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ABSTRACT

Many Diesel engine development programs concentrate almost exclusively on steady state investigations to benchmark an engines performance. In reality, the interaction of an engine's sub-systems under transient evaluation is very different from that evident during steady state evaluation. The transient operation of a complete engine system is complex, and collecting test data is very demanding, requiring sophisticated facilities for both control and measurement.

This paper highlights the essential characteristics of a Diesel engine when undertaking testbed transient manouevres. Results from simple transient sequences typical of on-road operation are presented.

The tests demonstrate how transient behaviour of the engine deviates greatly from the steady state optimum settings used to control the engine. The operation of the EGR system and its interaction with other sub-systems, in particular VGT, has a significant effect on emissions, fuel consumption and driveability, highlighting the need for dynamic optimisation as an integrated system.

INTRODUCTION

The high speed Diesel engine is now well established in the European passenger car market, with projected sales expected to encompass 25% of the market by 2005 [1]. Direct injection , rather than indirect injection, will be the predominant future version [2]. The main attractive feature of the Diesel engine, particularly in its turbocharged form, is its high efficiency which can surpass 40%. This enables Diesel engined vehicles to achieve lower fuel consumption figures than equivalently rated gasoline ones. For Diesel engines the development emphasis is on reducing emissions of NOx and PM where these emissions are typically higher than those from equivalent port injected gasoline engines equipped with 3-way catalysts, a summary of the current and impending requirements is given in Table 1. Although carbon dioxide is not yet a legislated emissions species, it is becoming increasingly important owing to its connection with global warming. Limiting CO2 production can only be achieved by improvements in fuel economy, or reducing the carbon content of the fuel. The fact that fuel consumption figures must now be calculated on all new vehicles from 1 January 1997 [3] can be considered evidence of future legislation of CO2 emissions. There is also a need for the passenger car Diesel engine to achieve gasoline engine levels of NVH and provide equivalent acceleration response on demand.

Today's Diesel engined cars demonstrate greater fuel efficiency than ever before while simultaneously achieving emissions levels some 50% lower than those of five years ago [4]. This has been made possible by the application of advanced technologies in the areas of EGR, VGT, multiple valves per cylinder, air flow events, oxidation and de-NOx catalysts, and electronic fuel injection systems (see Figure 1). These engine sub-systems have to be precisely controlled by software within the ECU. These technological advances have led to a significant increase in the complexity, and hence cost, of the engine and its control system. Consequently, the cost of a Diesel engine to meet European Stage 3 emission legislation is estimated to be 35-40% over its equivalent gasoline counterpart. The emissions challenges facing the diesel passenger car for the proposed European Stage 4 are substantial, particularly in relation to PM for which a 50% reduction from Stage 3 levels is required [5,6]. Although hardware improvements can still be made to engine design the greatest benefits will come from optimising the interaction of all the associated engine sub-systems.

A current area of research at the University of Bath centres on the reduction of engine emissions and fuel consumption through the development of dynamic control strategies. A dynamic testing programme has been performed in order to identify the characteristic behaviour under transient operation of a HSDI Diesel engine and its sub-component interactions. Identification and evaluation of these characteristics are being used as a basis for predictive modelling, leading to new control strategies which are able to exploit the potential benefits of transient optimisation. A selection of results from this test program is presented in this paper.

STEADY STATE TESTING AND ENGINE CALIBRATION

Steady state testing involves measuring and analysing engine performance at discrete points within the operating range of the engine. The engine is allowed to settle at each operating point before data are logged, large matrices can be constructed that map the steady state behaviour of the engine. These matrices form the basis of the engine calibration, by analysing the maps optimum settings for the engine sub-systems can be chosen from the map for any engine operating point to deliver maximum torque for the best compromise between low emissions and fuel consumption. The selected settings are stored as maps within the ECU where they are used to command the sub-systems via control algorithms, such as Proportional Integral Derivative (PID). The aim of the controller is to attempt to keep the settings as close to the mapped steady state values as possible. For example Figure 2 is a boost pressure map taken from the calibration for a prototype HSDI engine. At any operating point (determined here by engine speed and fuelling quantity) the ECU looks up a target boost pressure which it relays to VGT vane position, EGR valve position and other subsystem parameters.

Steady state mapping provides a straightforward route to engine calibration. However, it must be remembered that very little real-life driving is steady state, even on motorway journeys the seemingly constant engine conditions are permeated with changes in speed and load alongside many other variables. The outstanding characteristic of all emissions test procedures (drive cycles) is that they involve transient operation of the engine, even though the object is to establish the cumulative mass of each nominated exhaust gas species emitted during the test. Such tests do not indicate where in the cycle these emissions are being produced, and as such, it is difficult to attempt any form of optimisation without a detailed knowledge of how the engines sub-components react under dynamic conditions. Although steady-state optimisation is carried out it can, at best, be considered as a baseline for transient investigations, the main reasons for this being:

1. Steady state measurements give a good indication of how an engine will perform in vehicle emission test cycles.
2. The facilities required to undertake testbed engine transient performance investigations are expensive and the interpretation of transient test results can be difficult.
3. There are severe time and cost constraints on the development process.

