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CO2 Reduction Through Low Cost Electrification of the Diesel Powertrain at 48V

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Abstract

In order to achieve fleet average CO2 targets, mass-market adoption of low CO2 technologies is required. Application of low cost technologies across a large number of vehicles is more cost-effective in reducing fleet CO2 than deploying high-impact, costly technology to a few. Therefore, to meet the CO2 reduction challenge, commercially viable, low cost technologies are of significant interest. This paper presents results from the 'ADEPT' collaborative research program which focuses on CO2 reduction through the application of intelligent 48V electrification to diesel engines for passenger car applications. Results were demonstrated on a C-segment vehicle with a class-leading 4-cylinder 1.5 litre Euro 6 diesel engine. Electrification was applied through a high power, high efficiency, switched reluctance belt-integrated starter generator (B-ISG) capable of both generation and motoring, and an Advanced Lead Carbon Battery for energy storage. The conventional alternator was replaced with a highly efficient DC-DC converter to supply energy to the 12V system. These technologies enabled powertrain efficiency improvement through the recovery of kinetic energy with regenerative braking and reapplication of the recovered energy through motoring to offset fuel usage. Efficiency was further optimised through application of engine downspeeding and advanced auto-stop strategies to extended engine-off time. Additional electrification was investigated through 48V ancillaries, including water-pump and air-conditioning compressor, and a turbo-compound generator for waste heat recovery from exhaust gas. These technologies have demonstrated a combined CO2 reduction of 10-11% against the conventional vehicle baseline. Additional studies of advanced thermal systems for improved warm-up, and lubrication control for FMEP reduction have also been conducted on this program. These indicate that by applying intelligent electrification to ancillaries a further 3-4% reduction in CO2 is achievable. Overall, this program shows that 48V technologies can achieve CO2 savings with a lower cost per gram CO2 than full hybrid solutions.

Introduction

Over recent years there has been an increasing trend towards reducing the CO2 emissions of vehicle fleets through legislated limits. The actual limits and nominated test cycles differ from market to market but the overall trend is the same, as illustrated in Figure 1.

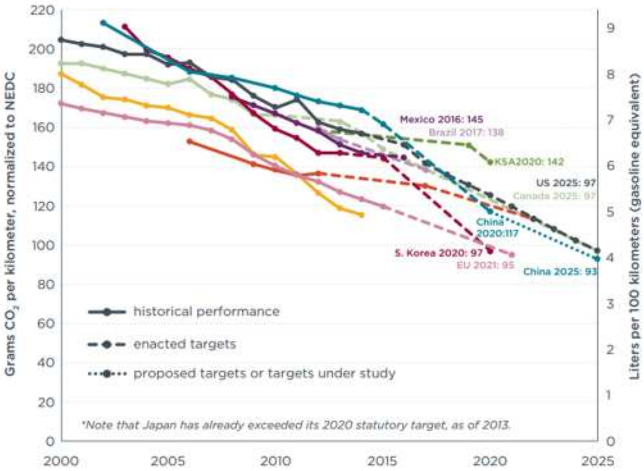

Figure 1. Comparison of global CO2 regulations for new passenger cars. (Source: ICCT Ref [1])

The task of meeting these legislated requirements has become ever more difficult, with the "low hanging fruit" options such as low rolling resistance tyres and smart charging already applied. The base vehicle selected for this programme has a class leading CO2 emissions performance and represents the current state of the art in conventional diesel powertrains. Further reduction through improvement to the conventional combustion and exhaust aftertreatment systems is becoming prohibitively expensive. The objective of this programme was to demonstrate that a combination of much lower cost technologies could be applied to further improve emissions on a class leading example.

High voltage hybridisation is a proven technique to reduce vehicle emissions, and with the other options largely exhausted it is a possible route forward. However, the cost of a full hybrid is expensive both in terms of the hardware fitted and the re-engineering required of the powertrain. For mass market deployment this is a significant obstacle. Medium voltage (<60V) mild hybrid Belt-Integrated Starter Generator (B-ISG) systems offer the promise of significantly lower implementation costs both in terms of the system engineering and piece cost of the components, while still retaining a large proportion of the benefits of a high voltage integrated solution. King et. al [2] discuss the potential for such an approach applied to a downsized gasoline engine. The addition of a second electrical bus at medium voltage also offers the potential for moving high power consumers to this bus, thereby reducing losses, and opens up the potential for adding new electrification features - air conditioning compressor, oil/water pumps and so on – further increasing the overall efficiency of the system with minimal impact to existing powertrains. Still further efficiency gains can be made if energy lost from the internal combustion engine through the exhaust gas can be captured and reapplied. An electric turbo-compound waste heat energy recovery system is a potential solution, however if energy is extracted from the exhaust gas then care must be taken to manage the thermal state of the aftertreatment catalysts.

This paper will describe a 48V mild hybrid architecture that has been applied to a best in class CO2 C-Segment diesel vehicle. Results measured under the New European Drive Cycle (NEDC), the Worldwide harmonized Light vehicles Test Procedure (WLTP), and in real world conditions will be discussed.

