

# Estimation of deviations in NO and soot emissions between steady-state and EUDC transient operation of a common-rail diesel engine

P G Eastwood, K Tufail, T Winstanley  
Ford Motor Company, UK

A Darlington, S Karagiorgis  
AVL Powertrain UK Ltd., UK

Y Hardalupas, A M K P Taylor  
Imperial College London, UK

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## ABSTRACT

The study measured Mass Air Flow, (MAF), Manifold Absolute Pressure, (MAP), and emissions of NO and soot during fourteen transients of speed and load, representative of the Extra Urban Drive Cycle (EUDC). The tests were conducted on a typical passenger car/light-duty truck powertrain (a turbocharged common-rail diesel engine, of in-line 4-cylinder configuration). The objective was to compare NO and soot with corresponding steady-state emission results and propose an engine measurement methodology that will potentially quantify deviation (*i.e.* deterioration with respect to steady state optimum) in emissions of NO and soot during transients. Comparison between steady state, quasi-steady-states (defined later in the paper) and transients indicated that discrete quasi-steady-state engine operation, can be used for accurate *prediction* of transient emissions of NO and soot. Furthermore, quasi-steady-state engine characterisation quantified NO and soot deterioration that may occur due to MAF and MAP deviations from their optimised (steady-state) values. Therefore, the results from quasi-steady-state can be used to estimate deterioration in emissions during transients. These results are potentially of use in modelling with a view to assess component to engine compatibility during the engine development phase and minimise emissions deterioration (due to component ageing and production variability) during the life-time of engine.

## INTRODUCTION

The diesel community has been avidly investigating several key technologies in order to meet future emission legislation - chiefly one of the following: combustion (*e.g.*, Homogeneous Charge Compression Ignition, HCCI),

airpath (*e.g.*, Low Pressure – Exhaust Gas Recirculation, LP-EGR, twin-turbocharging), NO<sub>x</sub> aftertreatment (*e.g.*, Lean NO<sub>x</sub> Trap, LNT) and soot aftertreatment (*e.g.*, Diesel Particulate Filter, DPF). The huge proliferation in hardware choice confronting manufacturers, the implications held for vehicle attributes, and the expectations of customers (*e.g.* Specific Fuel Consumption, SFC, Noise Vibration and Harshness, NVH, statutory emissions), represents a challenge in engine management. The best contributions must be obtained from individual components, without affecting, adversely, the contributions of others, or of the complete system. The consequences of not managing this design process properly *i.e.*, through a system approach, may be an unnecessarily high cost of hardware investment on the one hand, or an overall failure to deliver a workable solution on the other. A significant input to this design process must also involve a proper understanding of the impact of duty cycle or driving mode.

The objective of the present investigation was to compare the NO and soot emitted by an engine under three modes of operation, namely, (a) 'steady-state', to be used as optimum baseline reference, (b) 'transient' (b) and (c) 'Quasi-Steady-State, (QSS)'. These terms we shall define explicitly as follows.

- (a) ~~Steady-state (SS)~~: stable engine operation at a EUDC (European Drive Cycle) cruise condition for at least several seconds.
- (b) ~~Transient~~: engine operation according to the accelerations realised in the EUDC, at normal ambient conditions, and for a fully-warm engine. Measurements include cycle-resolved magnitudes of Mass Air Flow, (MAF), Manifold Air Pressure (MAP) and injected fuel mass per cycle.

(c) Quasi-Steady-State (QSS): steady engine operation at a speed within the locus of a transient with magnitudes of MAF, MAP and injected fuel mass per cycle taken from the corresponding speed during transient engine operation, with concomitant deviations from steady-state values. One quantity, amongst others, which is expected to differ between the QSS and the SS is temperature, particularly of the intake manifold.

This distinction was made with a view to characterising a powertrain *solely* under quasi-steady-state engine operation; and thereby *predicting* transient behaviour and its implications for emissions of NO and soot, and, furthermore, to exploit the potential of Model-Based Control (MBC) in minimising emissions caused by transients.

The paper first reviews work conducted so far in the field. It then describes the problem definition; and proceeds to a description of our experimental facilities and the tests we conducted. Finally it discusses the results, highlights further work and draws conclusions.

