Engine Technology for Sustainable Vehicle Applications: An Interactive facility for student exploration

Institute for Advanced Teaching and Learning Academic Fellowship Grant

Final Project Report

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Executive summary

This Institute of Advanced Teaching and Learning (IATL) Academic Fellowship grant has funded the customisation, installation, commissioning and base-line evaluation of an automotive passenger car engine, along with enabling the development of teaching materials and supporting documents to allow immediate utilisation across a range of School of Engineering and WMG educational programmes at the University of Warwick. The engine will engage students from a diverse range of backgrounds and at a range of educational levels. It gives the capability for students to partake in explorative, problem based, practical learning by working in small groups and individually using the equipment now established. The activities they undertake embeds their knowledge and skills in engine operation, control, calibration, fuel efficiency, carbon dioxide emissions and pollutant emission formation and control mechanisms, in the context of engine applications in next-generation sustainable vehicles. The engine replaces an older, inappropriate, proprietary demonstration engine and the application of an open control system extends student activity significantly beyond what was previously possible. Customisation, installation, interfacing, commissioning and baseline performance evaluation has been successfully completed, on time and within budget.

Acknowledgements

The author would like to express his personal thanks for the support of numerous individuals, companies and organisations in the completion of this project, including but not limited to IATL, Ian James of ISJ Engineering Ltd, PowerTorque Engineering Ltd, Prof Paul Jennings, Mark Amor-Segan, Terrance Timms, Adrian Taylor, Dr Yue Guo, Sina Shojaei, WMG finance and many others whose contribution was invaluable.

Introduction

The revolutionised application of combustion engine technology underpins automotive industry-wide roadmaps for low carbon vehicle propulsion systems to 2040 and beyond. Conventional approaches to the teaching of combustion engine theory is through formal lectures and sometimes desktop computer simulation packages such as GT Power or WAVE. Warwick's School of Engineering, MEng, 4th year Vehicle Propulsion module previously had no practical content, and WMG's industry focussed Technical Accreditation Scheme (TAS) gave heavily restricted access to a non-representative engine operating under a proprietary, and therefore closed, control system. Other higher education institutions do not typically give students access to a real engine due to a lack of access to appropriate test-cell facilities and the prohibitive difficulties in undertaking hands-on exploration with a real engine due to the proprietary, i.e. closed, engine control unit that would typically be installed.

This project has delivered an engine technology learning platform which is both novel and innovative. It gives students extended hands-on access to a state-of-the-art automotive engine, controlled and reconfigurable through an open-access electronic management system.

Practical experience is a key element of educational initiatives targeting the Science Technology Engineering and Mathematics (STEM) skills gap and is a fundamental requirement for relevance to graduate employability in the automotive industry. This project gives Warwick students exposure to real engine phenomena without the limitations of a fixed boundary of simulation or closed control system. This learning facility establishes Warwick as an innovative leader in the provision of automotive engine engineering education, aligned directly with automotive industry strategy for the shift to next-generation sustainable vehicles. It also enables the teaching materials and module format from an industry funded professional MSc programme to be redeployed for diverse student access across non-industry funded programmes which otherwise would not have any practical engines content at all.

Inclusivity and deployment

The learning facility will be utilised from 2016/17 academic year onwards by students from two departments (Warwick School of Engineering and WMG), across undergraduate, full-time masters and part-time professional programmes. The facility will be available for use by doctoral students, and a strategic target is future utilisation in project work by students at the two WMG academies.

A strong international student demographic has been recruited into WMG's new MSc in Sustainable Automotive Engineering launching in October 2016. This is consistent with existing WMG full-time MSc intakes. By targeting the full range of higher education provision (and potential to include key stage four and five WMG academy students) the facility enhances the learning experiences of a diverse student population.

This project has configured and installed a state-of-the-art automotive petrol engine (Ford 1.6 litre Sigma VVT) with open control system in WMG's Vehicle Energy Facility (VEF) for immediate deployment in a range of degree programmes targeting engineering skills for next-generation sustainable vehicles:

- School of Engineering, MEng in Automotive Engineering:
    - 4th year core module: Vehicle Propulsion
    - Established module under redevelopment for 2016/17
    - Typically 40-50 students per year
- WMG, full and part-time MSc in Sustainable Automotive Engineering:
    - Brand new course launching Autumn 2016
    - Core module: Propulsion technology for hybrid and electric vehicle applications
    - 22 students with accepted offers as at 31 July 2016.
- WMG part-time MSc Technical Accreditation Scheme (TAS)
    - Professional programme delivered to industry
    - New module: Propulsion technology for hybrid and electric vehicle applications
    - 40 students per year expected from 2016/17 onwards

Students will gain hands-on experience of engine operation, control and calibration, being uninhibited by on-board diagnostics, immobilisers, and restricted operating modes found in proprietary closed systems. Through small group extended practical sessions they will explore fuel economy, carbon dioxide and pollutant emission formation in both conventional and sustainable vehicle applications utilising a state-of-the-art research and development facility. The facility will also support several individual student projects on these degree schemes. In total approximately 100 students will utilise this facility as a learning resource in 2016/17 and subsequent academic years.

In line with WMG strategic aims, use by WMG academy students is predicted, along with further utilisation in international TAS programmes such as that currently being trialled to Tata motors.

When not in use between module occurrences the modular pallet-based layout enables rapid removal and reinstallation in the VEF test-cell, with intermediate storage within WMG's external weatherproof cabinets, utilising space previously occupied by the legacy TAS teaching engine.

Deliverables

IATL's Academic Fellowship grant has funded the following activities and specific deliverables:

1. Application specific design, development and customisation of mechanical hardware to enable installation as a bespoke learning facility in WMG's VEF.
2. Application specific base-calibration of the open control system, and supply of supporting documentation and data files.
3. Interfacing of the engine to the dynamometer, fuel meter, emissions analyser, controls and monitoring systems.
4. Commissioning, including evaluation of base-line performance as the starting point for student evaluation and optimisation investigations.

Additional support was obtained from the WMG VEF technicians and support staff who were on-hand throughout, as for all VEF activities, and funded from existing VEF development and maintenance budgets. Services from PowerTorque Engineering Ltd and ISJ Engineering Ltd were funded directly from the IATL grant. The engine itself was purchased from the module development budget of the TAS professional MSc programme. When deployed, running and maintenance costs will be covered by departmental teaching budgets as per the previous TAS teaching engine that this replaces, with no significant change.

