

Analysis of Deviations from Steady State Performance During Transient Operation of a Light Duty Diesel Engine

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ABSTRACT

Deviations between transient and steady state operation of a modern light duty diesel engine were identified by comparing rapid load transitions to steady state tests at the same speeds and fueling rates. The validity of approximating transient performance by matching the transient charge air flow rate and intake manifold pressure at steady state was also assessed. Results indicate that for low load operation with low temperature combustion strategies, transient deviations of MAF and MAP from steady state values are small in magnitude or short in duration and have relatively little effect on transient engine performance. A new approximation accounting for variations in intake temperature and excess oxygen content of the EGR was more effective at capturing transient emissions trends, but significant differences in magnitudes remained in certain cases indicating that additional sources of variation between transient and steady state performance remain unaccounted for.

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INTRODUCTION

While much engine research and calibration is performed under steady state conditions, most real world applications, and particularly automotive applications, involve continuously changing operating conditions. To reflect this reality, federal on-road emissions regulations for both heavy and light duty vehicles are based on transient test procedures which are intended to approximate real world operating conditions. Since transient engine testing is expensive and time consuming, it is often convenient to estimate transient cycle emissions using available steady state data over a range of speed and load conditions. Unfortunately, the literature repeatedly shows that engine performance under steady state conditions is not a reliable indicator of transient or in-use emissions [1,2,3,4]. Significant portions of the overall emissions are generated during relatively short periods of time when rapid speed or load transients occur [5]. These effects are not captured by steady state mode-point data. Attempts to approximate overall emissions for transient test cycles using steady state mode points are therefore generally ineffective. A complete system-level approach to engine optimization must consider the mechanisms which affect transient operation and the associated deterioration of performance relative to steady state optima in order to develop appropriate control strategies.

Tests conducted by the EPA [1] compared results of the ISO 8-mode steady-state duty cycle test with several transient test cycles for a number of different engines. While the 8-mode test was generally effective at predicting transient NOx emissions within a 10% margin of error, HC and PM emissions were under-predicted by more than 60% on average. The increases in emissions for the transient test cycle relative to the 8-mode test varied by more than 120% depending on which transient cycle was used for comparison, and results for the same cycle varied by more than 130% for the different engines tested. Further work [2] proposed alternate methods of weighting the steady state mode points to better reflect the speed-load frequency distribution of specific transient test cycles. Some improvement in agreement between the steady state and transient tests was obtained, but HC and PM were still underpredicted by as much as 60%. These results clearly illustrate the complex nature of transient engine performance. Empirical correlations or correction factors to relate steady state to transient performance will therefore only be valid for the specific engine, calibration, and transient cycle for which they were developed, and may produce erroneous results if used to predict emissions for other scenarios.

Various forms of low temperature combustion are being increasingly utilized to reduce emissions while maintaining

high efficiency. Low temperature combustion (LTC) is particularly sensitive to variations in intake charge conditions since combustion phasing is controlled largely by reaction kinetics [6,7,8]. In addition, typically high EGR rates make it more susceptible to delays in air system response and cross-sensitivity between turbocharger lag and EGR response [9]. These delays make control and calibration for LTC transient operation particularly challenging, and may cause significant differences in the relation between steady state and transient performance for LTC compared to more conventional diesel combustion strategies.

One method of understanding and quantifying differences between transient and steady state operation is to compare transient data to steady state data for a particular speed and fueling rate condition, or a sequence of conditions encountered during a transient. Two variables that are often observed to differ between the optimal steady state conditions and the conditions achieved during transient operation are MAF and MAP. Adjusting the steady state operating conditions to obtain the MAF and MAP values observed at the same speed and fueling rate conditions during the transient, as in [3], can produce some of the emissions trends unique to transient operation. This approach could potentially be useful for modeling or real-time estimation of operational emissions, but the magnitudes of transient emissions spikes are not reliably reproduced. This lack of agreement indicates that additional other variables deviate from steady state optimums and are at least partially responsible for variations in emissions during transients.

In an effort to identify these missing variables and incorporate them into a more complete representation of transient engine operation, the current study extends the work of [3] by accounting for additional operational parameters that have previously been shown to have strong influence on transient emissions formation in LTC regimes. In [3], differences in intake temperature between transient operation and steady state operation with the same MAF and MAP values were identified as a likely cause of the variation in emissions. Other work utilizing high frequency emissions measurements [10, 11] has shown that the concentrations of product species in the EGR and intake manifold can vary independently of fresh air or EGR flow rate during transients, and that this variation can play an important role in transient emissions formation. Based on these previous studies, intake manifold temperature and oxygen concentration as well as other variables were included in a new representation of transient operation referred to as “quasi-transient,” which accounts for the thermodynamic conditions and flow rates of fuel and major gaseous species actually entering the cylinder during a transient event.