## LITERATURE REVIEW

A Mean Value Model (MVM) can be used to predict with reasonable accuracy the dynamic and steady-state performance of a diesel engine [1]. Model Based Control (MBC), based on a physical representation of the entire engine system, *e.g.* using a MVM, presents two main advantages when used in the Engine Control Unit (ECU), namely, ease of conventional engine calibration (by shifting the majority of the calibration work up-front), and ease of adapting to different types of management architectures [2], *e.g.*, HCCI [3], LP-EGR etc. A comparison between MBC and conventional controllers, conducted on an Audi TDI engine, using Exhaust Gas Oxygen, EGO sensor for EGR Model Based Control, MBC [4], indicated that similar performance (as conventional controllers) could be achieved for the standard engine. Similarly, [5] illustrated implementation methods for MBC in a passenger car, and highlighted that controller design, and the corresponding identification procedures for the engine, required simplification and improvement for use in a production ECU. Thus, a method of improving the accuracy of MBC (in the ECU) can be exploited by introducing additional sensors. However, the two main reasons militating against installation of additional sensors are: (i) increases in manufacturing / production cost [6]; and (ii) compromised model-based predictions because of sensitivity to installation *e.g.*, vehicle packaging vs. test-bed, instrumentation level etc. [7]. Another method of achieving accuracy in MBC is through improving the quality of the model input data, *e.g.*, turbocharger maps [8] or control algorithms [9]. As a result of implementing MBC, such as the above, potential improvements in managing engine-out attributes, *e.g.* NO<sub>x</sub>, soot [10], NVH, SFC etc, may be achieved.

## MBC AND PROCESS SIMPLIFICATION

Recent work using various forms of MBC has shown how engine calibration effort can be simplified, as compared with the conventional approach; and greater accuracy is furnished in choice of set-points, so that different types of management architectures are more easily accommodated.

The engine closed-loop calibration process, conventionally, uses PID control, and gains therein, to achieve the desired targets *e.g.* MAF, MAP, etc. [11]. To control EGR, the desired MAF set-point is determined on test-bed and then entered on a three-dimensional map (using engine speed and load as indices). Obviously, the system response during transient and steady-state operation, assuming the target value is accurate (as discussed in the next sub-section), depends, inevitably, on how well the PID controllers are tuned or calibrated (Figure 1).

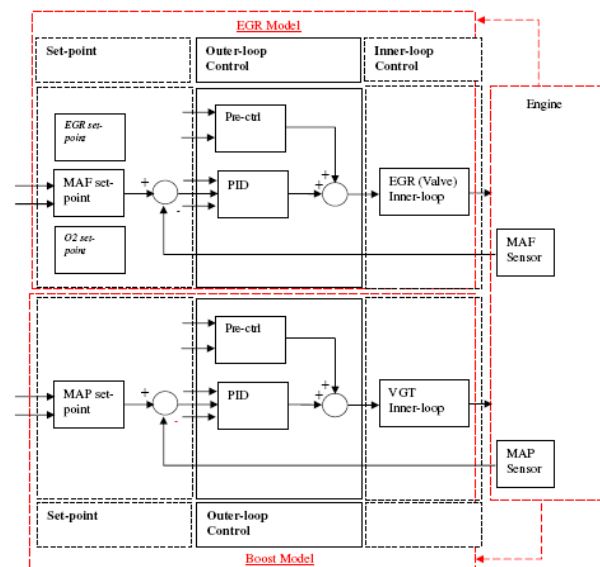


Figure 1 A typical control structure for MAF-MAP controllers

Owing to the limited amount of available memory in the ECU, the performance of the PID, as designed, cannot be maintained irrespective of vehicle environment, and shifts according to variations in barometric pressure and ambient temperature. Applying an the alternative approach, namely MBC, to the actuator, incorporating a physical representation of the entire engine system at any given point [12], offers, potentially, an instant correction, thus maintaining optimum performance. This simplification in the engine calibration process - of the PID gains, that is - through MBC, not only reduces calibration effort considerably, but also improves the actuator field performance by taking account of vehicle operating environment. Several researchers are working towards improving the accuracy of individual (stand-alone) strategies that work together to represent a complete engine model. An example of such a strategy,

illustrated by [13], uses three states for feedback, MAP and turbocharger speed; while exhaust pressure was estimated with an observer (Mean Value Model, MVM based on data from a steady-state test-bed). However, due to non-linearities in the system, a complete solution may contain complex algorithms. The MVM approach used by [14] simulates the exhaust system, and the results are used to develop aftertreatment devices through black-box models, taking account of thermal transients and soot accumulation / oxidation in the DPF.