Student engagement

A WMG doctoral student has taken a key role in this project, leading some aspects of the commissioning of the facility. An account of their involvement is quoted later in this report.

Student engagement with the facility, in addition to that described above, is in the form of practical group activities, problem based learning, and explorative learning. This is a huge improvement in student experience compared to classroom learning or simulation based methods. That improvement will be reflected in student feedback, the national student survey and through feedback mechanisms to support the recently proposed Teaching Excellence Framework. Additionally, the practical nature of the learning environment is directly aligned with graduate engineering skills requirements in the automotive and wider engineering industries.

Concept requirements

The aim was to provide a much more worthwhile student experience from this new resource and so over many discussions with relevant stakeholders and colleagues, the concept was refined to target the following desirable features:

- The engine should be gasoline (petrol) powered as is typical of most hyrid automotive applications.
- Engine size should suitable for a parallel hybrid vehicle, say between 1.4 and 2.0 litres, to make it most relevant to the students who would work with it.
- The engine should be as late a unit as possible, to maximise its relevance and useful working life. The one area where this was not followed through was in our preference for a port fuel

injection (PFI) engine. A gasoline direct injection unit (GDI) would have been more up-to-date, but the PFI system suited the available experience and is more tolerant of a poor calibration (during student exploration) than a GDI unit. There has also been some moves back to PFI engines within the automotive industry for reasons including reliability, simplicity and cost so a total shift to GDI technology is by no means assured

- The engine control system calibration should be completely accessible to the project. Ideally, from a calibration standpoint, it should be easy to understand and simple to use. The practical learning sessions that were envisaged were to be around four hours long. A complex production engine management system could not even be introduced in that time scale.
- VEF staff were involved from an early stage to ensure that the project solution met the needs of all the Stakeholders. Advice from the VEF staff suggested that the engine installation needed to be as self-contained as possible so that it was easily removed from the test-cell and re-installed when required, with the minimum of difficulty. The test-cell to engine interface needed to be straightforward.

Engine and supplier selection

Various routes to provide an engine and appropriate control system were considered in the autumn of 2015. The solution chosen was provided by PowerTorque Engineering Ltd of Binley, Coventry. PowerTorque is one of the largest Ford Component Sales outlets worldwide. The Ford Component Sales organisation provides a route to parts and vehicle sub-systems (such as engines) for Ford customers such as low volume vehicle manufacturers.

PowerTorque were thus well placed to support the project. Discussions with their team identified the Ford 1.6L Sigma engine as a unit that would fulfil our needs. The engine is in current production (2016 model year Ford Focus and others) and it provides appropriate feature content. The engine is a four cylinder, double over-head cam, 16 valve unit equipped with electronic throttle control (ETC), dual variable valve timing (VVT) actuators, port fuel injection (PFI) and closed loop fuel control.

PowerTorque had recent experience of mounting a similar engine on a cradle for demonstration and teaching purposes in a commercial setting. It was understood that the engine could be supplied with a wiring harness and open aftermarket engine control unit (ECU), pre-configured (“calibrated”) to suit the engine. Acceptable cost, and PowerTorque’s inclusion of further assistance with ancillary systems such as exhaust system and dynamometer propshaft together with the possibility of problem solving support during commissioning from a local site made this a low risk solution.

Installation

The engine to test-cell interfaces that needed to be engineered are detailed in the subsections below:

Engine pallet mounting

The engine cradle was produced by PowerTorque to suit the WMG’s Vehicle Energy Facility (VEF) dynamometer pallet. Pallet CAD drawings were provided by WMG and PowerTorque’s design was a straightforward adaptation from that fitted to the previous demonstration and teaching engine they had supplied.

Mechanical output - Propshaft

PowerTorque produced a propshaft adaptor flange for the engine and co-ordinated with another local company to specify a simple propshaft with Hooke’s joints and a plunge joint to suit the maximum rated engine speed of 6500 RPM. This included the custom designed mating flange matched to the face plate of one of WMG's Froude-Hofmann dynamometers.

Cooling

Connections to the test-cell water cooling system were straightforward using generic pipework and followed conventional engine test-cell installation practice. The engine's standard equipment includes an oil to water heat exchanger which eliminates the need for a separate oil cooling circuit.

Electrical

The engine was supplied with a complete engine wiring harness, fuse/relay box and ECU. Wiring diagrams were provided so that the test-cell side of the wiring installation could be produced.

The key connections to be made were main system 12V power and ground from the test-cell power supply (KL30 and KL31), and 12V ignition feed from the test-cell system (KL15).

An engine system control box was manufactured on site to provide ignition switch, emergency stop and throttle input functions. Warning lights for high coolant temperature, low oil pressure and malfunction indicator were also included. The ECU provided a 5V supply which was fed to an accelerator pedal in the form of a simple potentiometer to provide the ECU with its power request input. As the engine was equipped with ETC, no throttle actuator was required in the test-cell.

