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Increasing Functionality of the Micro Hybrid System at Low Cost

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Abstract

The Advanced Lead Acid Battery Consortium (ALABC) has since 2000 been working to demonstrate valve-regulated lead-acid (VRLA) batteries in hybrid electric vehicles and has shown that advanced designs can cope with this duty cycle with good reliability [1]. This demonstration work has been done by converting existing vehicles and thus all work to date has utilized Japanese mild hybrids.

The European market is coming at hybridization from a different direction, with the introduction of low-cost micro-hybrid stop/start systems, such as the BMW EfficientDynamics [2], in order to meet CO_2 regulations. Recently, Controlled Power Technologies (CPT) has been promoting an alternative way of achieving mild hybrid performance [3], which would meet projected CO_2 regulations, at a fraction of the cost of the current Japanese approach. This new system would operate with advanced VRLA batteries at 12V or 48V and provides an opportunity for lead-acid to be at the leading edge of hybrid technology.

Keywords: Lead-carbon, HEV, Downsizing, Electric Supercharger, Turbocharging

1 Introduction: The LC Super Hybrid

The ALABC became aware of CPT when both organisations had been present on the UK Stand at earlier JSAE Exhibitions in Yokohama. CPT had expressed interest in working together to explore the advantages of advanced VRLA batteries in increasing the functionality of micro-hybrid systems. We first became directly involved with them in a UK Technology Strategy Board sponsored project known as HyBoost which was being coordinated by Ricardo in the UK. This involved using a greatly down-sized Ford Fox 1.0 litre engine to replace a naturally aspirated 2.0 litre engine in a Ford Focus vehicle. The engine was turbocharged and was also fitted with the CPT electric super-charger (VTES)[1]. However in this project the stop/start and energy recovery system was provided by Valeo and involved the use of super-capacitors (the StARS '12 + X' system). The EALABC's role in the project was to investigate lower cost energy capture and storage systems based on advanced VRLA batteries. While we were happy to work with CPT in the HyBoost Project, both companies realised that, with the '12 + X' system in that project, it was unlikely to provide the answers that both companies were seeking – namely a truly

[1] The CPT electric supercharger business was subsequently sold to Valeo in December 2011.

low-cost solution to increased functionality of the micro hybrid approach. It was therefore decided to work together on an alternative approach utilising the CPT technology alongside the ALABC's battery experience.

1.1 Project Methodology

The challenge facing the automotive industry, as it emerged from its most recent financial stresses, is the urgent need to deliver an investment efficient, CO_2 reduction technology roadmap, compatible with consumer price expectations and legislative demands. As always, the engineering community had initially responded well by taking advantage of the readily available CO_2 reduction technologies such as mild engine downsizing and down-speeding, transmission optimization and simple starter motor based Stop/Start systems. Unfortunately corporate objectives for CO_2 reduction are demanding affordable but more significant (i.e. >15%) reductions in the high volume and average margin 'middle weight' vehicle segments, which are normally key to OEM commercial success. Within this middle ground, cost effective 'mild hybrid' solutions are in short supply and this market segment remains mostly unsatisfied in terms of synergistic value-optimized systems offering significant CO_2 reduction. Moreover current first generation mass market 'eco' solutions are often associated with premium price and degraded driver enjoyment – a marketing nightmare! Where it is a choice between fun and fuel efficiency it is difficult to persuade people to go the 'green' route – especially at a higher cost. We need therefore to do some innovative things to try and satisfy both objectives with minimum compromise and the CPT approach is to focus on engine technology, optimised to deliver 'more from less' (figure 1).