Several solutions that use non-linear model-based controllers, albeit still in the research domain, assume that the state variables are being measured. This assumption is valid in the case of an experimental set-up realised in test-beds, or vehicles tested under laboratory conditions. However, in the production ECU, this may not be the case, due to the corresponding increase in component and installation costs. An attractive alternative is provided by models [15] able to replace measured quantities by estimated state variables. [16] were able to estimate exhaust manifold pressure, for a turbocharged diesel engine, assuming constant intake manifold temperature (during transients), using four state variables. [17] used MVM to estimate exhaust manifold pressure for production engines, and verified the results under various transient environmental conditions. Similarly, the MBC reported by [18] limited turbocharger speed under various transient conditions. The MBC proposed by [19] indicated 50% reductions in  $\text{NO}_x$  and 10% reductions in soot, mainly due to increased activity of VGT and EGR, compared with standard controller.

It can be seen, then, that several solutions are being used to reduce calibration complexity, and to reduce – concurrently – emissions of soot and  $\text{NO}_x$ . However, these MBC systems assume that the target set-points are optimum. The next sub-section summarises strategies that offer accuracy (and relevancy) of set-points.

## SET-POINTS AND EMISSIONS

Tests conducted by [20], and more recently by [21], confirmed that advanced control strategies alone cannot significantly improve cycle emissions, if the set-points are not addressed appropriately. [22] and [23] present a new control method based on estimated oxygen concentration of charge gas and excess air ratio. The oxygen concentration in the charge is estimated from EGR, and the air mass flow rate is estimated from the pressure and temperature in the intake manifold. The papers highlight that an emissions discrepancy can arise between steady-state and transient operation, due to corresponding boost-pressure deviations. The effects of boost-pressure deviations can be met using new control methodology, making improvements possible in  $\text{NO}_x$  emissions during transients. [24] investigate transient air-path control, including during HCCI mode, and conclude that Burnt Gas Residual, BGR [25] needs close control; providing the lean limit of AFR is not reached *i.e.* the intake pressure need not be accurately tracked. They

also notice that, during higher engine operating loads, set points are more difficult to reach as the turbocharger inertia effects are at their greatest under these conditions. Neural networks have also been considered for optimal control of EGR and boost pressure [26, 27] together with combustion control [28]. An adaptive air-charge estimator for a turbocharged diesel engine, using MAP, Air Charge Temperature (ACT) and engine speed measurements, is applied without EGR. The design scheme cannot estimate fast transients, and its performance deteriorates as a result of phase lags in the temperature sensor [29].

CAE tools *e.g.* 3-D CFD simulations, together with empirical measurements [30, 31], during the development phase of an engine programme, are also being used to predict local and global emissions *e.g.*  $\text{NO}_x$ , soot etc. However, the associated CFD computational time, and cost of empirical in-cylinder diagnostic measurements, to realise these benefits, render this method unattractive for engine management and real-time calibration. A simpler approach to 3-D modelling is presented by [32], where MBC, based on a quasi-steady-state gas exchange model, including EGR and VGT, combined with a two-zone zero-dimensional combustion model, using fuel-flow parameters to generate heat release, calculates in-cylinder pressure traces and temperatures, for the prediction of  $\text{NO}_x$  emissions via the well-known Zeldovich mechanism. [33] report that  $\text{NO}_x$  emissions can be predicted using the Zeldovich mechanism in combination with a simple empirical compensation algorithm. [34] show that the  $\text{NO}_x$  concentration can be modelled as the sum of the  $\text{NO}_x$  set-point, and a deviation from it. Furthermore, five relevant engine inputs are established, namely, SOI, injection duration, injection pressure, air mass flow and boost pressure, as key contributors for  $\text{NO}_x$  modelling accuracy. Vehicle performance with emissions are also estimated through generating model parameters which are then calibrated, using the emission data obtained on a chassis test-bed, to understand the behaviour of driving styles associated with various means of transport [35]. The data gathered can be used to estimate emission-specific characteristics that can improve a powertrain *e.g.* transmission-engine compatibility. The reviews above indicate that researchers are actively attempting to predict  $\text{NO}_x$  but *not* soot; whereas, in reality, control improvements in  $\text{NO}_x$  should be measured along with deterioration in soot; hence soot estimation is also required.

It is important to realise that, often where simultaneous reductions of  $\text{NO}_x$  and soot are reported using novel control strategies, similar results are nevertheless achievable with conventional controllers. In order to highlight, with fairness, the benefits conferred by a novel controller, it is important to declare a reference starting point on the  $\text{NO}_x$ -soot curve, and then to indicate how such a strategy shifts these two emissions to a new, improved location. Engine operation at a given point on

the NO<sub>x</sub>-soot trade-off curve is often a compromise forced by other attribute constraints such as NVH, SFC etc.; and therefore any deviations from the NO<sub>x</sub>-soot curve, e.g. due to novel controllers, can effect other attributes. Consequently, a movement along the NO<sub>x</sub>-soot curve should not be taken as the ultimate reference of success during optimisation. An alternative measure of success, of a novel controller performance, can be accurate estimation of degradation, or improvements in attributes such as emissions, fuel economy, NVH etc., with consequent use of these results to prioritise various actuators and their responses.