The ADEPT concept

The ADEPT (Advanced Diesel Electric PowerTrain) programme, sponsored by Innovate UK and the Office for Low Carbon Vehicles, was a collaborative research programme between partners Ricardo, Ford Motor Company, Control Power Technologies, the European Advanced Lead Acid Battery Consortium (EALABC), Faurecia and The University of Nottingham. The ADEPT programme's target was to demonstrate a 15% reduction in CO2 from the baseline vehicle, a MY2015 Ford Focus ECOnetic with 1.5l Turbo-Diesel engine and six speed manual transmission, whilst maintaining comparable vehicle performance, drivability and emissions compliance. A schematic of the key modifications to the conventional powertrain can be seen in Figure 2.

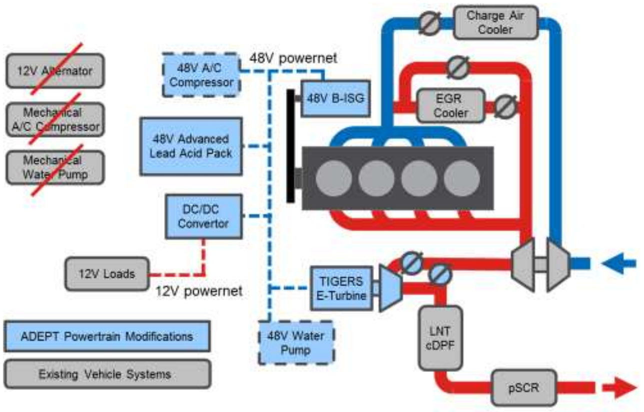

Figure 2. The ADEPT concept applied a 48V powernet to the diesel powertrain, removing the 12V alternator and replacing it with 48V B-ISG, DC-DC converter and 48V rechargeable energy storage device. Electrified ancillaries and waste heat recovery through electrified turbo-compounding were investigated

Core to the ADEPT system was the addition of a 48V powernet. The conventional 12V alternator was removed from the Front End Accessory Drive (FEAD) and replaced by a high-power 48V switched reluctance B-ISG. The B-ISG is a bi-directional machine, capable of significant regenerative braking, up to 12kW, as well as torque assistance up to 7.5kW. The function of the 12V alternator was replaced by a DC-DC convertor, which continues to supply the conventional 12V loads. A 48V rechargeable electrical energy store was then added, in the form of an advance lead-carbon battery pack, in order to store the regenerative energy for later use.

A novel waste heat recovery system was investigated as part of the ADEPT programme, in the form of the TIGERS (Turbogenerator Integrated Gas Energy Recovery System) turbo-compound generator. This system consists of a 48V electric machine connected to a turbine placed in the exhaust line between the conventional turbocharger and after-treatment catalysts. Novel exhaust control valves were installed to allow the exhaust gas flow to be modulated between the TIGERS turbine and directly into the catalyst. In this manner, after-treatment thermal requirements could be managed whilst recovering energy from the exhaust gas when efficient to do so.

Finally, a number of electrified ancillary concepts were studied, including electrified engine coolant pumps, electrified air conditioning compressors and electrified engine oil pump.

Diesel engine

Ford's production 1.5l Duratorq DV5 turbo-diesel engine was used in the ADEPT programme. This engine provides best-in-class performance from a modern production diesel, with extremely good Brake Specific Fuel Consumption (BSFC) figures across the majority of the engine operating range.

48V Mild Hybrid System

Belt-Integrated Starter Generator

Control Power Technologies' 'SpeedStart' B-ISG is a bi-directional water-cooled electric machine which replaces the conventional alternator on the engine's FEAD belt. It can extract or add energy from the crankshaft through the FEAD belt and as such is permanently coupled to the engine. It is therefore not possible to provide a pure electric only drive mode, but has the advantage that fitment requires only minimal modification to existing powertrains.

The SpeedStart device uses Switched Reluctance (SR) motor technology, giving a nearly instantaneous torque response as no pre-fluxing of the machine is required. The mechanical design of the SR motor is very simple, with a low inertia rotor that helps to minimise parasitic losses. It also has the advantage that no permanent magnets are required, making vehicle end of life recycling simpler and also removing the danger of self-excitation.

The SpeedStart variant used for this programme (Table 1) has a substantial peak generation power of 12.5kW (electrical) which by virtue of its water cooling and SR design can be maintained for significant time periods. This allows for good regenerative braking potential from the B-ISG. The SR design also allows for a wide speed operating range whilst maintaining high generation efficiencies (75-83%) compared to conventional alternators (typically 60-70%).

In addition to its generation capability, the SpeedStart device can also provide torque assistance via the FEAD allowing the energy recovered during regen braking to be re-applied to the engine, thereby offsetting fuel usage. Up to 7.5kW (mechanical) is available from B-ISG for application to the crankshaft in torque assist mode, with a torque rise rate that is only limited by the belt system. This enables engine downspeeding without a corresponding loss of vehicle performance. For reference, 7.5kW at 1000rpm is equivalent to 70Nm on crankshaft.

Finally, the SpeedStart is able to crank the engine via the belt system at any point, without requiring the engine to be stopped. This gives a huge improvement in restart speed, responsiveness and quality when compared with a conventional 12V starter motor.