TRANSIENT TESTING

Evaluation of the performance of automotive engines is based, to a considerable extent, on the dynamic characteristics when changing state. To quantify these characteristics, especially in relation to emissions, fuel consumption and driveability, transient testing and analysis is required. The purpose being to study the overall response of the engine, the interaction of its sub-systems and the engine management system to the many kinds of transient to which it will be subjected in service. Typical examples of aspects of engine performance under transient conditions that require investigation include:

1. Response of the engine and control to changes, initiated either by the driver or as a result of changes in road load
2. Interactive behaviour of fuel system, turbocharger and EGR under accelerating conditions
3. Short-term changes in exhaust emissions accompanying changes in operating regime
4. Study of the response of different engine control strategies to the whole range of possible transient conditions

Transient testing is highly demanding and requires complex and sophisticated facilities. For this reason, most typical engine development programs concentrate almost exclusively on steady state performance optimisation. In reality, the interaction of engine sub-systems under steady state evaluation is very different during transient operation and this does create dynamic control problems.

Further possibilities of reductions in fuel consumption and emissions via steady state techniques are now very limited, it is necessary to look at the transient behaviour of the engine to identify areas where such reductions can be made. For example, previous transient test work performed at the University of Bath with a 1.8 litre HSDI with Continuously Variable Transmission (CVT) indicated that 50% of NOx emissions during the European Drive Cycle stem from periods of acceleration and deceleration. Figure 3 illustrates an acceleration transient performed on the 1.8 litre HSDI with CVT, where both engine speed and load are allowed to increase during the fuelling step-up transient. The plot shows transient uHC (measured with a fast hydrocarbons detector) overlaid onto the steady state map for fuelling and engine speed vs. hydrocarbon emissions . The start of the step is indicated by (1) and the finish by (2). As can be seen, the deviation from mapped values during the transient is significant, and both the start and the finish of the transient ‘hover’ above the map surface. This can be attributed to differences in engine temperature between the steady state and transients tests, which strongly affect uHC emissions.

TRANSIENT TEST CELL

The transient engine test facility is shown schematically in Figure 4. The basic design was described by Dorey and Guebeli [7] and it was used by Brace et al [8] for a research program with a continuously variable transmission powertrain. The engine is a prototype 2.0 litre HSDI Diesel engine equipped with VGT, a distributor pump fuel injection system and a standard 5-speed manual gearbox. Physical inputs such as accelerator position, clutch and gearchange controls can be operated manually or automatically via a PC equipped with the Ricardo Engine Management Prototyping System (EMPS) environment, used here for driver emulation purposes. This system is also used to control the engine air and water temperatures. The engine management system can be interrogated and altered via the Kleinknecht MCS interface and Gredi software which also permits data logging of engine management variables. General data acquisition is performed by the HPVee DTVee software with 12 bit ADC. The hydraulic dynamometer can be operated in constant speed, constant load or vehicle emulation modes.

The results presented here were generated from pedal steps, these are performed at constant speed and show how the engine responds to step changes in fuelling. The dynamometer is used to maintain constant engine speed (1500, 2500 and 3500 rev/min) and 2 torque levels are manually set using fuelling potentiometers. A toggle switch allows switching between the 2 settings to emulate a step change.

TRANSIENT RESULTS

STEADY STATE VS. TRANSIENT BOOST PRESSURE – Figures 5a and 5b illustrate the deviation of inlet manifold pressure from steady state map values during 3 pedal steps (10-170Nm at 1500 rev/min, 10-170Nm at 2500 rev/min and 10-135Nm at 3500 rev/min). The boost pressure map is taken direct from the ECU calibration and is used in the VGT vane position control loop with boost pressure feedback. During the pedal steps, the fuelling quantity achieves the target value far faster than the air charge, the transient does not follow the surface of the map. In a turbo-charged engine undergoing such a transient, the first thing that happens is the quantity of fuel injected increases rapidly, this in turn puts more energy into the exhaust gases which then accelerate the turbocharger. As the turbocharger accelerates, the flow and pressure to the inlet manifold increase which in turn permits more fuel to be injected.

Figures 6a - 6f detail the 2500 rev/min 10-170Nm transient and are described below. This type of transient is particularly severe and simulates the onset of hard acceleration, such as during a ‘foot-down’ overtaking manoeuvre.

TRANSIENT AIR FUEL RATIO (AFR) – During the initial stages of a large transient when the fuelling is rising rapidly, the lack of immediate boost (‘turbo-lag’) means that the AFR ratio will decrease sharply (see Figure 6b Nominal AFR). To exacerbate the problem further there is the effect of EGR, which is well known to have adverse consequences on smoke, hydrocarbons, particulates and brake specific fuel consumption. The air fuel ratio derived from exhaust gas analysis (Figure 6b Exhaust Gas Analysis AFR) takes into account EGR. The data have been corrected for transport lags in the exhaust system but not for the response of the analysers, hence the fast dynamics shown in the nominal plot are not reflected in the true plot. As is to be expected, the initial and final values of air fuel ratio are lower due to the presence of EGR before and after the transient.