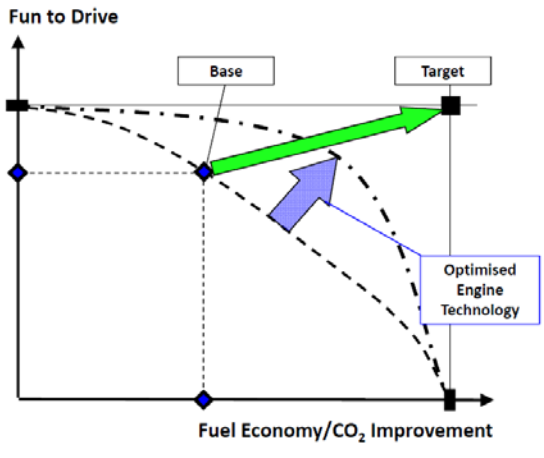

Figure 1: Delivering 'More from Less'

In this context, CPT had already been working with AVL to enhance further their Electric Boost Low Cost (ELC) Hybrid concept to address this mild hybrid 'affordability gap' with a value driven yet fun to drive solution, for current technology and mainly 'middle weight' (1400 – 1700 kg) family sized vehicles. The approach is to combine synergistically the electric supercharger and the SpeedStart® integrated starter generator technologies to bridge the gap between micro and mild hybrid segments to create an innovative, high value yet low-cost micro/mild approach to low voltage hybridisation. The intent is to enable aggressive yet near-term downsizing and down-speeding of existing engine families, delivering proven CO_2 reduction and fuel economy improvement, without the usual dynamic compromises that typically limit market acceptance. When this combination is applied to a downsized 1.4l turbocharged direct injection gasoline engine variant of the ELC-Hybrid power unit, there is potential to take this concept to an even higher level of capability, where it can offer a cost-effective alternative to other high voltage mild hybrid solutions.

In the Project CPT and ALABC have commissioned AVL Schrick to convert a vehicle to the mild hybrid system proposed and the chosen vehicle is the current model Volkswagen 1.4 litre TSI 'Blue Motion' Passat (figure 2). This has been converted to accommodate:

Figure 2: The Project Passat

- The Valeo Electric Supercharger (ES) unit (matched to B-ISG voltage).

The engine is super-charged by a highly responsive electric supercharger with integrated control and power electronics. Unlike a crankshaft driven supercharger or exhaust turbocharger, the direct drive electric supercharger operates independently of engine speed and without direct parasitic loss. This crucial difference makes it perfectly suited to maintaining vehicle performance and driveability even in conjunction with an aggressively downsized engine.

A typical 2.0 l C-segment vehicle with a rated output of 80-110 kW can be replaced by a 1.0–1.4 l direct-injection turbocharged spark-ignition engine. Unfortunately, the turbocharger match necessary to maximise high-speed performance gives unacceptable low-speed dynamic engine response. To address this issue, the electric supercharger significantly increases the air charge density over the critical 500 milliseconds of a low speed transient. In a 12V configuration, the compressor accelerates from idle to 70,000 rpm in less than 350 milliseconds (figure 3), whilst this can be reduced further at higher voltages.

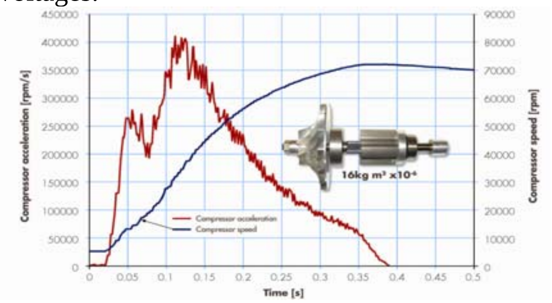

Figure 3: Dynamic response of the electric supercharger

This speed of response enables the system to react instantly and thus deliver significant additional charge air when required and in so doing enabling up to 20 kW of extra power to be developed at the engines crankshaft. The effect on typical 4th gear acceleration is seen in figure 4.

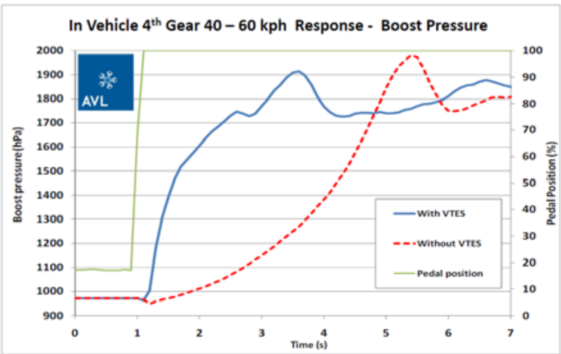

Figure 4: Impact of the electric supercharger on boost dynamics

- SpeedStart B-ISG (either in 12V or 48V configuration)