Table 1. B-ISG specifications

Operating voltage range	20V - 55V
Peak cranking torque	55Nm
Peak generating power / efficiency	12.5kW / 83%
Peak motoring power / efficiency	7.5kW / 85%
Generating speed range	1500rpm - 20000rpm
Motoring speed range	1000rpm - 10000rpm
Belt pully ratio	3.06:1
Coolant	Water (engine)
Coolant temperature range	-40°C -113°C
Weight	11kg

Advanced lead acid battery pack

The East Penn 'UltraBattery' lead-carbon advanced lead-acid battery technology applied in this programme provides high dynamic charge and discharge performance at a significantly lower cost point than competing battery chemistries. Dynamic charge acceptance tests were conducted to understand the optimal charge-discharge profile for this chemistry and applied in the programme. The lead-carbon batteries show an increased ability to accept charge on regeneration coupled with the ability to operate at partial state of charge when compared against conventional lead-acid. The battery chemistry also allows for much more straightforward thermal management when compared with competing chemistries, further reducing the system cost impact. The addition of carbon into the chemistry of the cells dramatically reduces the effects of sulfation which afflict conventional lead-acid batteries. This substantially extends battery life on a mild-hybrid usage cycle compared to traditional lead-acid. A 150K mile endurance testing programme has been conducted by EALABC to prove the concept.

In addition, the battery construction includes an ultra-capacitor element which further assists with the dynamic behaviour of the battery. ProVector supplied an integrated pack and Battery Management System (BMS) incorporating the East Penn UltraBattery cells, with the parameters defined in Table 2.

Table 2. UltraBattery pack specifications

Nominal voltage	42V
Operating voltage range	36V- 54V
Capacity	20Ah
Maximum charge rating	12kW
Maximum discharge rating	12kW
Operating temperature range	-40°C - 60°C
Cooling	Air (Active)
Weight	35kg

The battery pack has no lithium content and is an inherently cheap technology with commercially viable recycling in place. A weight trade off exists compared to other chemistries as the UltraBattery cells are heavier than lithium equivalents for a given energy capacity, but in a 48V mild-hybrid application this weight penalty is minimised.

Under testing, the high power performance of the first generation battery cells under NEDC conditions was less than expected, with peak regeneration powers circa 6kW. This is considered to be due to the batteries operating well below their optimal temperature for charge acceptance for the duration of the cycle. This effect is less pronounced on WLTC and particularly on Real Driving Emissions (RDE) tests, where higher dynamics allow cells to reach optimum temperature. Under these circumstances regen powers are seen to reach the expected 10kW, as illustrated in Figure 3. East Penn – the battery cell manufacturer - claims generation 2 and 3 cells show improved low temperature behaviour, but this was not possible to confirm within the time constraints of the programme. Figure 4 clearly illustrates the relationship between temperature and its charge acceptance on the performance of the tested first generation battery.

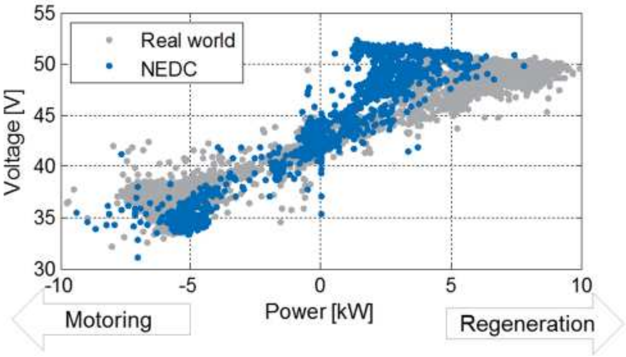

Figure 3. Battery charge and discharge powers under real world conditions and on the NEDC test cycle. Substantially higher powers are achieved in the real-world data set.

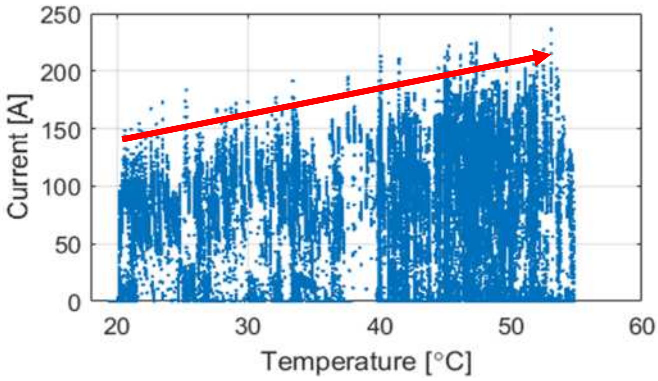

Figure 4. Increase in peak charge current as a function of battery temperature. Data collected under 10 hours of real-world driving conditions.

DC-DC convertor

As the ADEPT concept removes the conventional 12V smart alternator, a method of powering the 12V network is required. This is achieved through the use of an efficient DC-DC buck converter, which transfers energy from the 48V powernet to the 12V powernet. The DC-DC converter operates at power levels up to 3kW continuous, sufficient to sustain all vehicle 12V loads. The specifications for the DC-DC converter are shown in Table 3.

The charging voltage of the DC-DC is highly controllable, allowing the ADEPT system to increase the charging current passed during regenerative braking events. This synergistic operation allows the recuperation of more regenerative energy into the system than would be accepted by the 48V battery alone, effectively charging both 12V and 48V batteries simultaneously. The current drawn by the 12V system outside of the regenerative braking periods is thereby reduced.