EGR CONTROL DURING TRANSIENTS – Figure 6e shows the position of the EGR valve during the transient. Initially the valve is open, then at the start of the transient it shuts rapidly in an attempt to maintain a good air fuel ratio. Immediately after the valve closure there will still be exhaust gas residuals present in the inlet manifold, particularly so if the exhaust manifold pressure rises sharply whilst the valve is closing (see Figure 6f Exhaust Manifold Pressure) due to the flow restriction of the closed VGT. The peak in pressure causes a brief high EGR flow into the inlet manifold, which in turn results in very low transient air-fuel ratios. Poor air-fuel ratios are associated with poor combustion, reflected by the 90% opacity spike on the smoke plot (Figure 6c). Large smoke spikes such as these are clearly undesirable, and are associated with similar spikes in hydrocarbons and particulates [9]. Also of note is the brief opening of the EGR valve during the transient, this is the result of control being derived directly from steady state maps. At the start of the transient, the boost error exceeds acceptable limits and this in itself disables EGR, however the ECU still looks up the new EGR valve position demand based on the new fuelling and speed conditions. As soon as the boost error falls to within acceptable limits, control is handed back to the EGR map-based system, which in turn opens the valve because in the steady state condition EGR is scheduled for the current engine speed and fuelling.

FUEL INJECTION QUANTITY LIMITING – As a measure to prevent excessively low air-fuel ratios a maximum fuelling limit can be imposed, in the case of the control strategy shown the manifold pressure is used to calculate the air charge density which, in conjunction with engine speed, determines the maximum fuelling. This method does not take account of residual EGR which explains why it permits the large smoke peaks. Figure 6a shows the fuelling limitations applied during the transient, with the dotted line representing the actual pedal demand and the solid line the command sent to the fuel pump. Fuel limiting involves a fine compromise between emissions and driveability, limiting fuel until all EGR residuals have passed through the system would eliminate black smoke but give very sluggish response to accelerator demand. In order to maximise transient response, as high an air fuel ratio as possible should be maintained at all times to allow injection of as much fuel, hence generation of as much torque, before air density limitations cut-in. VGT permits higher air fuel ratios at lower engine speeds by virtue of increased boost, and can therefore improve driveability.

VGT TRANSIENT BEHAVIOUR – The use of VGT can minimise the boost pressure response time. The optimisation of flow across the turbine for a wider range of engine conditions increases the acceleration of the rotor and hence gives a rapid boost pressure rise time. Never the less, the boost pressure dynamics are far slower than the fuelling dynamics which is why there is such a large deviation from steady state map values (figure 5a and 5b). Figure 6d shows the VGT vane position during the transient, with 100% corresponding to the smallest flow area. As can be seen, the flow area is kept at a minimum until boost pressure builds up sufficiently then the vanes are opened to prevent overboosting. A dynamic problem associated with this particular type of VGT is illustrated in this test, figure 6f shows large overshoots in boost pressure and airflow, this is due to hysteresis in the VGT vane mechanism. The vacuum to the vane actuator (figure 6d) reduces steadily but the response of the vanes themselves is non-linear, which leads to a period of stagnation followed by a sudden flip open. The stagnation causes an overshoot in pressure and airflow, then the rapid opening leads to undershoot, settling only after several seconds. VGT's are typically controlled by PID controllers which react to errors occurring between demanded steady state values and actual values. PID control is not ideal for non-linear systems as can be seen by the response of the VGT.

ABSENCE OF EGR – Figures 7a - 7f illustrate the same transient with the EGR valve disabled, comparisons between the 2 tests highlight the significant effect EGR has on the dynamic behaviour of the engine. The initial AFR (Figure 7b) is much higher as expected, though the final AFR is very similar with and without EGR, this is can be explained by the small pressure difference between final inlet and exhaust manifold pressures in the EGR-on test. This pressure differential drives the EGR through the valve, as it is small the EGR flow is small, in this situation VGT can be used to increase the exhaust backpressure hence EGR flow.

The smoke response (Figure 7c) shows a dramatic improvement, from which it can be concluded that residual EGR was the most significant source of smoke in this particular test. VGT response (Figure 7d) is more controlled, the VGT is operating around mid vane position as opposed to the extremities of its travel and therefore remains out of the hysteresis band. There is still overboost, but this settles rapidly, the absence of the EGR leakage path also allows boost pressure to rise faster (Figure 7f).

FURTHER WORK

Now that areas for improvement have been identified and the behaviour of various components characterised, dynamic models of the engine and sub-systems are being developed for ultimate use in the design of control algorithms. Once validated on computer simulation, these strategies will be evaluated on the transient test facility as well as in-vehicle using a chassis dynamometer.

CONCLUSION

A definition study of the dynamic behaviour of a High Speed Direct Injection Diesel engine has been performed. The interactions between EGR and other sub-components such as VGT and fuel injection have been shown to have significant effects on the dynamic behaviour of the engine. The most important performance parameter is the AFR, which indicates the combustion quality and hence dictates the emissions behaviour, fuel consumption and performance. Control of EGR needs to optimised for dynamic operation as the current steady state approach allows too much degredation of the AFR by residual EGR at the onset of a transient. Also, better co-ordination between the sub-systems to prevent events such as EGR valve opening momentarily during the transient, combined with more intelligent transient fuelling strategies, is necessary in order to reduce transient smoke and give benefits to fuel consumption. Attention must also be paid to the dynamics of particular devices, such as the hysteresis of the VGT mechanism or the inherent transport lags in the EGR system.