CPT has developed a next-generation stop/start solution with a highly responsive control strategy and the additional benefit of efficient low voltage recovery of braking energy. The system is configured as a belt-driven integrated starter/generator with fully integrated electronics. Not only is it the world's most powerful belt-driven unit to operate at 12V but also the first system that could change drivers' minds regarding the use of start/stop technology. This lack of driver acceptance has been largely responsible for the fact that car-makers have been, until recently, reluctant to introduce start/stop for high volume production.

With response times of less than 10 milliseconds required to establish full current in the windings, the switched reluctance motor ensures there are no pre-flux delays, allowing the engine to restart immediately. This instant responsiveness fully addresses the 'driver change of mind' challenge and is quite unlike a conventional starter motor where the driver has to wait until the engine is completely shut down before restarting (figure 5).

Under NEDC test conditions, the SpeedStart system provides a 3 – 5% reduction in CO_2 emissions. The switched reluctance motor's increased efficiency compared with a conventional alternator provides a further 1% improvement. The use of regenerative charging during vehicle decelerations, combined with an optimised battery storage system provides a further 3 – 5% improvement. A higher voltage machine can therefore provide up to a 10% reduction in carbon emissions and is very cost effective.

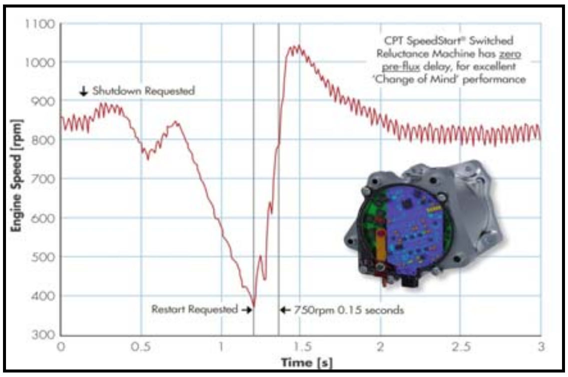

Figure 5: SpeedStart 'change of mind' performance

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The initial iteration of the demonstration vehicle is at 12V and utilises a battery of 100Ah capacity – approximately 30 Ah higher than the standard battery fitted to the vehicle. The ALABC canvassed those member battery manufacturers thought to be producing batteries suitable for hybrid vehicle applications – namely those with carbon in various forms in the negative plate. Several companies expressed interest in participating and batteries were collected at the University of Sheffield for some preliminary cycle testing.

Initial investigations on the new vehicle indicated that the additional space required in the engine compartment for VTES and SpeedStart would necessitate moving the new battery to the rear of the vehicle. Fortunately there is plenty of available room there which does not impinge on the use of the pre-determined luggage space. To minimise both resistive losses and the voltage drop to the two electrical units, an aluminium bus bar was constructed to carry the current to and from the battery.

As there appear to be moves to increase the voltage in this type of vehicle to 48V, a later iteration of the car will be built to operate at this level. This will enable increased regenerative capability from the SpeedStart unit (figure 6) and an even greater efficiency from the electric supercharger. It is likely that the architecture for this vehicle will contain both a 25 Ah capacity 48V lead-carbon VRLA battery and a 12V flooded battery to carry out the remaining electrical functions of the car.

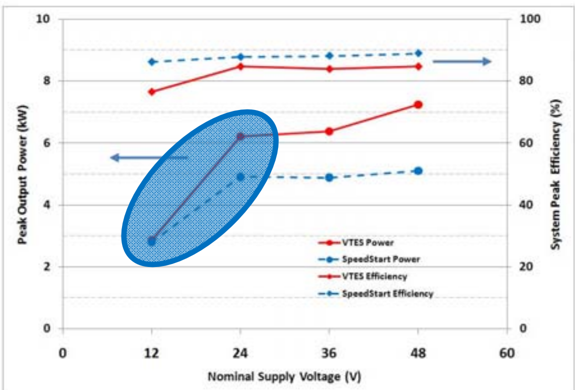

Figure 6: Potential for significant power increase with modest voltage increase.