Table 3. DC-DC converter specifications

Peak Power	3kW
Efficiency (1kW to 2.5kW)	>95%
Voltage control	300mV between 12V and 14.5V

Waste heat recovery

The TIGERS device is designed to recover waste energy from exhaust gas downstream of the engine turbocharger but upstream of aftertreatment catalyst under operating conditions where an overall benefit can be obtained. The energy is captured by a turbine running directly in the exhaust stream and then converted into electrical power by a high speed switched reluctance generator operating at 48V and directly coupled to the turbine.

The TIGERS device is bypassed for operating conditions where the increase in back pressure would result in an overall efficiency loss, where insufficient waste energy exists in the exhaust stream or where the energy is needed to maintain viable operating temperatures for the aftertreatment system. Faurecia's twin fully modulated exhaust control valves provide this bypass facility by directing exhaust flow either through the TIGERS or directly into the aftertreatment catalysts. The exhaust control valves are designed for low leakage under the challenging conditions present in the exhaust system close to the engine (Table 4).

Table 4. Exhaust Control Valve specification

External leakage	< 0.15kg/h @ 300mbar, 680°C
Internal leakage	≤ 6kg/h @ 750mbar, 750°C
Validation testing	> 1,000,000 cycles, 680°C
Failsafe modes	Open OR Closed
Actuation speed	< 200ms full travel
Position control	Proportional
Weight	< 1.5kg

The TIGERS turbine was sized for full load to avoid choking flow with the originally proposed single control valve only able to provide an on or off state. In practice, with the two valve system applied, the system could be further optimised by reducing the size of the turbine to extract more energy from lower load conditions. This was not possible within the constraints of the current project. This has reduced the NEDC cycle benefit, but it has still been demonstrated that useful levels of energy can be recovered under real driving conditions. The specifications of the TIGERS unit are shown in Table 5.

Table 5. TIGERS specification

Variant	12V	48V
Peak Power	2kW	2.4kW
Continuous power	600W	1.4kW
Maximum speed	45000rpm	
Generating efficiency	Up to 70%	
Cooling	Engine coolant	
Weight	11kg	

Electrified ancillaries

At the time of this study, the market for electrified ancillaries was immature. The majority of suppliers are focusing on the core 48V electrification components, such as e-Machines, batteries, DC-DC converters and e-Superchargers. However, there is believed to be significant scope for efficiency improvement in moving electrified ancillaries to 48V where higher powers can be achieved at lower weight and higher efficiency than 12V equivalents. The electrification of three specific ancillaries was studied as part of this programme, namely the engine coolant pump, the engine oil pump and the air conditioning compressor.

A 48V electric water pump was sourced from Pierburg with a flow and pressure characteristic (11m3/hr at 1.5bar) that is suitable for replacing the conventional belt-driven mechanical water pump. The pump requires up to 1kWe at full load and as such is more suitable for 48V than 12V application due to this high power requirement. Overall efficiency (electrical to hydraulic) is 52%. When the efficiencies of generating the electrical energy to supply the pump are considered, then running the pump with the same mission profile as the mechanical pump does not bring any benefit. However, if the pump speed is decoupled from the engine speed, the pump can be optimised to provide only the minimum flow required for the given load and thermal state, thus minimising parasitic losses. Adding a ‘micro-circuit’ to the system layout makes it possible to shut off engine flow completely during warm-up for ‘zero-flow’, whilst maintaining flow through the EGR (Exhaust Gas Recirculation) cooler to control EGR gas temperature. McCartney et. al demonstrated significant benefit through shutting off coolant flow on a diesel engine [3]. A detailed 1D simulation study was conducted to investigate these scenarios. Thermal models were developed in FlowMaster and correlated against vehicle test data. These simulations indicate that a 1.7% NEDC CO2 benefit is achievable though decoupling the pump and engine speed, translating to 0.7% on WLTP. Furthermore, additional benefit of 1.1% NEDC and 0.5% WLTP can be achieved through the addition of the micro-circuit and zero-flow.

An experimental testbed study was conducted as part of the ADEPT programme into the potential benefits of electrification of the engine oil pump, using the Ford 1.5l diesel engine as used on the demonstrator vehicle. The study investigated the behaviour and benefits of a system with an electrically driven fixed displacement pump with distributor providing control over the flow to the crankshaft main and big end bearings. The results of this study are presented in Shayler et al. [4] and indicate that a CO2 benefit of up to 1.5% is possible over the NEDC.

System integration

A mild hybrid supervisor control system (HCU) was developed by Ricardo to manage the new functions introduced in the ADEPT vehicle. Ford provided a modified Powertrain Control Module (PCM) with customised control hooks to allow tight integration of the HCU with engine management system functions such as torque control and engine stop-start. The new components (B-ISG, UltraBattery, DC-DC, TIGERS, Exhaust Control Valves, etc.) were fitted with standalone intelligent control systems. The HCU calculated set points for each of these components to manage to overall system in an optimal manner. The communication and power topology of this system is illustrated in Figure 5.

