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Parallel Hybrid (Boosted) Range Extender Powertrain

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Abstract

The parallel hybrid powertrain developed by Punch Powertrain provides also a nice solution for range extender and boosted range extender vehicles. While most range extender solutions like the GM Volt or the Jaguar XJ Limo Green Hybrid Concept have a series hybrid topology Punch's uses a parallel hybrid topology. A parallel topology offers a higher efficiency when the vehicle is driven in hybrid mode. This is even more the case by applying the strategy developed at Punch for this powertrain. This strategy can narrow down the combined engine and CVT operation to peak efficiency.

This parallel topology does not only offer the possibility to extend the EV-range of the vehicle, it also allows extending the power in cases the vehicle is used in high power situations its EV powertrain is not designed for. By applying this powertrain in vehicles used for urban and suburban deliveries the electric powertrain can be sized for the majority of its use, i.e. low to medium speed driving using low to medium power. The engine can kick in when more power is required, e.g. high speed driving or accelerating with high payloads.

Consequently this concept allows using a lower power rating for the electric powertrain (motor/generator and battery). Due to its parallel topology also one electric machine is required. These cost advantages come with the necessity to use a CVT transmission. Most parts of this transmission are already made in high volume while the other parts are carried over from the other hybrid powertrains from Punch. Consequently this CVT transmission can be produced at low cost.

As such Punch Powertrain offers a valid alternative to equip electric vehicles with a cost and fuel efficient range extender or boosted range extender powertrain.

Keywords: parallel HEV, series HEV, PHEV, simulation, vehicle performance

1 Introduction

Powertrain's hybrid powertrain as presented at EVS-24 is a parallel hybrid powertrain for charge sustaining and plug-in hybrid powertrains. Following the vehicle test in the summer of 2009 Punch concluded that the switched reluctance electric motor/generator was capable of driving the vehicle in electric mode up to fairly high speeds.

This implies that the electric motor/generator can also be used for EV applications.

The many announcements of EVs with range extender, as production vehicle or as concept/demonstrator vehicle, made Punch Powertrain consider whether a range extender option can be created with its parallel powertrain configuration. Some conceptual thinking revealed that applying a more powerful motor/generator, a battery pack matching the EV-range and a smaller

engine allowing continuous operation with a depleted battery matches the needs of the application.

This paper focuses on the comparison of the series hybrid range extender topology and the parallel hybrid range extender topology based on Punch Powertrain's developments. Both energy efficiency as well as a cost comparison are reported.

2 The Parallel Powertrains Developed by Punch Powertrain

Punch Powertrain has already presented its parallel hybrid powertrain development at different occasions [1, 2, 3]. Since mid 2009 the powertrain is built into a demonstrator vehicle (see Figure 1) for functional tests and calibration for driveability. When the driveability is realized an identical powertrain is planned to go on a chassis dynamometer test bench for strategy validation.

Figure 1: The hybrid powertrain in front of the Smart Forfour demonstrator

As the hybrid powertrain is built into the demonstrator no engine downsizing is applied. Hence this hybrid powertrain has more power than its conventional counterpart. This hybrid configuration is the power hybrid. The typical engine downsizing for fuel economy would be replacing the engine by an engine 25 to 30% smaller. In most cases a 3-cylinder engine can be used. Depending on the battery size and the strategy this economy hybrid can be used as charge sustaining or as plug-in. The plug-in option will change the blending of engine power and electric power until the battery is depleted to a certain level. The (boosted) range extender concept, subject of this paper, even requires a smaller engine, in most cases a 2-cylinder engine. The different powertrains are depicted in Figure 2.

Figure 2: Hybrid configurations being developed by Punch Powertrain

How the different configurations have an effect on powertrain length and hence space in the engine compartment is shown in Figure 3.

Figure 3: Pictures of the 3 Powertrain Concepts

3 The Powertrains

The range extender powertrains under consideration can be seen as EV powertrains. In the case of the parallel hybrid range extender, a conventional powertrain with an engine and transmission is mechanically connected to EV powertrain transmission. For the series hybrid range extender a genset comprising an engine and generator is linked to the vehicle DC-bus.