- Battery Management System (BMS) and System Controller

The BMS for the battery package has been constructed by Provector who have been associated with the ALABC during all its work on hybrid vehicles This will monitor voltage, current and state-of-charge of the battery as well as controlling the temperature management system. There will also be provision for data logging to monitor battery performance. AVL Schrick have incorporated an open architecture engine system controller to manage engine, B-ISG, ES and BMS interaction and base engine calibration.

- Gear Box

A revised manual gear box with longer gear ratios has been fitted to increase engine 'downspeeding' and hence CO_2 reduction.

Utilising this system (figure 7) when compared to a baseline 2.0l TSI vehicle of equivalent engine specification AVL would expect to deliver a 20 – 25% reduction in CO_2, at current vehicle mass (1500 – 1600 kg) with the new low cost hybrid vehicle configuration.

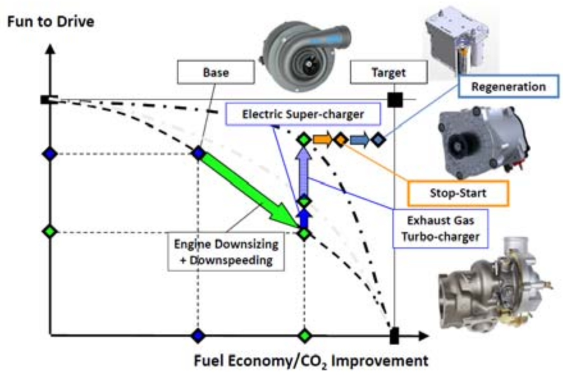

Figure 7: The LC Super Hybrid configuration – adding performance to a downsized engine

This level of CO_2 reduction would compare well with the current NiMH/Li-Ion mild hybrids in development at OEM's and would compete head-on with the full hybrid gasoline vehicles following the Prius into production. Table 1 also indicates that the new classification of 'micro/mild' hybrid offers good value CO_2 reduction compared with other options.

Table 1: Better Functionality at Reduced Cost

System ► Metric ▼	Micro Hybrid	Micro/Mild CPT Concept[1]	Mild Hybrid	Full Hybrid	Plug-in Hybrid
Voltage	12V	**12-48V**	24-144V	200-276V	300-400V
e-Motor Power	2-3kW	**3-6kW**	10-15kW	10-50kW	60-70kW
Regen. Power	0.5-3.0kW	**3-8kW**	~10kW	~20kW	20kW+
Launch Assist	0	**20-35kW**	>15kW	<15kW	<60kW
e-Drive Range	0	**0**	0	~2 km	~30km
OEM on-cost	€150-700*	**€750-1,500**	€1,600-3,000*	€3,000-5,000*	€6,000-10,000*
CO_2 Benefit %	3-7%	**15-25%+**	8-12%	15-20%	20%+
OEM Cost/ Benefit	€35-100 per 1%	**€50-60 per 1%**	€200-250 per 1%	€200-250 per 1%	€300-500 per 1%

[1] with downsizing/downspeeding

1.2 Battery Evaluation

At the start of the project, the ALABC went to its member battery companies for them to suggest candidate batteries for the modified vehicle. It was decided to run the first iteration of the vehicle as a 12V option with a 48V variant to follow (as proposed in a recent draft German Standard). Five companies offered various types of batteries with carbon-containing negative plates for evaluation.

The original vehicle had a 68Ah 12V VRLA battery mounted in the engine compartment. There was discussion as to whether we should use a single battery approach or to separate the regenerative energy system from the normal 12V hotel loads experienced on the car. It was decided for simplicity in this first conversion to use a single battery and this was sized at approximately 100Ah so as to allow the battery to operate at partial state-of-charge. As the space occupied by the battery in the original Passat was required to accommodate the electric supercharger, the new battery was re-located in the rear luggage compartment together with the BMS and the system controller. It did not however compromise luggage-carrying capability as it fitted under the floor of the compartment in the former wheel well. It was however necessary to give consideration to carrying the anticipated large currents to and from the front of the vehicle. In order to minimize both weight and I^2R losses a specially designed laminated bus bar was used. It is anticipated that this would be less of a problem in a 48V variant where currents will be lower.