It has been shown that steady state characterisation of an engine cannot be applied to transient behaviour. Further improvements in economy and emissions will require precise control of the engine during transients, this is not achievable through steady state based techniques alone.

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GLOSSARY OF ABBREVIATIONS

AFR – Air to Fuel Ratio

ECU – Engine Control Unit

EGR – Exhaust Gas Recirculation

HSDI – High Speed Direct Injection

IDI – Indirect Injection

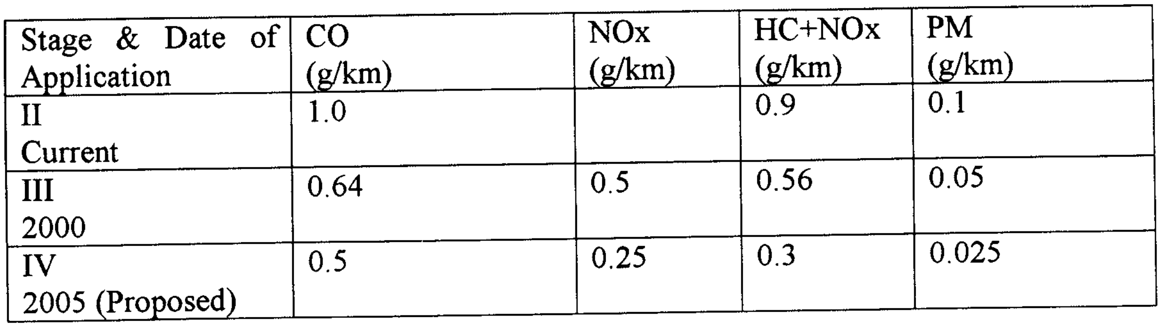
NOx – Oxides of Nitrogen

NVH – Noise Vibration & Harshness

PM – Particulate Matter

VGT – Variable Geometry Turbocharging

uHC – unburned Hydrocarbons



Stage & Date of Application	CO (g/km)	NOx (g/km)	HC+NOx (g/km)	PM (g/km)
II Current	1.0		0.9	0.1
III 2000	0.64	0.5	0.56	0.05
IV 2005 (Proposed)	0.5	0.25	0.3	0.025

Table 1 Emissions legislation for Direct Injection passenger car diesel engines

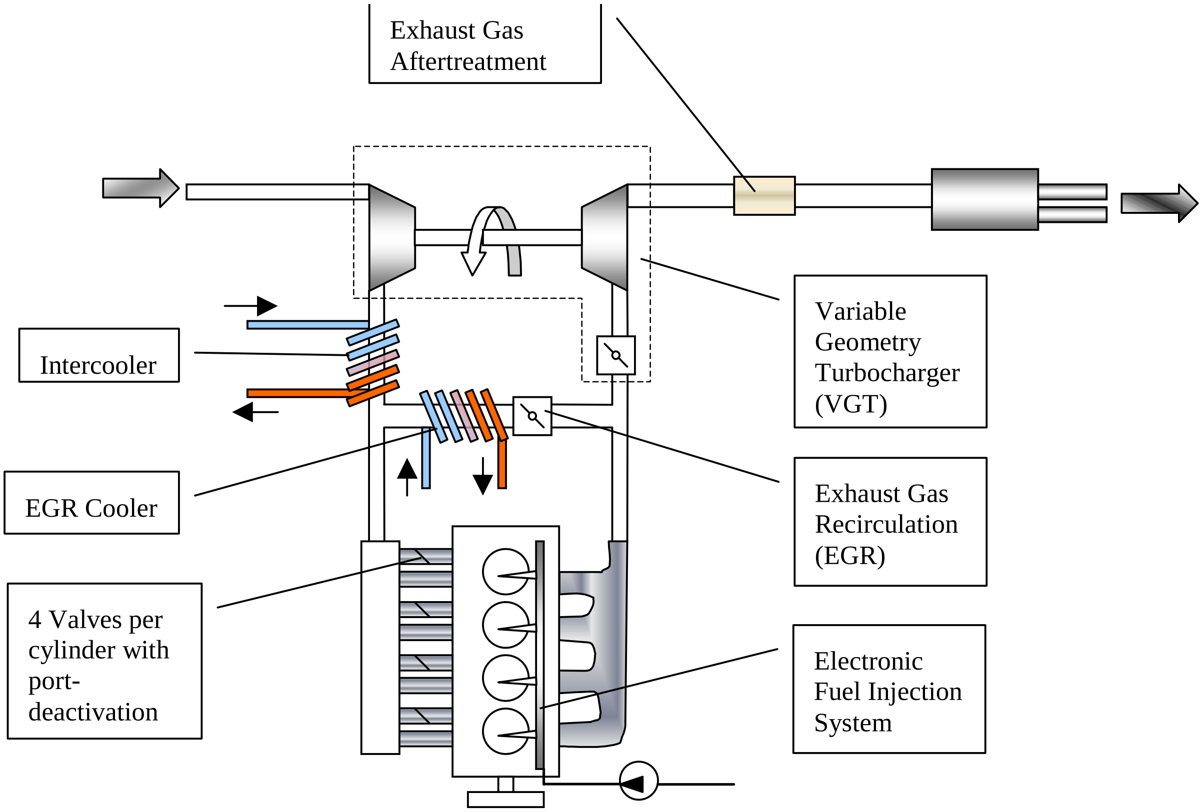


Figure 1. Schematic represetation of a modern high speed direct injection diesel engine