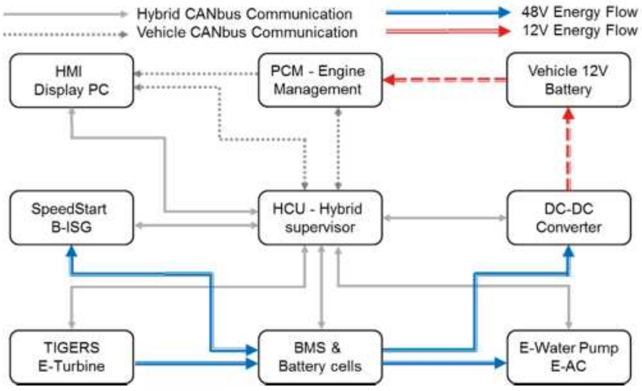

Figure 5. Mild hybrid control system layout showing key control and power flows

The ADEPT Demonstrator vehicle and components developed as part of the programme are illustrated in Figure 6.This vehicle was tested for CO2 and emissions under the NEDC and WLTP test procedures. An additional assessment was made of its performance under real-world driving conditions.

Figure 6. The ADEPT demonstrator vehicle (a), fitted with the 48V mild hybrid system, including B-ISG (b), 48V UltraBattery (c), TIGERS e-Turbine (d), and Exhaust Control Valves (e)

Results

Electric torque assistance

Adding the B-ISG torque to the base engine torque, as seen in Figure 7, results in an increase in torque available at the wheels. This can be used to provide an increase in performance relative to the base vehicle, which considered in isolation does not act to decrease fuel consumption. However, this does provide opportunity to consider modification to final drive. Simulation shows a taller final drive gives a fuel consumption benefit of up to 2.5% on the NEDC test cycle. Simply decreasing final drive may compromise vehicle performance by reducing torque available at the wheels. When B-ISG torque assistance is added, the base vehicle levels of wheel torque can be maintained.

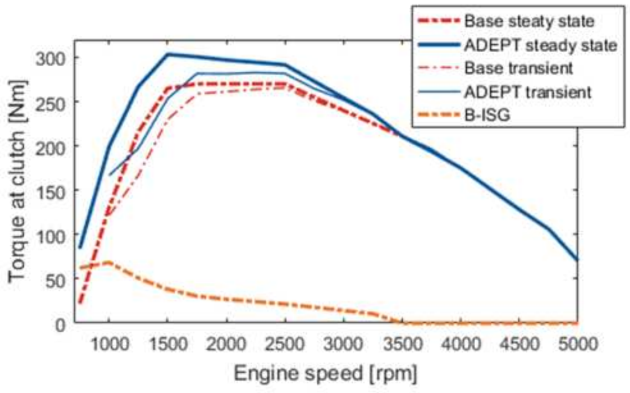

Figure 7. Base engine torque curve and ADEPT powertrain torque curve shown for both steady state and transient (chassis dyno, 3rd gear) conditions

The ADEPT system implements two paths whereby B-ISG torque is used to enhance vehicle performance. Firstly, the full load torque curve of the engine is augmented with the torque of the electric machine. Secondly, the electric machine is used to supply a lag-compensation toque to fill-in the temporary difference between the engine torque and the driver demand during part load transients.

Figure 8 shows the performance of the vehicle compared over a range of in-gear acceleration manoeuvres. Here three configurations are shown; namely ‘conventional’ mode, without torque assistance, ‘hybrid’ mode, with full torque assistance, and finally a second hybrid configuration with overall gear ratios extended by 6% and full torque assist. The data illustrates the improved performance in acceleration times achievable through the application of torque assistance when the same gearing is used. Additionally, it shows that torque assistance can be used to maintain the acceleration performance with the taller gearing in place.

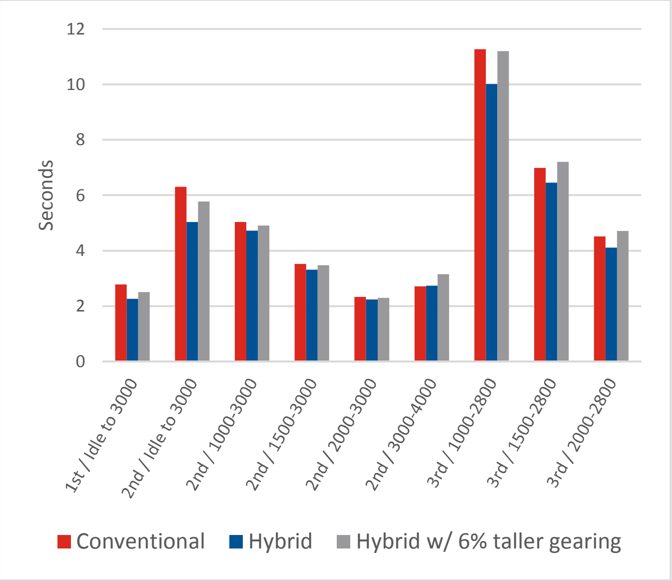

Figure 8. In-Gear acceleration performance compared

Downspeeding through final drive and optimised shift points

The BSFC of each engine design is unique and dependent on the specific technologies and design approaches used. In all cases, for a given output power demand, modifying the gearing ratio allows the position of the engine operating point in the speed-load space to be moved along iso-power curves. The optimal operating point for any engine, in terms of CO2 generation, will be the point along this iso-power curve with the lowest BSFC. Both manual transmissions and many types of automatic transmission allow discrete ratios to be selected along this curve, so some scope for optimisation is possible though gear selection in this way. UNECE R101 [5], the regulation governing the testing of vehicles under the NEDC test, allows the free selection of gear shift points on the test cycle for vehicles classed as hybrid (defined as vehicles with multiple sources of propulsive torque) through the use of a Gear Shift Instrument (GSI). The requirements for the implementation of the GSI in Europe is defined [6]

Additionally, as discussed above, the modification of the final drive ratio is a further source of freedom for optimising the powertrain CO2 output on a given drive cycle. As the previous section demonstrated, it is possible to increase the overall ratio by 6% whilst maintaining vehicle acceleration attributes through the addition of torque assist. This brings a simulated 2.5% benefit to CO2 on the NEDC. When the free selection of gear shift points is also considered, the total CO2 benefit can be increased to 3.3%.