Prior to the selection of the battery for the vehicle, all the batteries submitted were subjected to some testing at the University of Sheffield. We were anxious that, on high rate discharge to the electric supercharger and SpeedStart units, that the battery voltage should not drop below 9.6V. In order to test the batteries to the anticipated duty cycle, it was decided to use a cycle modeled by Ricardo for the parallel project (HyBoost) This was based on the Artemis test cycle and is illustrated in figure 8.

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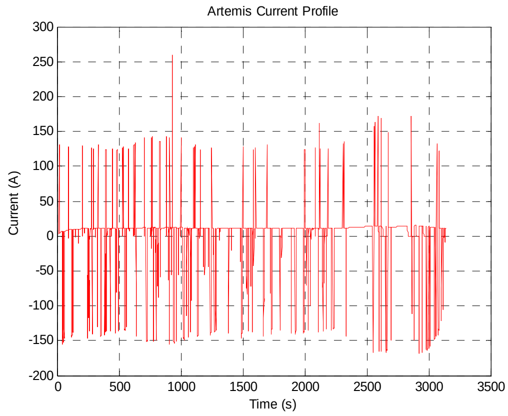

Figure 8: The Artemis current profile

It can be seen that in this cycle there is a maximum discharge peak current of over 250A and many recharge events in the region of 150A. There is no space in this paper to cover all the batteries tested but Figure 9 shows a portion of a test cycle on a 90Ah prismatic VRLA battery at 60% state-of-charge with a carbon-enhanced negative active material.

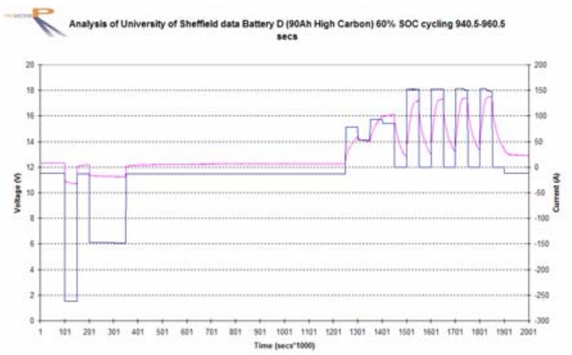

Figure 9: 90Ah battery with carbon at 60% SoC

As can be seen on the left of figure 9 there is no problem with the big discharge in that the voltage stays comfortably above 9.6V. The problem is on the recharge where the voltage climbs rapidly to about 17V until the current limitation takes place. This is obviously damaging to the battery but would also be inefficient in the terms of accepting the available regenerative energy if the current was limited further. The test was redone with the state-of-charge of the batteries as low as 30% without any obvious signs of improvement.

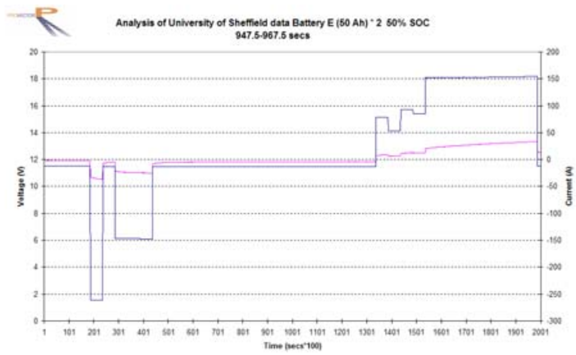

Figure 10: 2 x 12V 50Ah spiral wound batteries in parallel at 50% SoC.