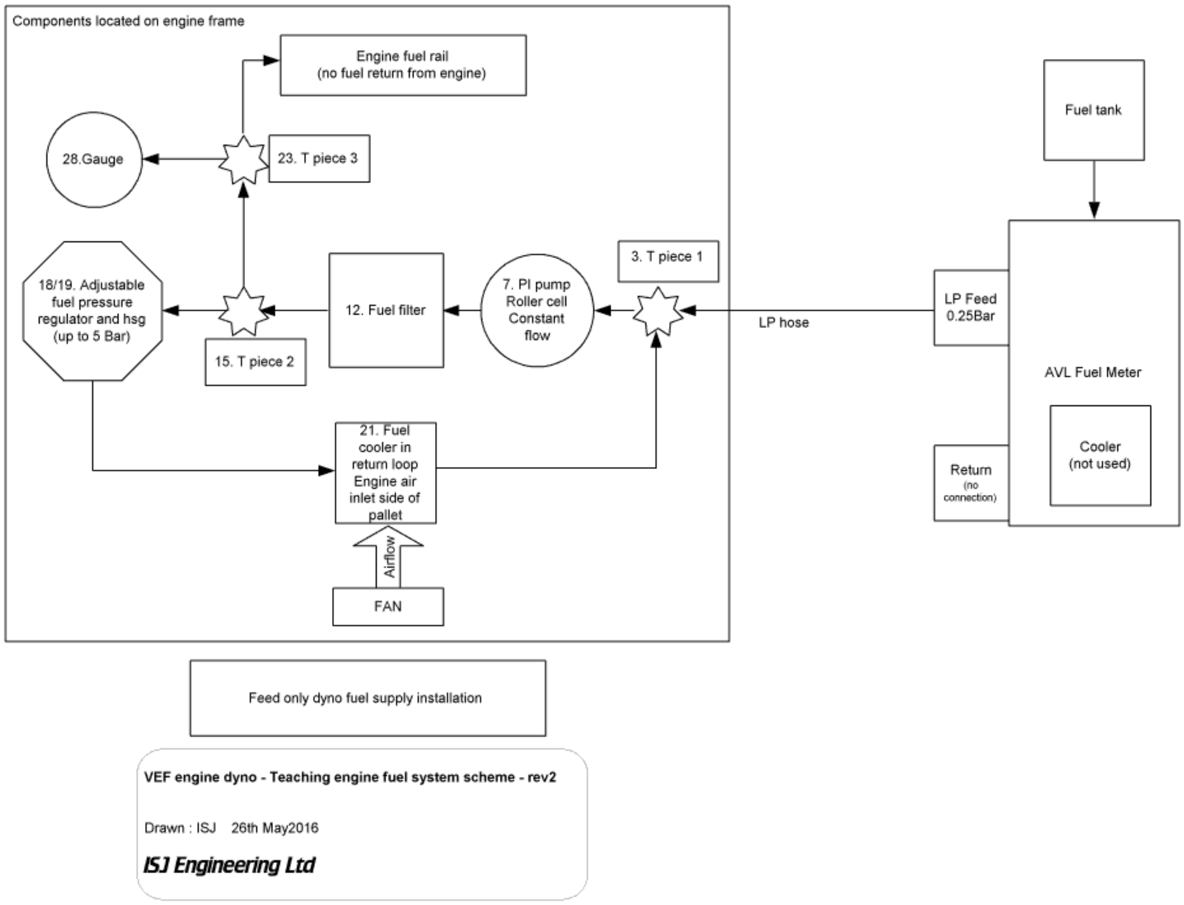
The control box was located in the remote test-cell control room. This required an extended cable run of about 25m but no difficulties have been experienced as a result.

The ECU communications to the laptop-based calibration tool are implemented over a controller area network (CAN) link. Again, no difficulties have been experienced using the extended cable run required to locate the laptop PC in the remote test-cell control room.

Fuel supply

The VEF test-cell is equipped with an AVL 753 fuel conditioning system. This unit provides an adjustable regulated low pressure fuel feed and return system with the integral fuel meter measuring the net fuel mass delivered. A fuel cooler is incorporated into the fuel return system. VEF staff advised that there are currently several issues preventing use of the fuel cooler and also due to the requirement for prompt changeover between gasoline and diesel fuel for different projects, it was preferable not to use the cooler facility to minimise the fuel flushing task. A dedicated gasoline fuel system was designed for the project. The engine system requirement was a regulated fuel delivery at a pressure of 3.8Bar. In a vehicle, the regulator and pump are contained in a unit at the fuel tank so there is no return to the tank from the injector fuel rail at the engine. This condition was re-created by using an adjustable fuel pressure regulator in the following way.

The AVL low pressure supply was taken to a high pressure roller cell fuel pump. Regulated flow was directed to the fuel rail while the return was passed through a fluid to air cooler fitted with three 80mm diameter 12V cooling fans. The cooled fuel was then returned to the system just before the roller cell pump. The fuel cooler was required to avoid the re-circulating fuel becoming overheated. The adjustable fuel pressure regulator was set to provide a delivery pressure of 3.8 Bar. The setting was made with maximum re-circulating flow when the engine was not running. This method compensated for the lack of a low pressure fuel return back to the tank. All the components of the fuel system were mounted on the engine pallet for simplicity and in this way, only one fuel pipe connection is required between the AVL flow meter and the engine, and the AVL fuel meter is able to correctly measure only the net mass flow into the engine. A schematic of this configuration is shown below:



The fuel system was built with typical motorsport quality parts based on high pressure steel braided hose. This approach allowed the pipes to been made up without specialist tooling and provided flexibility to make modifications to the system such as the late inclusion of a fuel drain tap to aid system de-pressurisation when the engine is removed from the test-cell. The steel braided hose provides abrasion resistance appropriate to the test-cell environment.

Exhaust

PowerTorque provided a simple exhaust system with an industrial type silencer. This allowed an appropriate length of straight tube to be fitted ahead of the VEF's exhaust gas emissions sampler.

Air intake

The air cleaner system as supplied was adapted with an extra length of hose to mount to the pallet. This minimised the possibility of damage or loss of parts while in transit or storage.

Commissioning

The commissioning process followed normal new-installation start-up practice for engines in dynamometer test-cells, checking the new systems step by step:

- Check engine oil level.
- Check engine coolant level.
- Check security of engine mounting fixings.

- Check security of propshaft fixings.
- Leak test fuel system: carried out in the test-cell.
- Set the working fuel delivery pressure at 3.8Bar with engine not running, using the gauge built into the fuel system on the pallet.
- Establish communications with the ECU. Initially, communications were proved locally in the cell, before introducing the 25m extension cable to the control room into the system.
- Confirm that the engine sensors, Air Inlet Temperature (AIT), Engine Coolant Temperature (ECT) and Throttle Position Sensor (TPS) were providing sensible readings.
- Check operation of all system emergency stop switches.

Once these checks were completed satisfactorily, then an attempt was made to start the engine. A minor problem with setting the operating voltage range of the accelerator pedal input prevented the engine running properly at the first attempt, though it did start and run at low speed.

PowerTorque confirmed that the accelerator pedal range needed to be set and no further difficulties were experienced. The engine subsequently ran through its break-in and early test programme.