Figure 4: The parallel and series hybrid configurations

3.1 The Powertrain Component Sizing

The powertrain components need to be sized according to the vehicle. For this study a C-segment electric vehicle from a prior study with the following characteristics was used:

Table 1: Vehicle Properties

Property	Value	Unit
Mass	1500	kg
Cx	0.35	-
FrontArea	2,33	m ²
Rolling resistance	0.013	-
EV-range	100-160	km
Battery capacity	~ 83	Ah
Battery voltage	307.2	V

To support a constant speed of at least 120 km/h, the electric traction motor needs to be capable of minimum 25 kW continuous mechanical output power as this is required at this speed. The battery is able to support this speed for less than one hour. Both the series hybrid range extender and the parallel hybrid range extender require this motor for traction. The electric motor efficiency map is derived from the current switched reluctance motor at Punch Powertrain.

3.2 Series Hybrid Range Extender Add-On

To sustain the constant speed of 120 km/h the genset needs to deliver about 28 kW electric power and an engine capable of delivering 31 kW mechanical power. The electric power rating is continuous because this power needs to be available for periods longer than the 20 to 30 s that peak power can be provided by electric machines.

The selected engine is a 1l engine for which detailed fuel consumption data is available. The generator uses the same efficiency map as the traction motor.

The engine and generator are matched to find the optimal operating points over the engine/generator speed range. Figure 5 depicts the maximum engine torque $T_{eng,max}$ as well as the nominal generator torque $T_{gen,nom}$. Additionally the engine torque corresponding with the most efficient engine operation ($T_{eng,opt}$) as well as genset operation as a system ($T_{sys,opt}$) are shown

Figure 5: Engine and generator performance

This results in genset system performance with a specific fuel consumption below 300 g/kWh in a power range from 8.3 kWe to 28 kWe as depicted in Figure 6 (SpFC and P_{out} respectively). This allows a fairly efficient load following strategy within this power range. When the required traction power is outside this range it is more efficient to use the batteries as buffer while operating the genset within the range or shutting it off.

Figure 6: Genset performance

Very often the series hybrid is described as a powertrain allowing the engine to operate in its sweet point. This principle was applied in an alternative strategy by using the genset at a fixed point when battery state-of-charge is low. The fixed point is the genset power resulting in the same state of charge at the end of the cycle as in the beginning. This power setting is within the power range with specific fuel consumption below 300 g/kWh. With this strategy the battery is more intensively used as a buffer.

3.3 Parallel Hybrid Range Extender Add-On

For the parallel hybrid range extender add on the same 1l engine is used and a CVT transmission as used in the parallel hybrid powertrain from Punch. The hybrid strategy applied during range extension is the same as the used by the “standard” hybrid

powertrain. Its strategy principles have been reported in earlier publications, as mentioned above.

4 Simulations

Due to the very early stages of development of this range extender concept Punch Powertrain decided to implement the series hybrid range extender in its basic simulation tool that was also used in the early development stages of the hybrid project. This tool uses a backwards calculation of power through the powertrain. The parallel hybrid range extender is also simulated with this tool. Since both powertrains perform equally in EV mode the simulations are restricted to range extending.

4.1 Drive Cycles

Different drive cycles were used in the simulation. First of all, the NEDC cycle because this cycle is still the reference for fuel consumption. Additionally the Artemis light duty cycle also called CADC is used. It is developed in the Artemis project, a project in the European 5th Framework Programme, and a likely successor of the NEDC-cycle.

Two cycles recorded in real traffic were also simulated, the MOL-cycle developed by VITO as well as an additional recording of this cycle made in the DECADE-project (also a project in the European 5th Framework Programme). This last cycle is called MOL Decade. The original MOL-cycle is fairly aggressive. The MOL Decade is recorded in different circumstances, like different routing, road works, busier traffic and lowered speed limits. This results in a less aggressive cycle. Table 2 gives an overview of the cycle characteristics.