Regenerative braking and smart charge management

ADEPT implements a regenerative braking system to recover kinetic energy when there is no forward propulsive demand. Here, a level of regenerative braking torque is applied when the accelerator pedal is released and the engine enters a fuel cut-out state. This torque is increased based on sensing the application of the mechanical foundation brakes, thereby increasing energy recovery during periods of braking. However, the level of brake force applied by the foundation brakes is not modulated based on the electric regenerative braking system. Whilst this approach limits the maximum regenerative braking effort that can be applied under some circumstances, it presents a good trade-off between energy recovery, system complexity and cost for this application.

The energy recovered through regenerative braking is used to supply the 12V and the 48V system's energy consumption requirements (including torque assist for performance enhancement). When regenerative braking cannot supply the full requirements of the consumers on these powernets, the system must configure the B-ISG as a generator to load the engine and provide a charging current, however this comes at some CO2 cost. The control system constantly monitors the BSFC of the powertrain to determine the cost of this generation and will choose an optimal level of generation to apply based on a limiting cost as a function of the state of charge of the 48V battery. That is, generating only when it is 'cheapest' to do so.

In circumstances when the regenerative braking can supply the full requirements of the 12V and 48V consumers, the excess energy is stored in the 48V battery. This energy is used by a 'motoring for efficiency' function, where the system applies torque with the B-ISG and reduces the engine torque by a corresponding level, thus saving fuel. The decision on when to apply this torque is based on a second cost function, which monitors the benefit to instantaneous powertrain BSFC that can be achieved by motoring the B-ISG at varying torques and applies the optimum value that exceeds a minimum benefit threshold.

Each time energy is stored or transferred between components there is some loss due to inefficiencies. In order to achieve the maximum overall efficiency, it is desirable to utilise the energy as it is being created rather than to store it in the 48V battery for use later. To that end, the system raises the power transfer through the DC-DC converter during regeneration events, directly charging the 12V battery from the B-ISG rather than charging it via the 48V battery.

On both the NEDC and WLTP test cycles the regenerative braking function is able to fully supply the vehicle's 12V and 48V requirements without requiring generation to apply load to the engine. This results in a CO2 saving of 0.7% on NEDC and 2.4% on WLTP when compared to the existing 12V smart alternator. The benefit here is lower on the NEDC cycle as the test procedure allows 12V batteries to be charged prior to the emissions test, resulting in a lower total generation requirement. Additionally, the conventional 12V alternator applies some level of regenerative braking, so a proportion of the energy that the 12V alternator supplied is free in terms of CO2. The WLTP test procedure does not allow charging of the 12V battery prior to the test, which results in substantially more generation being required to support the 12V consumers and maintain charge neutral condition in the battery.

In addition to fully supplying 12V consumers, on both cycles there is significant excess energy which is captured in the 48V battery and reapplied to the crankshaft through the 'motoring for efficiency' function, resulting in a saving of 3.5% on the NEDC and 2.5% on WLTP. Here the benefit is lower on WLTP as more energy has been directed to the supply of 12V consumers.

Figure 9 shows the energy profile of the system over a drive cycle, in this case the WLTP. It can be seen that the overall range in energy contained in the 48V battery is around 1Ah, the overall energy recovered through regenerative braking is 5.5Ah, from this 2.3Ah is used to supply the 12V consumers and the 3.2Ah remaining is used to provide electric torque assistance. Note that no generation is required on the drive cycle.

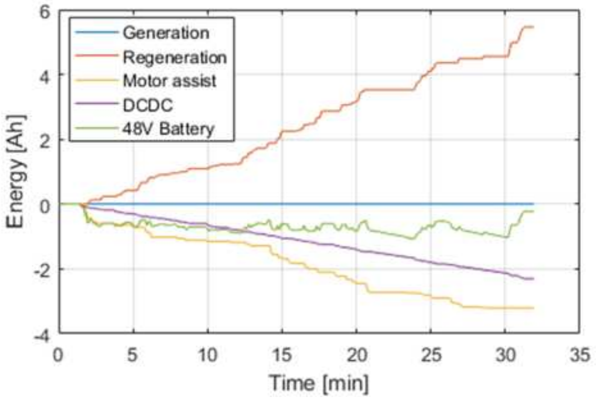

Figure 9. Energy profile of the system over the WLTP test cycle

Advanced start-stop

The B-ISG provides significant improvement in restart times compared to a conventional 12V starter. In most current manual transmission vehicles equipped with stop-start based on a 12-Volt electrical architecture, a 'stop in neutral' strategy is used. With engine restart triggered as the clutch pedal is depressed prior to the gear being selected. This gives the 12-Volt starter sufficient warning to bring the engine to idle speed before its torque is required. For the baseline vehicle, the time to idle speed is 600ms after the restart event is triggered, but with the B-ISG this is achieved in 300ms. Additionally, SpeedStart can restart the engine before it stops rotating, which allows a much more responsive reaction in change of mind situations where the driver triggers a restart a very short time after triggering an engine stop. These factors allow the stop trigger to occur earlier and the restart trigger to occur later, resulting in a more aggressive autostop strategy to be applied without compromising pull-away.