Initial running

Once the engine was running, progress was made in a further set of steps:

- Run the engine at low speed and light load e.g. 2000 RPM, 25Nm to warm up and begin the break in process.
- Confirm that the operator has control of the dynamometer speed set-point and engine torque
- Check that the test-cell cooling system begins to work to maintain the engine inlet temperature set-point.
- Confirm that the ECU calibration tool continues to display sensible data.

In order to make best use of the test-cell time, once the engine was running properly, the break in was undertaken by means of ignition loop tests, which form one of the investigatory optimisation exercises that the students will undertake. The ignition advance was adjusted retarded about 12 degrees from the calibrated point and then advanced at constant torque in 2 degree increments. A set of data was recorder at each point so that we could verify the operation of the AVL fuel meter and then the emission analyser.

Further tests looked at understanding the most efficient (lowest brake-specific fuel consumption - BSFC) speed at which to generate 20/25/30kW. This activity was a look ahead to another potential student exercise based around most efficient engine operation in a hybrid vehicle application to meet a constant power demand.

The operation of closed loop fuel and variable camshaft timing sub-systems was checked with further data gathered on the effect in emissions and BSFC of adjusting the variable cam timing calibration. Again, this looked forward to further student exercises.

Finally, with an acceptable break-in period completed, a full load power curve to the maximum allowed dynamometer speed of 5000 RPM (VEF large dynamometer machine) was undertaken to confirm that the installation was robust.

Outcomes

A 2016 model year Ford 1.6L gasoline engine has been procured and installed in the WMG VEF dynamometer test-cell as a teaching and learning resource. The test facility already included an AVL fuel meter and a Horiba 7000 exhaust gas analysis system. The engine uses a port fuel injection system and includes features such as variable inlet and exhaust camshaft timing and closed loop fuel control.

The engine control system uses the original equipment manufacturer (OEM) sensors and actuators but is controlled by an aftermarket ECU. This ECU provides full access to all of the calibration parameters contained in the engine control strategy.

Working with the ECU is straightforward as a Calibrator, and it is anticipated that students (under supervision) will be able to make their own calibration changes within the boundaries of a guided investigation after only 10 or 15 minutes familiarity with the system. The results of their changes will be monitored and displayed to the students by the various VEF systems already mentioned. This is a key feature of the project, allowing students to gain hands on experience of an engine optimisation process and interpretation of results without the need for an extensive training course on how to use the tools.

The engine has been commissioned and has completed a running in procedure.

Following completion of the running in procedure, various tests have been undertaken to:

- Verify the operation of engine systems such as closed loop fuel, variable cam timing and fuel delivery.
- Prove the installation durability ahead of student use.
- Quantify the initial engine performance, thereby providing baseline data for student investigation and optimisation tasks.

These tests included:

- Ignition loops at constant air fuel ratio (AFR)
- Brake specific fuel consumption (BSFC) tests at constant power output
- Engine out (raw) emission and fuel economy (BSFC) tests to examine the effect of varying camshaft timing.
- Wide open throttle (WOT) tests to understand the full load performance up to the dynamometer speed limit of 5000RPM.

Issues encountered

During the design, installation and commissioning of the engine a number of mainly technical issues were experienced, most of which were appropriately managed or resolved. These did consumed considerable time and effort by various parties. The most significant of these issues are outlined below:

Fuel system and fuel supply

The lack of availability of the AVL fuel cooler within the test-cell infrastructure necessitated the design and installation of the bespoke fuel pressure regulation and cooling circuit previously described. The VEF's large capacity petrol storage tank was also unavailable to store and supply fuel to the AVL equipment. It would have been more straightforward for this project to use the AVL unit and VEF fuel supplies as designed, but the practicalities preventing this could not easily be overcome within the time and budget available.

Dynamometer availability

The VEF contains two dynamometers. The smaller of the two is well matched to the testing of automotive engines with an appropriate power and speed range capability. The larger machine has a lower speed limit, but significantly more power capability. Unfortunately the smaller machine suffered a significant failure during recent operation on a research project, and has not yet been repaired. The timescale for this is difficult to predict because the original equipment supplier is currently in administration. As a substitution the larger dynamometer was made available to this project, and will be used for deployment with students until such time as the smaller unit is repaired and available for use. The consequence of this are three-fold:

1. An adaptor plate had to be specified and procured to mate the propshaft, which was originally designed to connect to the small dynamometer, to the face-plate of the larger dynamometer.
2. The engine is designed to operate up to 6500rpm, but the speed limit of the larger dynamometer is 5000rpm. This limits access to the full power capability of the engine which is reached at around 6000rpm, and will give students a restricted region of the engine's performance within which to work. Key phenomena are evident below 5000rpm so learning outcomes can be achieved, but the situation is far from ideal and gives the students a false impression of power capability of the engine where the restriction is actually due to the use of an inappropriate dynamometer.
3. Commissioning and baseline performance evaluation has been restricted by the 5000rpm speed limit, and the 5000 to 6500rpm range will have to be evaluated at a later date before students can operate to the full capability of the engine once the restriction is removed.

Propshaft connection durability

During the early days of engine running the mechanical connection between the engine and propshaft, and propshaft and dynamometer, failed. Initially this was due to the use of incorrectly rated fastenings and improper fitment. The failure caused component damage before the issue was identified. Repair was undertaken, involving two external suppliers, contingency departmental budget and considerable organisational effort by the engine commissioning team. Several days of engine development time was lost during this period. Subsequently the engine to propshaft fastenings were observed to move again during use, and a number of measures were then taken to prevent further failures:

1. Use of locknuts behind the engine faceplate which had to be custom modified to fit within the space available.
2. Use of high strength thread locking compound for both the adaptor plate and locknuts.
3. Design of a new procedure to bring the engine to rest more promptly at shutdown, and prevent sustained high torsional forces on the coupling at very low engine rotation speed.

Financial administration

Significant delays were experienced in the placing of orders for procurement of materials and services required by the project. To some extent this would have been expected and handled better in the early stages had the project manager been more experienced in the university's financial processes and procedures. However, issues such as staff vacations, lack of access to local engineering stores typical of an engineering department, confusion over the value added tax (VAT) status of the project budget, use of funding from multiple departments within the university and the need to add specialist suppliers to the university's approved supplier registry, all hindered progress throughout the project. In some cases individual purchase orders took between two and five weeks to reach external suppliers, which is a significant obstacle within a six month practically based project of this size and complexity. Furthermore, the project was late in commencing because formal confirmation of approval and budget arrangements did not arrive from IATL until well after the originally envisaged start date.