## CLOSURE AND CONTRIBUTION

The literature review indicated that several approaches are being researched [15], to: (i) simultaneously reduce; and (ii) improve robustness (with regard to production variability) in emissions of NO<sub>x</sub> and soot; whilst reducing the calibration complexity, and simplifying the traditional engine calibration process. These studies mainly focus on elements of transients, such as, intake manifold charge-composition, currently not measured by the ECU and conventional engine sensors, but are modelled, instead, by various experimental RTE/CAE algorithms. The accuracy of these RTE/CAE models is being improved by aiding the corresponding algorithm, and thus training the engine model, with actual engine data. The literature review also indicates that although individual models are being established, the complete engine system, together with fast-response emission measurements, are not being assessed.

The study undertaken in this paper measures (fast-response) NO and soot emissions during transient operation, with a view to quantifying the accuracy/benefits of using quasi-steady-state data to estimate these emissions. The study attempts to relate the emissions of NO and soot to air-path component control variables such as VGT, EGR, Intake Throttle, ITH etc., whilst minimising, over steady-state optimised values, transient emissions of NO and soot, by using a model-based control methodology utilising engine data generated by the quasi-steady-state method.

## EXPERIMENTS AND TEST FACILITY

The engine tested in this study was a common rail diesel of I4 configuration, employing air-air intercooling and a VGT, for a C/CD class inertia passenger car application. The engine performance was evaluated using a transient test-cell facility. This section documents details of the test-facility used and tests conducted.

### TEST FACILITY

A dynamic hydrostatic AC type test-bed dynamometer (Elin-AVL) APA 202/10 series (capable of torque rating 500Nm) in a test bed was used to conduct all experiments. The AVL EMCON series 300-dynamometer controllers and a robot driver worked in conjunction with

AVL Puma v5.6 (ISAC) software to control the test-bed dynamometer. Puma system architecture employed various types of Front End Modules (FEM) capable of recording digital data at 1–100Hz resolution. An additional Engine Control Unit (ECU) Personal Computer (PC) recorded data at a resolution of 20ms. The ECU recorded channels include engine inlet MAF and MAP, measured at air-cleaner outlet, and at intercooler-outlet, respectively. A road-speed fan simulated air flow conditions of the corresponding vehicle inertia class. All thermocouples used were of k-type and pressures were recorded using piezoelectric pressure transducers. The engine out NO emissions were measured using a Cambustion fast-response NO analyser [36] and NO<sub>x</sub> emissions with Horiba Mexa 7000 analysers [37]. It should be noted that, during analysis of emission results, steady-state measurements utilised the Horiba NO<sub>x</sub> and the transient tests Cambustion NO. Therefore, it is assumed that NO<sub>x</sub>-NO differences are negligible during the tests undertaken in this study. Similarly, it is also assumed that the difference between ECU fuel quantity demand and actual delivery is negligible. Thus during the analysis the ECU fuel quantity demand is used. A Universal Exhaust Gas Oxygen (UEGO) sensor was employed in the exhaust to monitor AFR. A Celesco opacimeter model 107 Berkely was used to measure opacity, whilst, the AVL 483 Micro soot sensor was used to measure concentration of soot in the diluted exhaust gas.

## TESTS CONDUCTED

Tests were conducted in two stages:

1. Steady-state and transient acceleration tests
2. Quasi-steady-state tests

Transient performance was evaluated on the New European Drive Cycle (NEDC), as used in homologation, and which is composed sequentially of two parts: the Urban Drive Cycle (UDC), and the Extra-Urban Drive Cycle (EUDC). In order to ensure repeatable starting points for subsequent analysis, only results from the EUDC are considered below, as, by then, any influence from the initial thermal state of the powertrain has passed.

Comparisons between steady-state and transient conditions were made by examining the engine performance under part-load operation as the engine speed varied between 850-2500 rpm. In order to capture the effects between *slow (steady state)* and *fast* transient maneuvers, the accelerations were performed at 14 different rates (*i.e.* a total duration of 180s, 120s until 5s).

The varying rates of engine acceleration, as shown in Figure 2a, represent vehicle accelerations in different gears *i.e.* faster-rated for low gears and slower-rated for high gears. Figure 2b highlights the varying level of fuel-demand for a slow and a fast acceleration