By contrast two 12V 50 Ah spiral-wound batteries were tested in parallel (12V 100Ah) and showed excellent performance as shown in figure 10. The batteries met the discharge requirement but also performed well on recharge where the voltage stayed below 14.4V thus avoiding the chance of gassing and dry-out. These tests have shown some sensitivity to temperature and further testing has been carried out in the region of 30-45^{o}C and it has been found that the operating SoC can be pushed closer to 70%. Following the testing the spiral-wound design was selected for the car. It clearly shows that grid and battery design are an important factor when considering batteries for hybrid electric application – not just the inclusion of carbon to the negative plate which is important to inhibit sulfation. The batteries were fitted in the rear of the car as illustrated in figure 13 where they are seen placed in what was the wheel well together with the Provector BMS and the autobox control unit. The connection to the front of the vehicle is provided by the aluminium bus bar to keep weight down while minimizing I^2R losses.

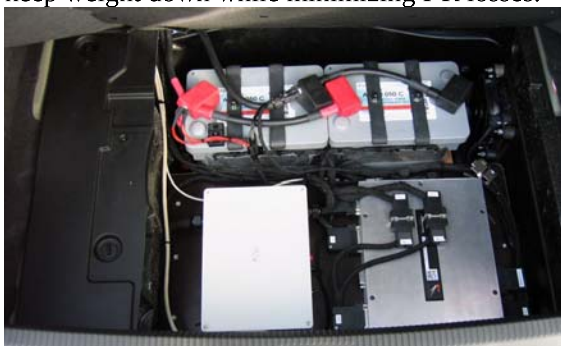

Figure 11: The battery installation and control boxes.

1.3 Project Status

Conversion of the vehicle was carried out by AVL-Schrick in Remscheid, Germany who had previous experience of fitting both the electric supercharger and the SpeedStart units but on different vehicles. This is the first time they have been utilized in an integrated system. The belt tensioner for the SpeedStart ISG was supplied by Mubea. Alterations were also made to the gearing of the car. After completion of the installation the vehicle was transferred to AVL in Graz for final calibration and testing. After some initial testing it appeared that there were still some fundamental integration issues that needed to be resolved which necessitated its return to Remscheid. With this work done, comparative figures for the converted vehicle with the base car and other models were obtained.

Table 2: Performance Comparisons

	Passat 1.4 l TSI	Passat 1.8 l TSI	**LC Super Hybrid**	Volvo S40 2.0 l
Acceleration	11.1 secs**	8.5 secs*	**8.7 secs****	9.5 secs*
Top Speed (mph)	127*	137*	127**	119***
Fuel: mpg/litres per 100 km Combined	45.6/6.2**	40.9/6.9*	**50.5/5.6****	37.2/7.5*
Emissions CO_2/km	140**	160*	**130****	176*

** Manufacturer's Figures **AVL figures *** Limited by ECU*

It can be seen that the 1.4 litre LC Super Hybrid is achieving a 7% improvement over the base car CO_2 emissions despite the 2.4 second improvement on the 0-100kph acceleration figure. It achieves a similar performance to the 1.8 litre version with about a 16% reduction in CO_2 emissions. This may seem relatively modest but it should be remembered that both vehicles are already mechanically turbocharged. However when compared with a naturally aspirated 2.0 l Volvo S40, the LC Super Hybrid has better acceleration and CO_2 emissions are improved by 26%.

2 Future Work and Conclusions

The vehicle has now been handed over to the ALABC and is scheduled to be premiered at the Geneva Motor Show in early March. In the meantime the vehicle has received an extremely positive report following a test drive by the influential UK car magazine Autocar. There are plans to try the concept in further configurations such as:

- A dual 12V set-up with a smaller VRLA battery to handle the regenerative energy and the VTES assist with a conventional SLI battery to handle hotel loads.
- A dual 48V/12V variant along the lines indicated by the draft new German Standard for micro hybrid vehicles.
- Some long-term testing of the system alongside trials of different advanced lead-acid battery types.

It is felt that this is an extremely promising concept which could lower the cost of hybrid electric vehicles while providing lower CO_2 emissions than the conventional technologies in use today. By producing low emission vehicles with attractive driving characteristics at low costs, it will be possible to increase market acceptance. It is an opportunity for advanced lead-acid batteries to promote change and provide lower emissions than can be achieved by the sale of a limited quantity of the more expensive electric or plug-in hybrid vehicles.

3 Acknowledgments

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