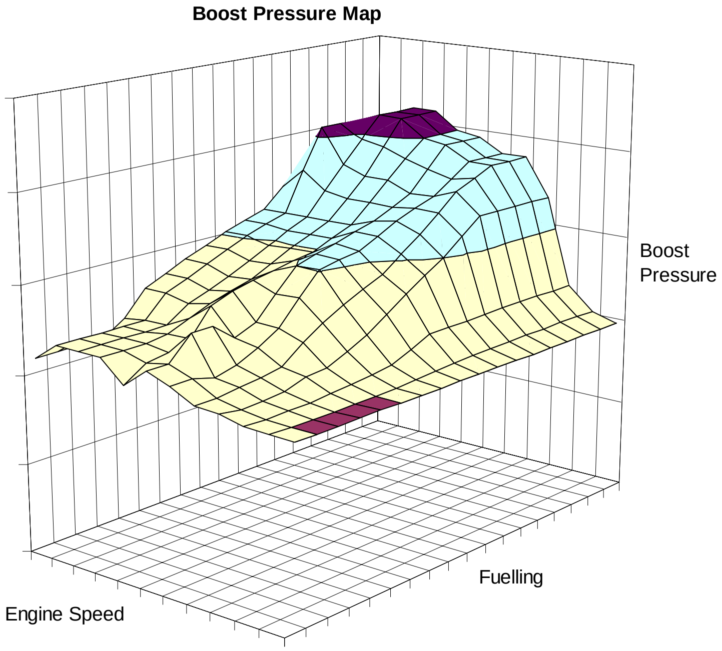


Figure 2.

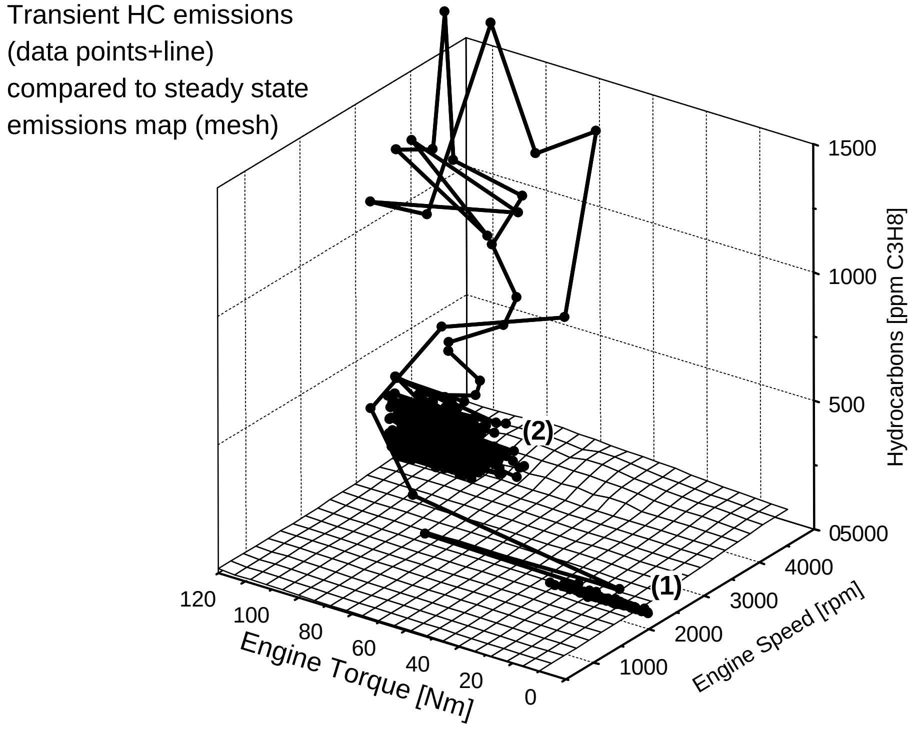

Transient HC emissions (data points+line) compared to steady state emissions map (mesh)