On-going work

The next stages of development is to produce finalised teaching materials for use on the various modules and courses where the facility will be deployed. Initially this was planned to take place for a July 2016 "Propulsion Technology" TAS MSc module, but this module was cancelled at short notice due to reasons unrelated to this project. This removed the priority requirement to create activity plans within the timeframe of this project, and allowed some of the various practical difficulties previously described to be solved with long-term, robust, solutions rather than short-term contingency which would otherwise have been necessary. Sufficient data has been obtained from the engine, and draft activity plans have been designed such that the remaining tasks are procedural and administrative.

The first deployment will now take place in December 2016 for the next instance of the propulsion technology module. Teaching materials will be finalised as part of the normal module preparation process during the early part of the 2016 autumn term, before entering a conventional cycle of reflective review and modification for subsequent uses.

Plans to use the facility with undergraduates on the School of Engineering's Automotive Engineering MEng course are advancing, and a willingness to make this happen during either the 2016/17 or 2017/18 academic year has been agreed by all parties.

Stakeholder comments

A number of relevant parties were approached for comments on the teaching engine facility as commissioning neared completion. This included various senior colleagues within WMG and a senior representative from the automotive industry. Their comments are quoted below:

"'Whilst the automotive horizon looks towards higher degrees of electrified powertrains, fundamental combustion engine controls and calibration expertise will continue to underpin the transitional activities towards hybrid powertrains. The course at WMG not only provides the students with an opportunity to develop their controls theory, it enables a unique opportunity for all of the students to apply acquired knowledge in a practical test environment, a vital skill for transitioning into industry."

Mark McNally
Senior Manager of Advanced Research Technology Demonstration & Low Carbon Vehicles
Jaguar Land Rover

"A vital part of our work in the Energy Innovation Centre is to support skills development and teaching activities alongside our other research work. Our aim is to give students access to state-of-the-art facilities to develop the skills that our industry partners demand. The new 'teaching engine' provides us with a dedicated resource that greatly enhances our ability to support teaching and skills development. It is great to see students learning and working in a world-class research facility."

Mark Amor-Segan
Principal Engineer
WMG, University of Warwick

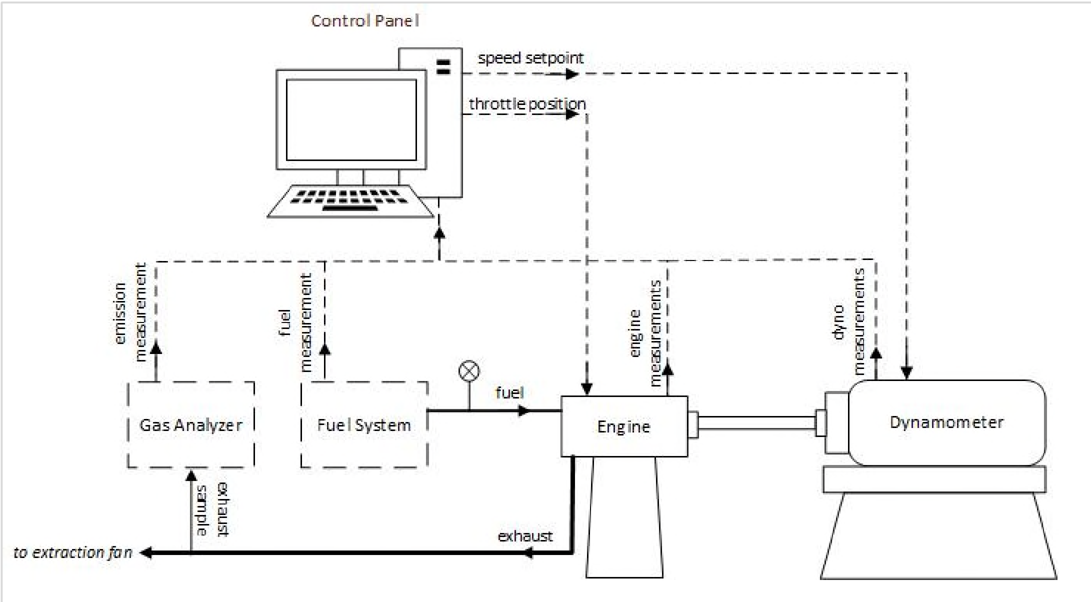
"The new experimental facilities that have been created to support the teaching of automotive engineering within WMG are very exciting. For the first time, it will be possible for students to use our state of the art research laboratories to apply and extend their own learning beyond the confines of the traditional classroom. Our graduates will possess not just the fundamental knowledge into the subject matter, but also the practical experience and skills to apply that knowledge to solve real-world problems."

Dr James Marco
Reader in Hybrid and Electric Vehicles
WMG, University of Warwick

Student involvement during commissioning

A WMG doctoral student, Sina Shojaei, spent around 35 hours working with the project leader and contractors during the installation and commissioning of the teaching engine facility, leading some aspects of the commissioning exercise. The following text describes Sina's experience of the project in his own words:

> "My involvement with the project started soon after the engine arrived at WMG. We planned to use the engine to demonstrate the process of characterising engines to students. The characterisation test briefly includes using a dynamometer to run the engine and measuring its power, fuel consumptions and emissions at various operating points. While the engine was setup in the test facility, I was familiarised with various features of its design, including the function and location of the electronic components, such as the lambda sensor, crankshaft position sensor etc. Preparing the test setup involved resolving various practical constraints, often through designing bespoke parts and components, which was a learning experience for me. One example was a bespoke fuel handling system that was required to pressurise and cool the fuel feed to replicate vehicle conditions. While this system was designed I learnt about the fuel pressure limits in different engines, its impact on fuel consumption, and how the requirements has changed over the years as engine designs have evolved.
>
> Below, the schematics of the test setup that was prepare for this project is shown:



Using the above setup, we carried out a number of tests on the engine, during which I had the opportunity to work with different equipment and gain a first-hand experience from the process. One aspect of the characterisation test was developing the energy efficiency and emissions maps of the engine. The process that we followed for this purpose was:

1. The maximum speed setpoint was specified in the dynamometer control software.
2. The throttle was opened to speed the engine up to the setpoint. Beyond the setpoint, the dynamometer applies a resistive torque to the engine, preventing it from exceeding the setpoint.
3. By adjusting the throttle position, the output torque and power of the engine were altered to achieve a desired operating point at constant speed.
4. Various signals such as speed and throttle position could be retrieved from the engine control unit.
5. Fuel flow to the engine was read from the fuel handling system. Knowing the output power of the engine, the fuel measurement could be used to calculate the efficiency.
6. The exhaust gas was continuously sampled and analysed in the gas analyser for its CO, CO_2 and NO_x content. Therefore the emission content relevant to each operating point could be established.
7. By repeating the above steps with a range of speed setpoints the complete operating envelope of the engine could be swept and the fuel efficiency and emission characteristics maps was developed.