Table 6. ADEPT Autostop strategy characteristics

Restart	12V Starter	48V B-ISG
Time to idle speed	600ms	300ms
Engine off strategy	Stop in Neutral	Stop in Gear
Engine off speed	Stationary	35kph
Engine off time NEDC	190s	315s

On ADEPT, a Stop in Gear strategy is applied, where the system turns off the engine when clutch pedal is pressed, regardless of gear position. This is coupled with a Stop on the Move strategy, which allows the engine to be turned off while vehicle is still rolling at speeds up to 35kph (22mph), compared to the maximum 4kph typically required by a conventional system. These concepts are illustrated in Figure 10. Overall, this serves to increase the engine-off time on NEDC from 190 seconds, as dictated by the drive cycle's definition of gear and clutch operation, to 315 seconds. This results in a CO2 saving of 3.5%.

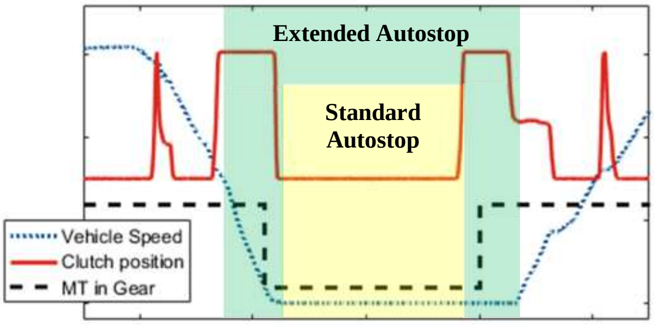

Figure 10. Example of an extended engine stop vs a standard engine stop. During an extended auto stop, the engine is held off whilst the transmission is in-gear, as long as the clutch pedal is pressed

Waste heat recovery

The TIGERS turbine was sized to pass the full-load mass flow of the engine as the original concept for bypass valves did not allow modulation of the gas flow. As such, limited benefit was seen on NEDC and WLTC due to low mass flows and the large turbine size. However, in real-world motorway conditions, where higher mass flows are seen, energy recovery operation in excess of 2kW is seen. Figure 11 shows the median generation power levels measured from the device under real world conditions. This illustrates that the regions of benefit are well outside the NEDC residency envelope. By rematching the turbine size and utilising the valves to modulate flow for lower power, higher residency operation may improve overall energy recovery, however this fell outside the time constraints of the programme.

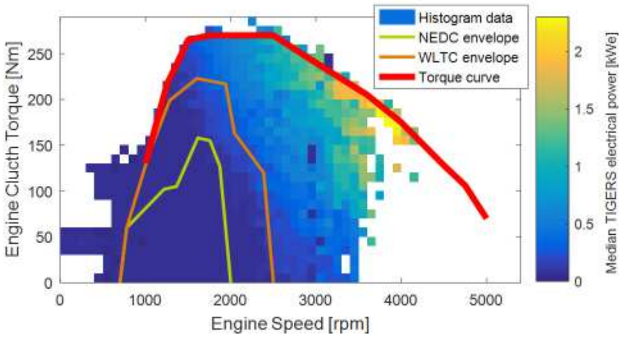

Figure 11. TIGERS energy recovery over engine operating range. Data collected over 10 hours of transient real-world driving shows the 50th percentile (median) current generated by the turbo-compound system. NEDC and WLTP envelops are overlaid for reference.

Optimised system results

The technologies outlined above were applied to the demonstrator vehicle and tested over the NEDC and WLTP emissions test procedures to assess the CO2 benefit and emissions compliance. Model based calibration was used to optimise the cost functions for the motor assist and generation functions to ensure the vehicle's rechargeable energy storage was charge neutral over the test cycle. Where the battery state of charge showed small deviation from neutral, corrections were applied according to the method defined in UNECE R101 [5]. All tests have been corrected for drive metric as defined by SAE J2951 [7] to ensure results are comparable.

Figure 12 show the breakdown of benefit the ADEPT powertrain brings to the NEDC test cycle against the measured baseline. Overall, an 11% benefit is seen on the NEDC, with 0.7% from the use of regenerative braking energy to supply 12V and 48V consumers via smart energy management, 3.5% from the use of B-ISG torque assist to improve instantaneous powertrain BSFC by reducing fuelling, 3.3% from the application of a 6% taller final drive ratio as well as the use of the GSI free shift point selection and finally 3.5% from extending the engine off time. Although not tested on the demonstrator vehicle, studies and simulation suggest that the benefit from electrified water and oil pumps could increase the overall benefit to 14.8%.

