	1.6l – 4 cylinder 1.0l – 3 cylinder
Vehicles	B-segment C-segment
Cycles	NEDC MOL (real world)

For all different configurations the full impact of the components (e.g. a larger, more efficient motor/generator or battery pack also implied increased vehicle mass) was included.

Because the simulations could easily be run overnight, all possible configurations were simulated. Figure 5 shows the main results. The size of the electric motor has the highest impact on the fuel saving, especially for the larger vehicle. Also the effect with a real traffic cycle is substantially larger.

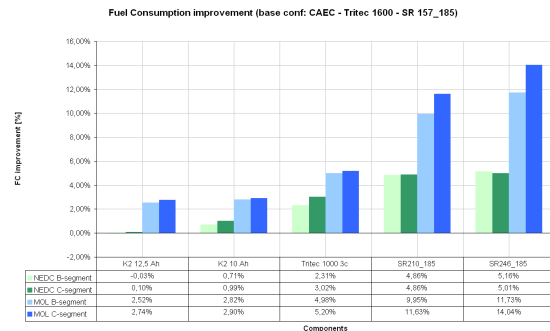


Figure 5: DoE results Ranked from Low to High Impact

The DoE was also used to investigate the robustness of the hybrid strategy. The optimal configuration derived from the DoE yields fuel savings above target. The savings are realised for representative vehicles in both segments and for both cycles (NEDC and real world).

## 4 Component and Subsystem Selection

The selection of the batteries and the electric motor/generator are two important cornerstones in how the hybrid strategy can achieve the fuel saving target. While maximising the efficiency gains on the engine side, and keeping the system within cost and mass constraints, the electrical losses must be minimized to maintain the total efficiency gain in the system.

### 4.1 Electric Motor/Generator Drive

The combination of the electric motor/generator and its power electronics must have a high efficiency over a wide speed and torque range. At the same time the drive should provide a high power density and a low cost. An investigation of available technologies, products and suppliers resulted in the choice for a switched reluctance (SR) motor/generator. This type of electric motor/generator is the best match to the above requirements.

Punch Powertrain decided to partner with PsiControl mechatronics to develop and produce the SR motor/generator. PsiControl mechatronics has more than 10 years experience in industrial SR drives.





Figure 6: SR Motor - Sample Stator and Rotor

PsiControl mechatronics needed to develop a new approach. In contrast with industrial applications with nominal speed and torque, the motor/generator loading in an automotive hybrid powertrain is very diverse. Different design tools like the thermal modelling needed adaptations to cope with the varying load.

The result is a compact but powerful electric drive. Tests show that the motor is matching its predicted performance. Currently it is tested using the HCU to control the motor output and the prototype battery pack to investigate their combined performance.

#### 4.2 Battery System

The efficiency and the EV-range target rule out the use of NiMH batteries. Classic Lithium chemistries as currently used for laptops and cell phones pose a serious safety risk especially when these cells are scaled to capacities as required for hybrid vehicles. Therefore Punch Powertrain opts for the LiFePO<sub>4</sub> chemistry. This emerging chemistry combines high efficiency, usable SoC range, sufficient power and energy density, excellent cycle life and safety.



Figure 7: Prototype Battery System

An evaluation of different suppliers of a combination of LiFePO<sub>4</sub> cells and battery management systems yielded a preliminary short list of possible battery system suppliers. The list is considered as preliminary because LiFePO<sub>4</sub> technology is still immature and important players are still expected to emerge.

### 5 Transmission Design

The design of the CVT transmission for the hybrid powertrain was based on the existing CVT transmission from Punch Powertrain. The new development should maintain a maximal level of compatibility to the current production CVT, to reduce manufacturing cost.

Some mechanical features of the transmission could be completely eliminated, such as the conventional reverse drive system (replaced by electric reverse function of the traction motor) and the engine driven oil pump (replaced by a separate electric powered oil pump).

A new feature that was added to the transmission is the connection of electric motor to the secondary variator shaft of the CVT. This was achieved by use of a high volute chain which combines high efficiency (> 98 %), durability and low acoustic noise. This chain connection causes minimal changes to the rest of the transmission and allows a fairly long electric motor/generator. Consequently a large number of parts is carried over from the conventional CVT.

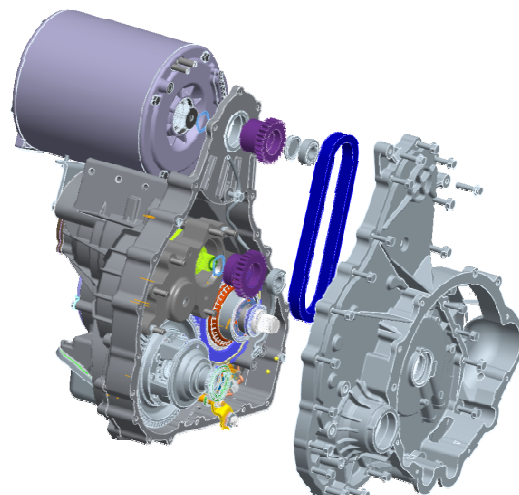


Figure 8: Hybrid Transmission with Electric Motor/Generator. New parts in exploded view

By meeting the tight sizing constraints the hybrid powertrain will fit in nearly any engine bay that

can accommodate a conventional powertrain with Punch Powertrain's CVT. This is illustrated by Figure 9.