Table below, gives an example of the measurements taken in one operating point of the engine after following the above process and corresponding energy efficiency calculation.

Point of Acquisition	Engine ECU	Dyno	Fuel System	Gas Analyser	Calculation	
Measurement	Speed	Torque	Fuel Flow	CO_2	Power	Efficiency
Value	1500 [rpm]	60 [Nm]	2.95 [kg/h]	13.8%	6.28 [kW]	469.5[g/kWh]

The engine purchased for this project has an open control unit, through which the calibration settings of the engine can be accessed and altered. This provides a unique opportunity for understanding the impact of various calibrations on energy efficiency and emissions and the response of the engine under different calibrations. One aspect of engine calibration that we investigated was the spark ignition timing of the engine. By modifying parts of the default ignition map of the control unit we observed the effect of ignition timing on efficiency of the engine. Adjusting the variable valve timing was another aspect of engine calibration that could be investigated, but one that I could not take part in due to other commitments. "

Media

Throughout the project the author has taken positive steps to disseminate progress through the use of his social media twitter account (@DrAntAllen), by having the project mentioned on BBC Radio 2 and in a pending academic conference paper.

Social media reporting

A total of 17 tweets have been posted, most of which included images or video content, the majority of which have been further publicised though "likes" and / or "retweets" by various individuals and organisations including IATL.

BBC Radio coverage

Delivery of the engine to WMG was announced on the Chris Evans' Breakfast Show on 24th May 2016. Chris was discussing people expecting deliveries of unusual vehicles that day, and futuristic / sustainable / electric vehicles had been mentioned earlier in the show. He congratulated the University of Warwick on the delivery of the new teaching engine, reading out the project strap line "an interactive student facility for exploration of sustainable engine technology". This was followed by light banter with the travel reporter Lynn Bowles during which the project was described as being so good that no vehicle was actually needed. The broadcast is available for a limited period on the BBC website (http://www.bbc.co.uk/programmes/b07bkc2r), with this content at approximately 55 minutes into the program.

Academic conference paper

The author has submitted a technical paper to the 2016 Institute of Engineering and Technology (IET) Hybrid and Electric Vehicle Conference, titled "Hybrid vehicle engineering: A vehicle to hybridise engineers". In the context of addressing the STEM skills gap the paper describes how four hands-on practical activities have been designed and deployed with MSc students on various programmes within WMG. One of those activities is the exploration of an automotive grade combustion engine for hybrid vehicle applications which has been made possible by this project. The abstract for the paper was accepted in the early summer of 2016, and at the time of writing the draft full submission has been submitted for peer review. IATL is referenced as having funded part of the development of the engine activity.

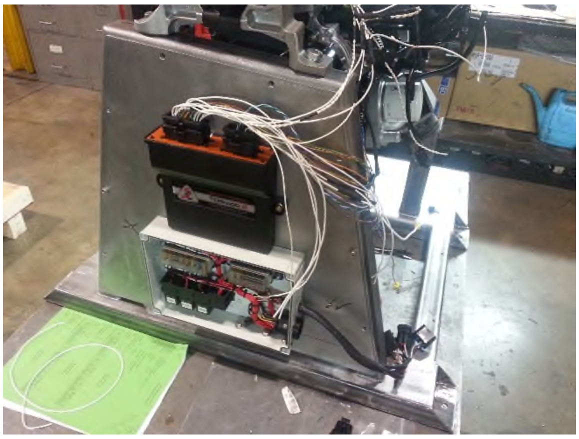
Finance

A total of £7,463.63 from the Academic Fellowship Grant has been spent, as detailed in Table 1 in Appendix A.

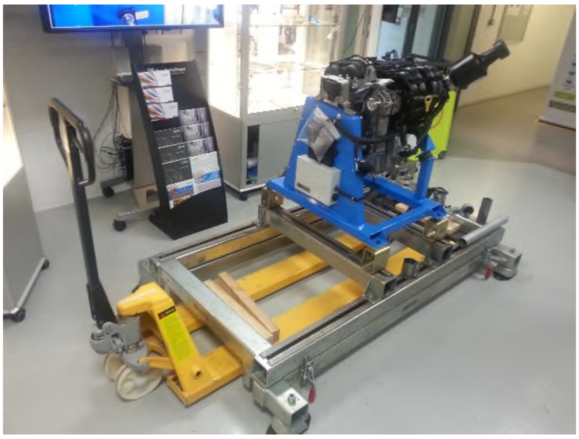
Additionally approximately £8000 has been spent from other departmental budgets to cover the initial engine hardware purchase and various components and services required to install the engine in the WMG dynamometer test chamber. A significant element of the latter is the high pressure fuel circuit components previously described.

Photo diary

Throughout the project a photographic diary of progress has been produced, illustrating major stages in the project and serving as a visual inspiration for interested parties. Various images were included in the social media reporting throughout the project and some are also included in the planned academic conference paper.