Table 2: Overview of cycles used in the simulation

Cycle	Duration [s]	Distance [km]	Avg. Speed [km/h]	RPA [m/s ²]
NEDC	1184	10.93	33.23	0.116
CADC	2970	49.65	60.18	0.169
MOL	2400	26.61	39.92	0.277
MOL Decade	3376	48.39	51.60	0.184

Figure 7: Non-type approval drive cycles

The RPA-parameter is the relative positive acceleration. It represents the amount of energy per kg vehicle mass required to perform the acceleration of the drive cycle. This parameter and its calculation method was originally been developed by van de Weijer [4]. The speed profile of the CADC, MOL and MOL-Decade cycles is given above.

4.2 Simulation Results

Before comparing the simulation results, it needs to be mentioned that the absolute levels of the fuel consumption should not be compared with actual vehicles. Furthermore, these differences should be placed in the context of a range extender vehicle that depending on the application may use its engine infrequently, in some cases never.

4.2.1 Load Following Series Hybrid Strategy

The simulations were run with an initial state of charge of 30%. If possible parameters influencing the EV-driving and the use of the genset were

changed to reach the same final SoC. If the final SoC could not be made identical to the initial by adopting the strategy, the difference in SoC over the cycle was corrected using the total fuel consumption and electric charge generated during the cycle.

Table 3: Simulation results, parallel hybrid vs. load following series hybrid

Cycle	Fuel Consumption [l/100km]			Diff.[%]
	Parallel	Series	Diff.	
NEDC	5.38	5.72	0.34	6%
CADC	7.19	7.62	0.43	6%
MOL	6.90	7.61	0.71	10%
MOL-Decade	6.96	7.56	0.60	9%

For all cycles the series hybrid range extender has a higher fuel consumption than the parallel hybrid range extender. Differences range from 6 to 9%. It needs mentioning that the simulation tool does not allow drawing conclusions if the difference in fuel consumption is small. In this case all results are considered to be significantly different.

To illustrate the operation of the genset two graphs were taken from the simulation of the MOL-Decade cycle. The first graph in Figure 8 is from city traffic with speeds up to 50 km/h. This part of the cycle shows accelerations followed by decelerations. So there is no part at constant speed. The generator is only activated during acceleration.

The second graph in Figure 8 shows a part of the extra urban part. Also here most part of the cycle exists of accelerations followed by decelerations. One exception is the part between 1908s and 1923s where speed is about constant. Here the genset generates about 10 kW to maintain the speed.

The power to maintain a speed is also illustrated in Figure 9. This figure is taken from the NEDC cycle. To maintain a speed of 70 km/h the genset generates 9 kW. At 50 km/h the required power drops below the minimum generated power and the genset is switched off.

Figure 8: Genset power versus vehicle speed in MOL-Decade cycle.

Figure 9: Genset power versus vehicle speed in NEDC cycle

4.2.2 Constant Load Series Hybrid Strategy

The simulations were run with an initial state of charge of 30%. The genset was set to operate at a fixed power whenever the SoC was below a given level. This power level of the genset was changed to reach the same final SoC. By adapting the SoC level under which the genset is active the power level of the genset could be lowered if it was on the high side and vice versa. This may also result in more efficient genset operation. Both parameters were changed until the lowest fuel consumption was reached with a final SoC equaling the initial SoC.

Table 4 shows the results of these simulations. Only two cycles, CADC and MOL, show a significant difference. In these cases the fuel consumption for the constant load series hybrid is

higher. This is most probably caused by extra conversion losses in the battery that are not compensated by a more efficient genset operation.

Table 4: Simulation results, load following series hybrid vs. constant load series hybrid

Cycle	Fuel Consumption			Diff.[%]
	[l/100km]			
	<i>Load following</i>	<i>Constant load</i>	<i>Diff.</i>	
NEDC	5.72	5.90	0.18	3%
CADC	7.62	8.32	0.70	9%
MOL	7.61	8.03	0.42	6%
MOL- Decade	7.56	7.50	-0.06	-1%

When comparing the results of the constant load series hybrid with the parallel hybrid the difference have further increased. The constant load series hybrid consumes 8 to 16% more fuel.