Figure 3. Comparison of transient and steady state hydrocarbon emissions

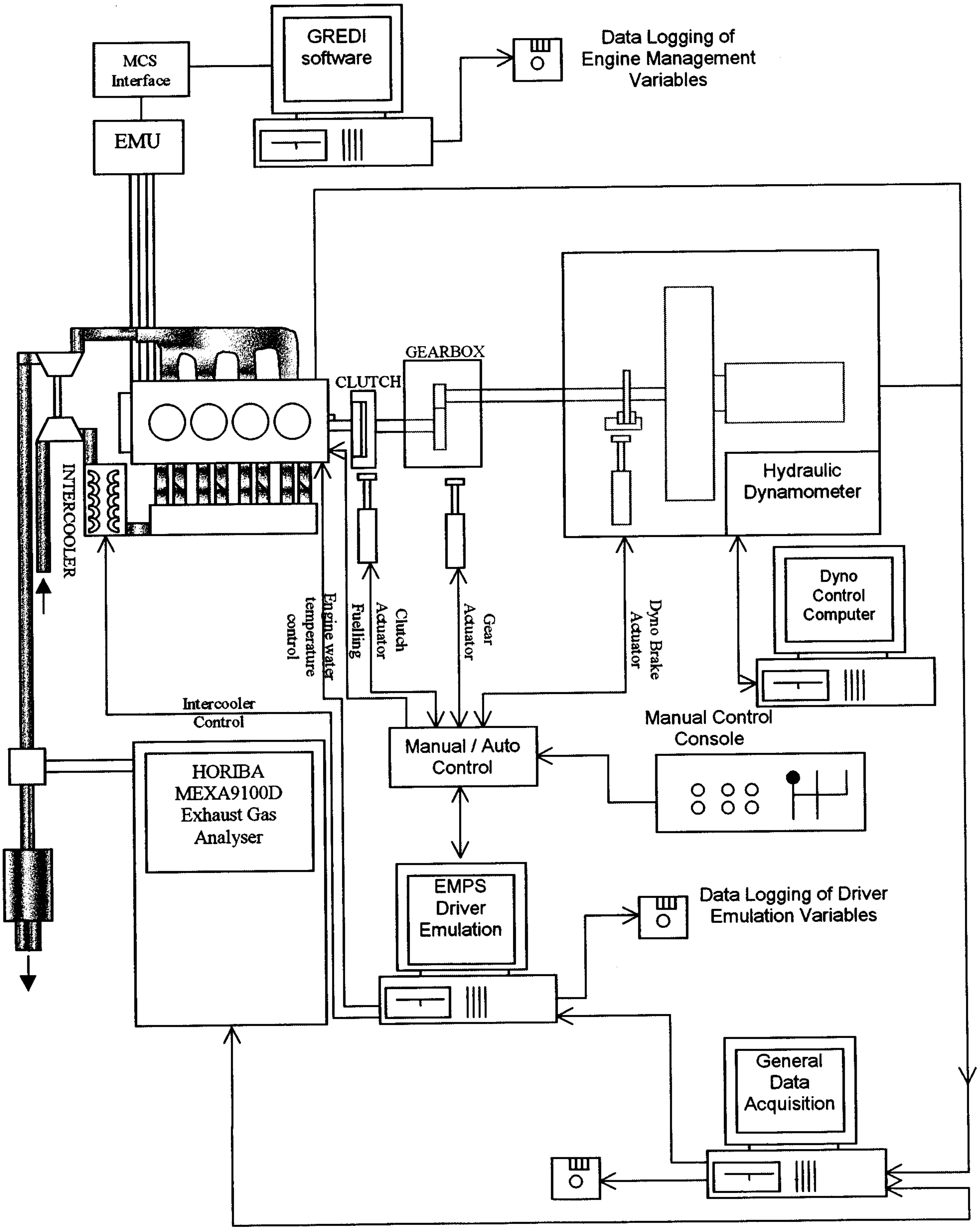
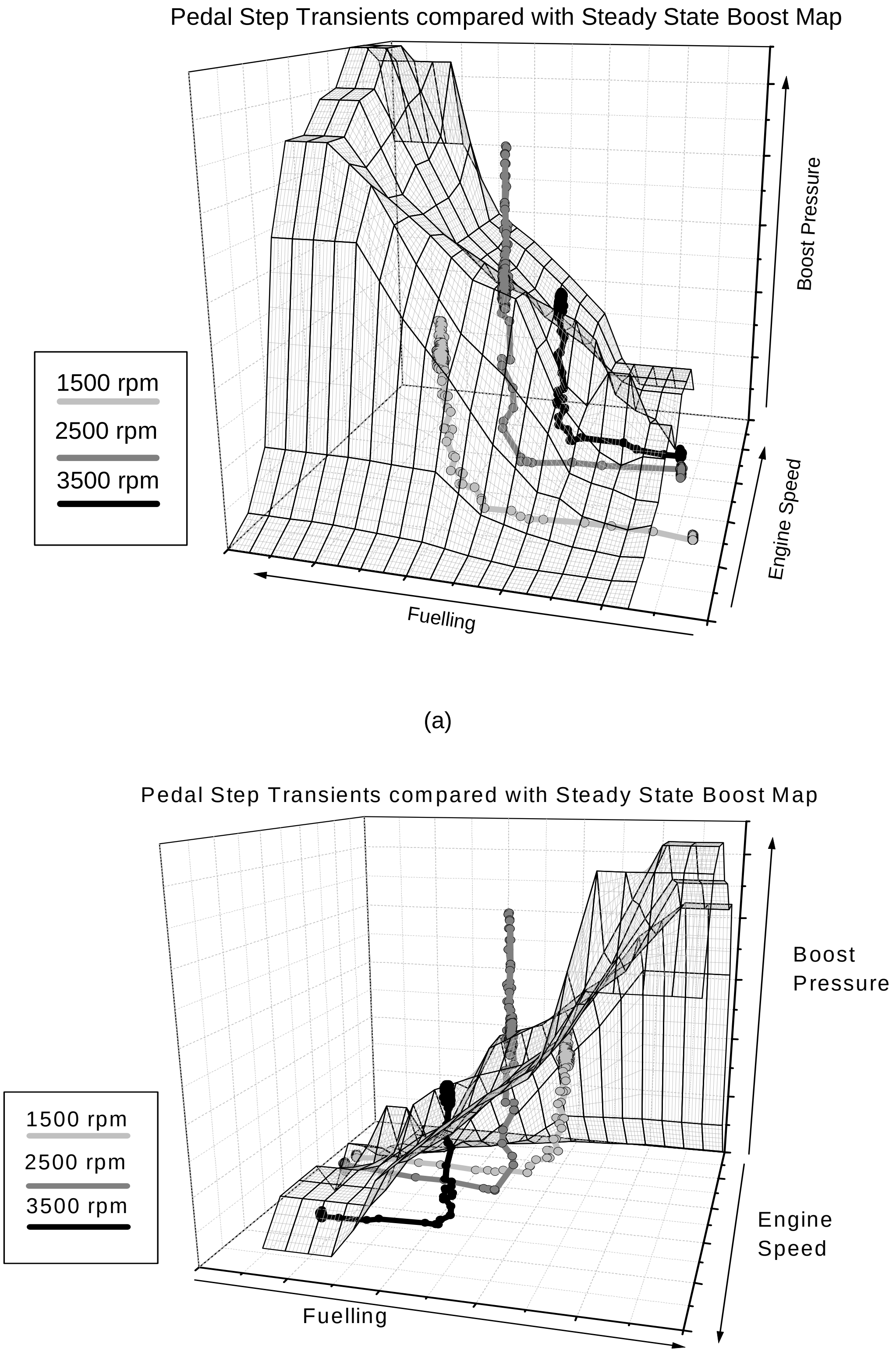