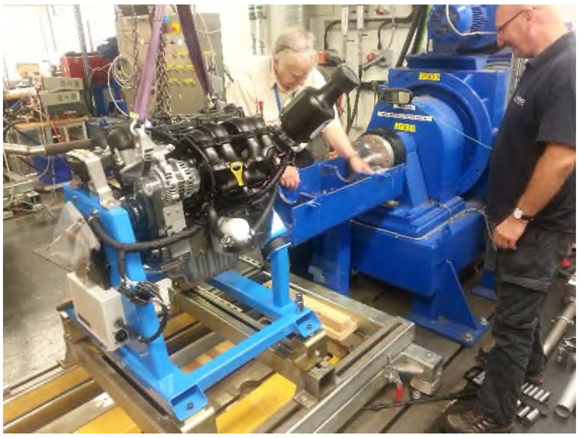
 15 Dec 2015: Initial visit to PowerTorque Engineering Ltd to understand options available, potential scope of supply, timescales and costs.	 11 May 2016: Engine part mounted on custom frame (unpainted) at PowerTorque Engineering Ltd.
 11 May 2016: Engine control unit with partially complete wiring and power distribution components (fuses and relays) with lid removed at PowerTorque Engineering Ltd.	 24 May 2015: Engine arrival at WMG immediately prior to unloading from delivery vehicle.

24 May 2015: Engine transfer into WMG International Automotive Research Centre (IARC) by WMG VEF technicians.



8 Jun 2016: Engine mounted on VEF pallet frame prior to transfer to test-cell.

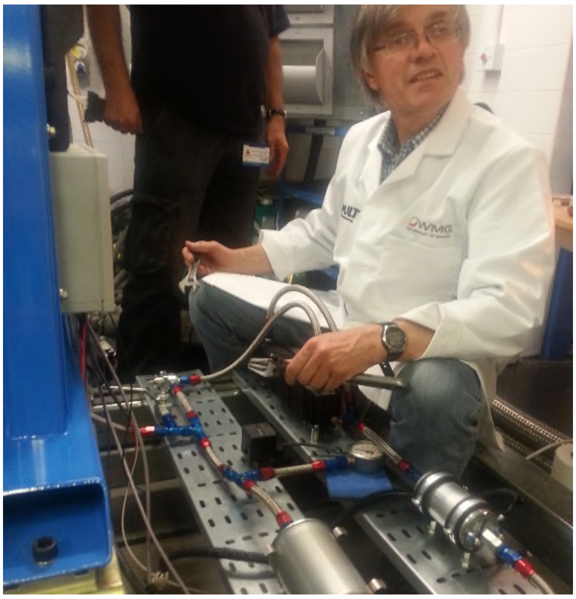
8 Jun 2016: WMG VEF technician trial fitting emissions gas analyser to the exhaust system.



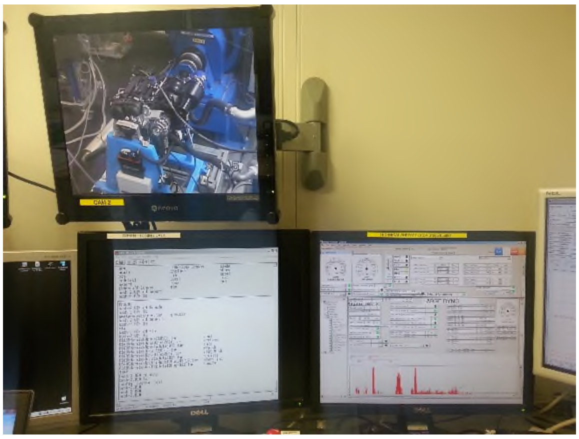
13 Jun 2016: WMG VEF technicians aligning the engine and mounting pallet with the dynamometer in the test-cell.

14 Jun 2016: External contractor undertaking bespoke wiring to interface the engine's ECU to the VEF 12V power systems.

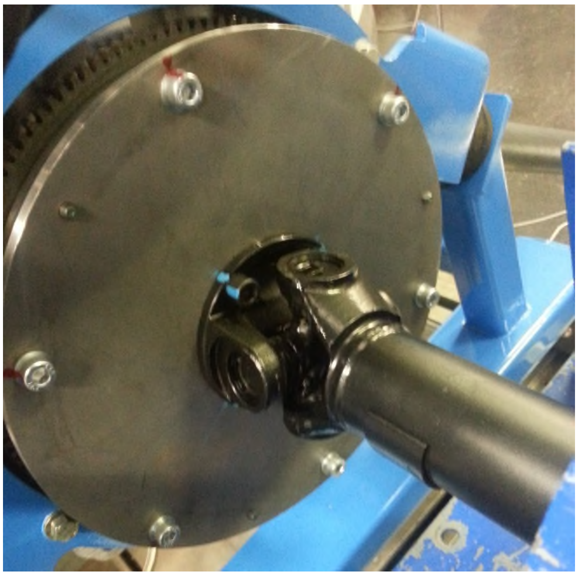
20 Jun 2016: Control of engine throttle established. Throttle plate near wide-open in this image.



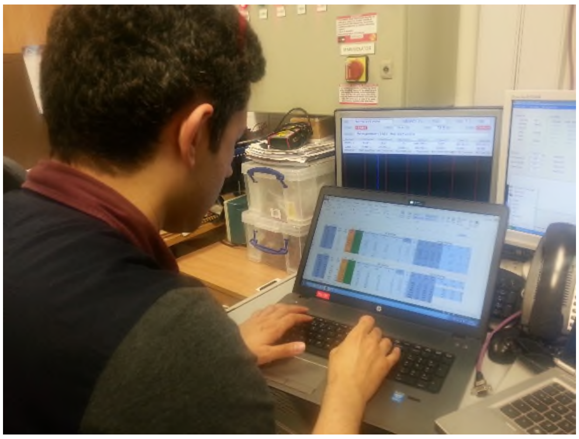
24 Jun 2016: External contractor completing high pressure fuel system connections.



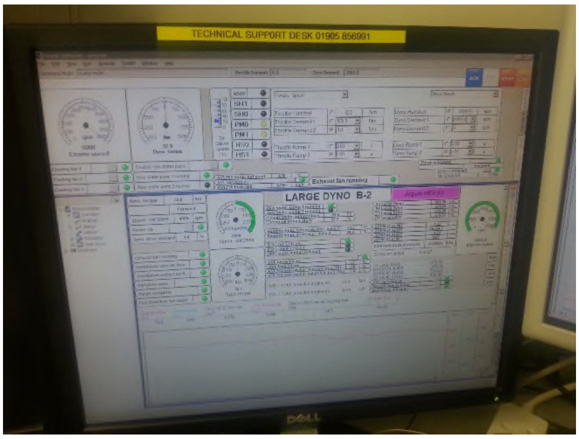
29 Jun 2016: Control room environment with graphic data displays and live video monitoring of engine operation.