Table 5: Simulation results, parallel hybrid vs. constant load series hybrid

Cycle	Fuel Consumption			Diff.[%]
	[l/100km]			
	<i>Parallel</i>	<i>Series</i>	<i>Diff.</i>	
NEDC	5.38	5.90	0.52	10%
CADC	7.19	8.32	1.13	16%
MOL	6.90	8.03	1.13	16%
MOL-Decade	6.96	7.50	0.54	8%

5 Cost Comparison

When looking at the subsystems used in both configurations the following overview in Table 6 can be made.

From Table 6 one can see that comparing the cost of both hybrid configurations comes down to comparing the cost of the standard automotive CVT with the cost of the generator plus the single ratio reduction gearbox. The current experience shows that the cost difference will be too small to be decisive if other factors come into consideration.

Table 6: Subsystems overview

Subsystem	Configuration	
	Parallel	Series
Traction Motor	30 kW nominal, 60 kW peak (matched to generator power)	
Engine	1 liter gasoline engine, approx. 55 kW peak	
Generator	None	30 kW nominal, peak matching the engine
Transmission	Standard automotive CVT	Single ratio reduction gearbox

6 Vehicle integration

One such factor in the decision to go for the series or the parallel configuration is vehicle integration. The parallel hybrid topology requires all main components except the battery to be built into the engine compartment. Therefore vehicles with this type of range extender will resemble more the standard vehicle. More or less standard engines are the preferred fuel converter because they match the transmission.

The series hybrid topology allows more freedom in accommodating the genset in the vehicle. The fuel converter does not have to be a standard engine like in the parallel topology. Other fuel converters like gas turbines can be considered if their efficiency and time to get up to speed allows a flexible operation.

7 Boosted Range Extender

The parallel hybrid configuration allows both the engine and electric traction power to simultaneously drive the wheels. This feature can be turned into a benefit in vehicles that very seldom require full power. Examples are mail distribution vehicles in cities and suburbs. During normal operation these vehicles never leave the area where they are used and high speeds do not occur. Only when these vehicles need to travel over longer distance, e.g. for maintenance or moving to another operating area, they may require the high power.

For these applications the parallel hybrid range extender allows reducing the electric motor to the requirements of the normal operation. Whenever more power is required the engine can kick in and the powertrain changes from EV to HEV operation. The benefit is a downsizing that can be applied on the electric drive, hence a cost saving.

8 Conclusions

This study has compared a parallel range extender powertrain developed by Punch Powertrain with a series hybrid range extender powertrain with similar performance. For the series hybrid powertrain two different optimizations were applied, one focusing on load following with an optimized genset performance and one with a constant load requiring more buffering by the battery. Simulations have shown that the parallel range extender hybrid powertrain is more fuel efficient than a series hybrid powertrain. The load following strategy of the series hybrid is more efficient than the constant load strategy.

Other factors are also considered. The costs of both powertrains are comparable. The vehicle integration of the series hybrid range extender allows more flexibility because the genset can be put in a more convenient place. Finally the parallel hybrid range extender allows opting for a boosted range extender depending on vehicle use.

As a result one can conclude that the parallel hybrid range extender developed by Punch Powertrain is a valid alternative for the series hybrid range extender.

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List of Abbreviations

CADC	Common Artemis Driving Cycle
CVT	Continuously variable transmission
DC	Direct current
EV	Electric vehicle
HEV	Hybrid electric vehicle
NEDC	New European drive cycle
PHEV	Plug-in hybrid vehicle
RPA	Relative positive acceleration
SoC	State of charge

9 Authors

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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 was demonstrated.

ing. Saphir Faïd

Saphir Faïd 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, including the development of the switched reluctance motors.

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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.