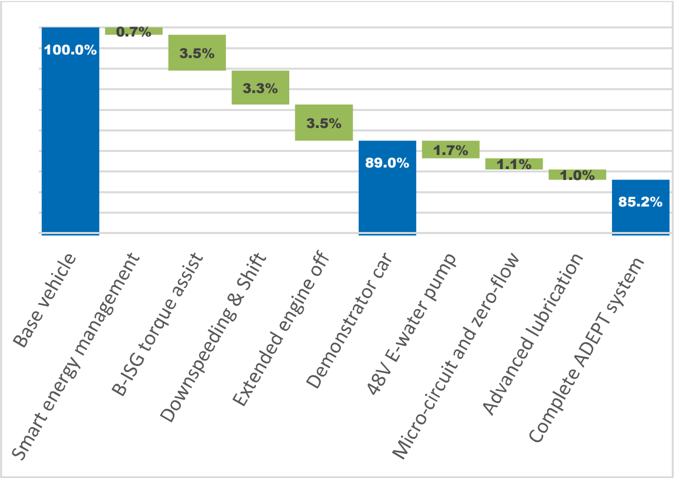

Figure 12. Breakdown of benefit over the NEDC

Figure 13 shows the equivalent results for WLTP. Here a 6.6% benefit is seen, with smart energy management increasing to 2.4% at the expense of B-ISG torque assist, which reduces to 2.5%. However, it is worth noting that the overall benefit from these two features, which both rely on regenerative braking, is higher on WLTP than NEDC as the battery's charge acceptance is improved due to the increased dynamics of the cycle. The benefit from downspeeding is reduced to 1.4% as it is most effective at low engine loads. There is no GSI free shift allowance for WLTP. The benefit of increased engine off time is 0.3%, significantly reduced from the NEDC case. It is worth noting that the benefit from this feature is highly dependent on driving style and usage patterns. Under certain real world conditions, such as urban driving, the benefit from the extended autostop is significantly higher. Finally, the electrification of ancillaries is predicted to bring the overall benefit up to 8.8%.

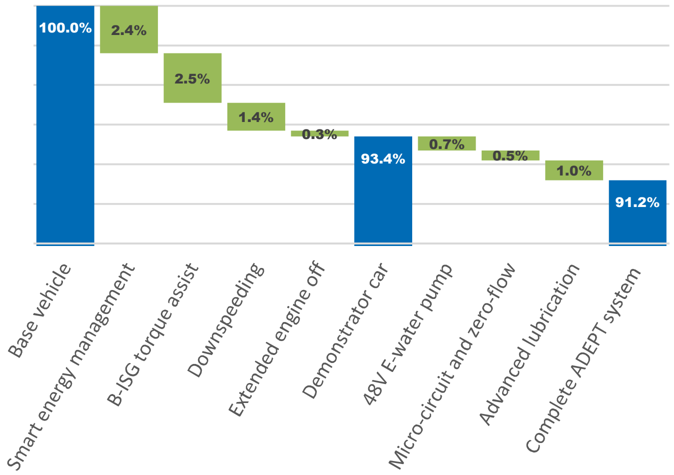

Figure 13. Breakdown of benefit over WLTP

The breakdown of results, in terms of benefit relative to the measure baseline, for both the NEDC and WLTP test cycles are summarised in **Error! Reference source not found.**.

Table 7. Summary breakdown of benefits by feature

Test cycle	NEDC	WLTP
Smart energy management	0.7%	2.4%
B-ISG torque assist	3.5%	2.5%
Downspeeding	3.3%	1.4%
Extended engine off	3.5%	0.3%
Subtotal	***11%***	***6.6%***
48V E-Water Pump	1.7%	0.7%
Micro-circuit and zero flow	1.1%	0.5%
Advanced lubrication concept	1%	1%
Total	***14.8%***	***8.8%***

Summary and conclusions

An ADEPT demonstrator vehicle, based on a Ford Focus with 1.5L diesel engine, was built and tested with a 48V B-ISG, 48V Advanced Lead-Carbon battery pack, DC-DC converter, mild-hybrid supervisory controller, TIGERS turbine and exhaust control valves.

The technologies presented in this paper indicate a reduction in CO2 emissions of 11% (relative to baseline) whilst maintaining the vehicle performance and other legislative emissions to Euro 6b levels.

The addition of the 48V electrification components utilised in this investigation to drive the diesel powertrain are estimated to cost 60€/g CO2/km. This study concludes that the engineering cost (relative to full electrification) of applying the considered 48V Mild Hybrid technology to the existing vehicle platform is relatively low.

Initial simulation results with additional installation of 48V engine coolant and engine oil pumps suggest reductions of up to 15% (relative to baseline) are feasible. It is envisaged that conversion of existing high power consumers from 12V to 48V will offer further efficiency improvements.

The Mild Hybrid technologies demonstrated here are not restricted to diesel vehicles and may also be successfully applied to gasoline and alternatively fuelled vehicles.

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Definitions/Abbreviations

ADEPT	Advanced Diesel Electric Powertrain
B-ISG	Belt Integrated Starter Generator
BMS	Battery Management System

BSFC	Brake Specific Fuel Consumption
DC-DC	Device to convert
EALABC	European Advanced Lead Acid Battery Consortium
EGR	Exhaust Gas Recirculation
FMEP	Friction Mean Effective Pressure
FEAD	Front End Accessory Drive
GSI	Gear Shift Instrument
HCU	Hybrid Control Unit
HMI	Human Machine Interface
NEDC	New European Drive Cycle defined in UNECE regulation 101
PCM	Powertrain Control Module
RDE	Real Driving Emissions test procedures
SR	Switched Reluctance
TIGERS	Turbogenerator Integrated Gas Energy Recovery System
WLTP	Worldwide harmonized Light vehicles Test Procedure