29 Jun 2016: Movement of mechanical fasteners at connection between propshaft flange and engine flywheel flange after limited running prior to rectification of issue.

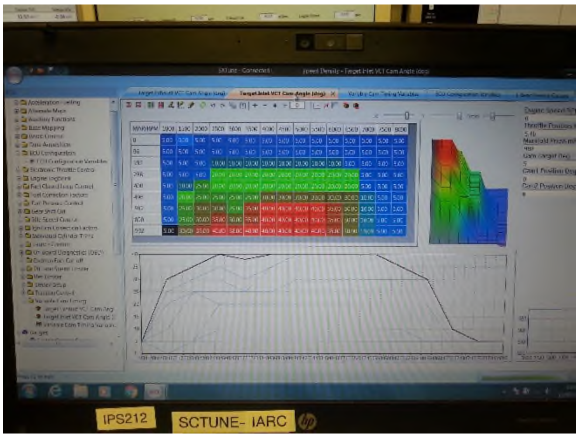


11 Jul 2016: WMG doctoral student operating the engine and collecting baseline data in VEF control room.

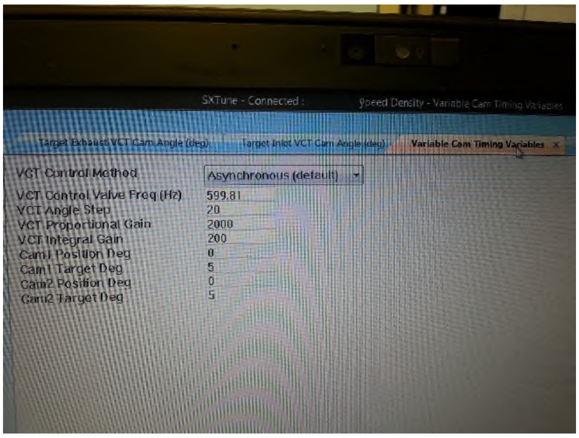


11 Jul 2016: Dynamometer and test-cell control and monitoring interface. Engine operating at 5000rpm, 32.9Nm.

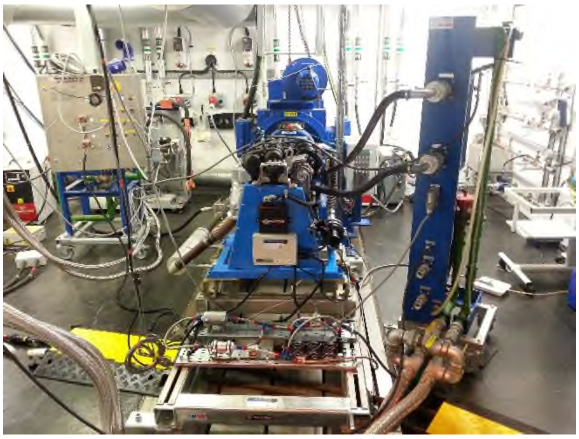
11 Jul 2016: Live monitoring of engine control system parameters through laptop open-ECU interface.



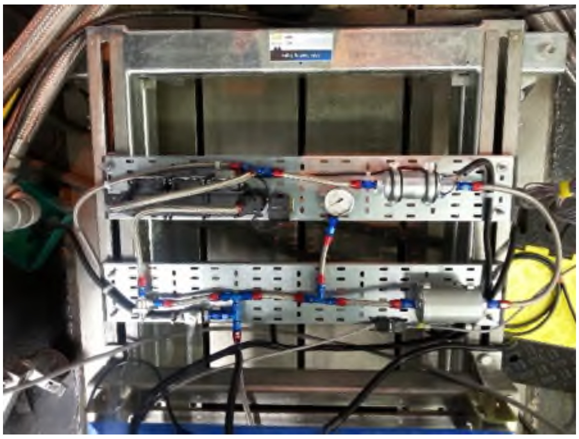
12 Jul 2016: Editing engine control parameters to investigate influence of variable valve timing on fuel consumption and emissions formation.



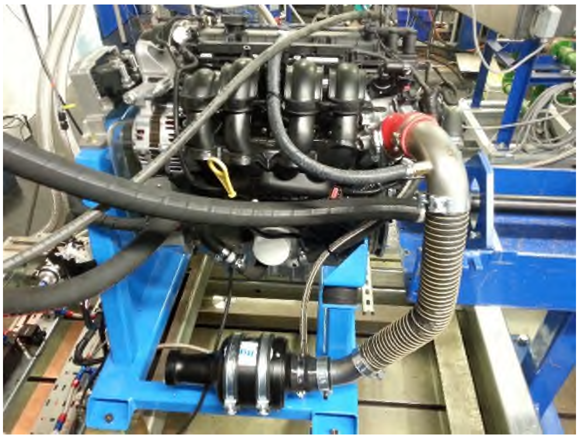
12 Jul 2016: Recalibration capabiliy for proportional-integral-differential (PID) closed-loop control of variable valve timing actuators.



19 Jul 2016: Final engine installation in VEF test-cell.



19 Jul 2016: High pressure fuel system showing pump, cooler and fans, filter, drain-off valve, pressure regulator, pressure guage and engine run time hours meter.



19 Jul 2016: Intake side view of engine installation. Note air filter final mounting position low on the engine frame with flexible ducting to throttle inlet.

19 Jul 2016: Engine open control unit and power distribution box showing WMG Teaching Engine label and logos.

19 Jul 2016: Equipment label attached to engine and controls interface indentifying purpose, sponsors and stakeholders.

Closing remarks

This project has established an innovative and novel facility to enable students to engage in hands-on, problem based, practical learning in the fundamentals of combustion engine operation. Increasing the practical skills of engineering graduates in sustainable technologies supports university, national and international aims for sustainability in transport solutions. The world needs a sustainable supply of engineers with practical skills, knowledge and expertise, to tackle the sustainable engineering challenges of our generation and future generations. This project, and similar initiatives in engineering education, are fundamental enablers of the entire global sustainability agenda.