Figure 4. Schematic of the University of Bath Transient Engine Test Facility



(a)

(b)

Figure 5. Deviation of boost pressure from steady state behaviour (alternative views of same plot)

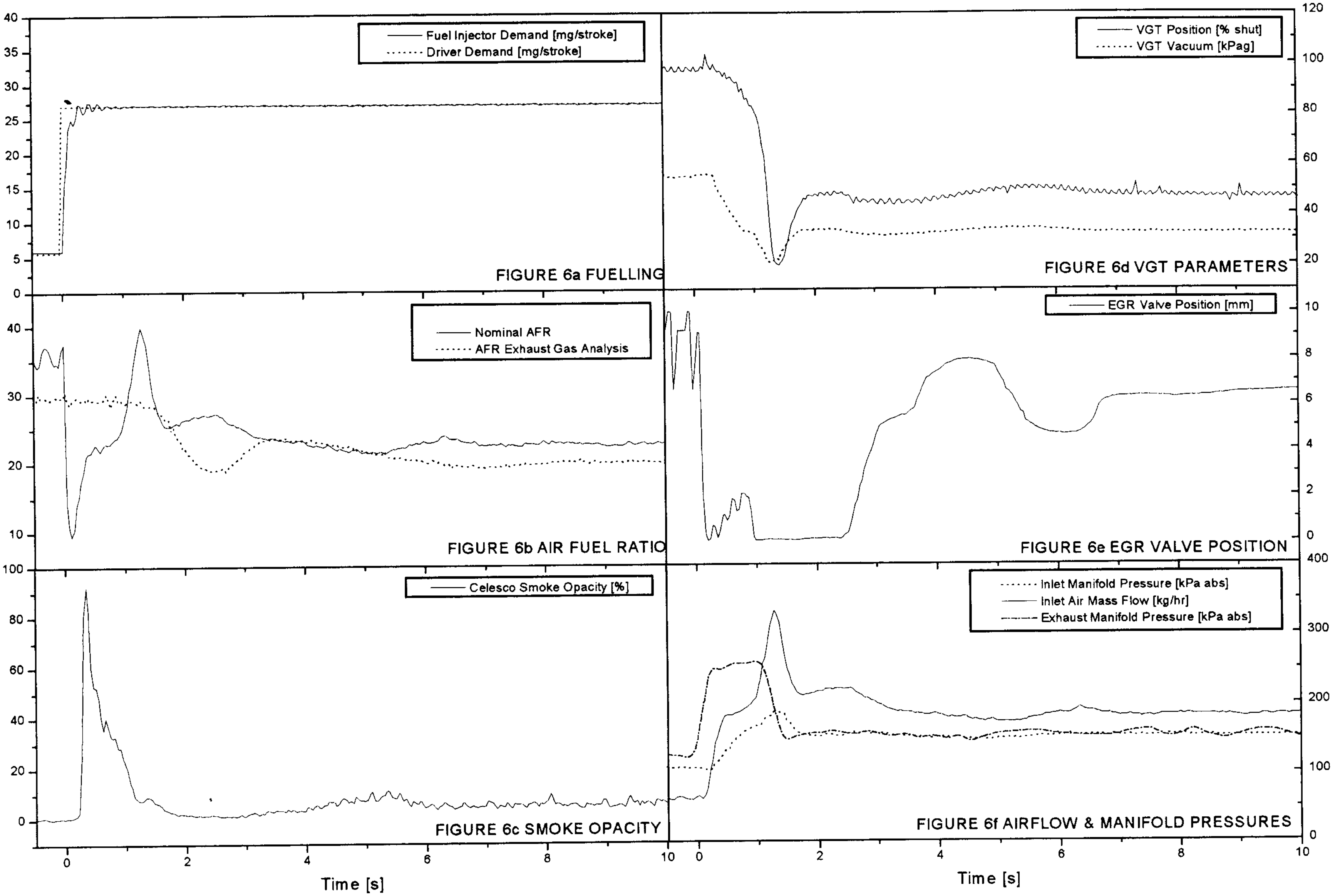


Figure 6a – 6f 10 – 170Nm step at 2500 rev/min EGR on

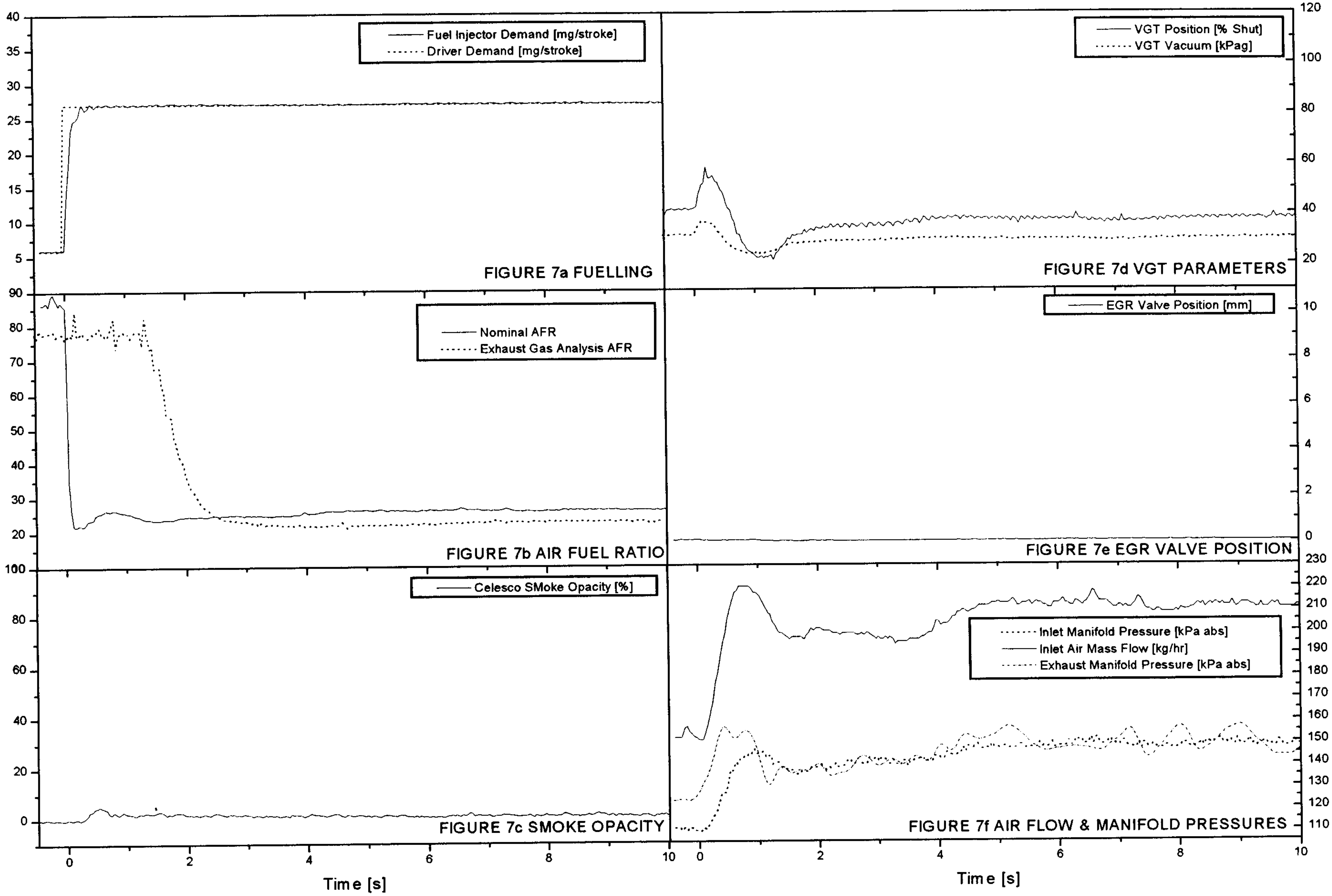


Figure 7a – 7f 10 – 170Nm step at 2500 rev/min EGR off