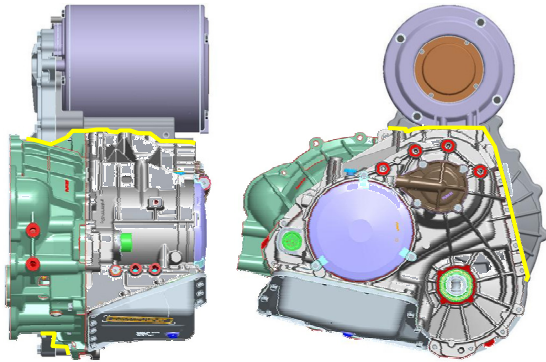


Figure 9: Comparison between Conventional and Hybrid Transmission

Once the hybrid powertrain has proven its potential a production intent design will be made. This new transmission will feature several efficiency improving components and designs. Today most building blocks of this next design are known.

## 6 Control System

The simulation tool mentioned earlier does not stand by itself. It is the first stepping stone in the development of an embedded hybrid powertrain control system. The logic developed in the Matlab®/Simulink® environment can be converted into embedded control software with a minimum of hand coding. Punch Powertrain has acquired different dSpace® rapid control prototype hardware and software tools to implement the hybrid control logic from the simulation in prototype controllers.

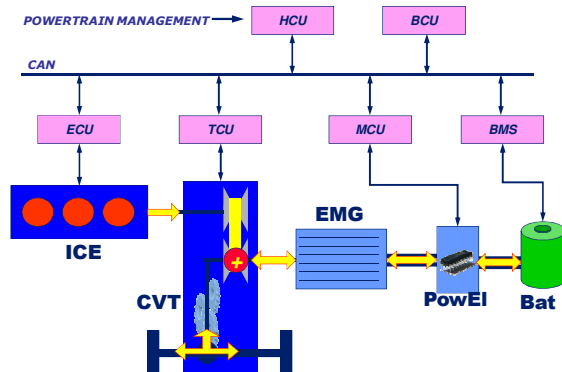


Figure 10: Powertrain Control Architecture

The hybrid control unit (HCU) is the master controller in the powertrain. The throttle pedal actuation by the driver is converted by the HCU into a torque demand for both the engine and the

motor/generator and a ratio setting for the transmission. The hybrid powertrain control continuously sets the most efficient operation parameters. The strategy is to a large extent robust. Consequently a substantial fuel consumption reduction is achieved for different cycles in charge sustaining mode.

## 7 Results and Short Term Plans

The calculations as well as the simulations have shown that the target fuel consumption saving is within reach. Currently results better than the 25% saving on the NEDC-cycle are obtained while other cycles also yield high savings. The first tests of the SR motor are also promising with respect to torque and efficiency.

Currently two prototype powertrains are being built. One powertrain will go through functional testing on a powertrain test bench. In parallel, the second powertrain is being integrated into a vehicle (Smart ForFour) for initial calibration and improvement of driveability. While the vehicle will be improved for driveability, the powertrain will be tested thoroughly on the test bench and further optimised for efficiency.



Figure 11: Hybrid Powertrain in Smart ForFour Engine Bay

## 8 Preliminary Conclusion

The hybrid powertrain under development at Punch Powertrain is made to be built into standard vehicles without too much modifications and compromises. It will provide a substantial fuel saving compared to similar conventional powertrains under most to all circumstances.

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## Authors



In 1985 Patrick Debal graduated as Master of Science in Mechanical Engineering at the University of Leuven, Belgium. He held several positions in research and development before joining Punch Powertrain 2006. At Punch Powertrain Patrick and his team develop a next generation, highly performing hybrid powertrain. In 2009 the first hybrid powertrain from Punch Powertrain will be demonstrated.



Saphir Faid graduated in 2004 as Master in Electro-Mechanical Engineering from GroupT University College in Leuven, Belgium. He worked on several electric vehicle projects including solar cars and a fuel cell race vehicle, before joining Punch Powertrain in 2008. Saphir is responsible for subsystems and components of the hybrid powertrain.



Steven Bervoets graduated in 2008 as Master of Science in Electro Technical and Mechanical Engineering at the University of Leuven, Belgium. In September 2008, he joined the Controls Group of Punch Powertrain to develop and test the hybrid control system.



In 2000, Laurent Tricoche graduated as Master of Science in Mechatronics Engineering at the University of La Rochelle, France. He held several positions in Controls/Systems development in motor sport before joining Punch Powertrain in 2007. At Punch Powertrain, Laurent coordinates the development of the complete hybrid control systems.



Brecht Pauwels graduated in 2002 as Mechanical Engineer, option Mechatronics, at the KULeuven. Since September 2002 Brecht is active within the R&D department of PsiControl Mechatronics as R&D engineer. As of May 2007 Brecht is responsible for the Motors, Actuators and Mechanics cluster within R&D of PsiControl Mechatronics.