Comparison of transient data to steady state results with different sets of variables matched to the transient conditions provides valuable insight into which parameters are primarily responsible for increased emissions during transient operation. This comparison should also provide information on what measurements would be needed to accurately predict

deviation of engine performance from steady state baseline conditions. In addition, the extent to which the transient emissions trends agree with the steady state measurements in which certain key variables were matched to the transient conditions is an indicator of how well the factors influencing transient behavior have been captured by the chosen variable set. This information should be useful in developing fundamental physics-based control strategies for transient operation that would be more generally applicable than manual trial-and-error calibration of a specific engine configuration.

EXPERIMENTAL CONFIGURATION

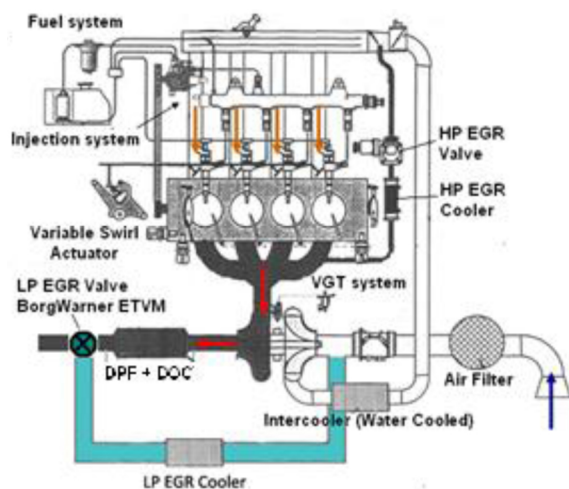
ENGINE AND CONTROLS

The experiments were performed on a General Motors Z19DTH 1.9 liter Euro-4 specification diesel engine equipped with standard production hardware including variable geometry turbine (VGT), high pressure EGR cooler, and variable swirl intake port geometry. Table 1 contains detailed engine specifications, and an engine system schematic is shown in Figure 1. All standard production hardware was used with the exception of the intercooler, engine control unit (ECU), and exhaust system downstream of turbine outlet. An air-to-water intercooler was used in the laboratory to replace the production air-to-air intercooler, but cooling water temperature and flow rate were limited to replicate the cooling capacity of the original production system. A Bosch ECU modified with an Embedded Tool Kit system from ETAS allows real-time access and modification to the engine maps and other control parameters via INCA software. This system enables injection timing(s) and pressure, EGR valve opening, VGT position, and other parameters to be adjusted to apply different combustion or control strategies. These parameters as well as other command set-points and measured values used by the ECU were recorded once per crankshaft revolution to provide an overview of the control system state and to supplement the data provided by other external instrumentation.

The fuel injection quantity is calculated by the ECU based on the rail pressure and injection command duration. This estimation method can produce significant errors due to rail pressure dynamics, particularly for short injections and when using a pilot injection, but comparisons to a fuel mass flow meter have confirmed that the estimated quantities are qualitatively correct and repeatable for a given set of injection parameters. More importantly, an estimated quantity can be provided for each injection event which is not possible with a fuel flow meter when injection quantities change rapidly from cycle to cycle.

Table 1. Engine Specifications.

Engine Type	Euro 4 Diesel
Bore	82 mm
Stroke	90.4 mm
Displacement	1.9 liters
Cylinder Configuration	Inline 4 4 valves per cylinder
Swirl Ratio	Variable (2.2-5.6)
Compression Ratio	17.5
Turbocharger	Garrett M53 VGT
EGR	Hybrid High/Low Pressure, Cooled
ECU	Bosch EDC16
Injection Pump	Bosch CP1H3
Injectors	Bosch CRIP2-MI 149° Included Angle 7 holes 440 flow number

**Figure 1. Schematic overview of the GM 1.9 liter multi-cylinder engine system with LP EGR loop added.**

A low pressure EGR loop was designed and fabricated based on technical guidance provided by BorgWarner [12] in order to optimize system performance and enhance the overall capability and flexibility of the air handling system. LP and mixed source EGR have been shown to provide further reductions in the soot-NO_x tradeoff for both diffusion controlled and kinetically controlled combustion compared to HP EGR only [13, 14, 15]. The longer length of the LP EGR route as well as differences in the interaction between EGR and the turbocharger compared to a HP EGR loop can also significantly affect transient performance [16, 17, 18]. The addition of LP EGR to the experimental engine configuration allows investigation of these unique effects which may become increasingly important if LP EGR is utilized more heavily in future engine systems.

The production catalyst and DPF were moved from their downstream location corresponding to a vehicle under-floor

position and mounted as close to the turbine outlet as possible in order to minimize the LP EGR system volume and response times. An exhaust throttle valve module (ETVM) provided by BorgWarner served the combined functions of a LP EGR valve and exhaust throttle to obtain additional backpressure as needed to increase the LP EGR flow rate. Additional information on the design and function of the ETVM is available in [15]. Engine coolant is used in the EGR cooler as with typical production engine applications to minimize condensation of exhaust gas components and to ensure a realistic amount of cooling power is applied. LP EGR is introduced to the intake air path via a Y fitting immediately upstream of the compressor. A schematic overview is provided in Figure 1.

The ECU's production control strategy modulates the HP EGR valve opening to obtain the desired mass flow rate of fresh air at a given engine speed-load condition, which is equivalent to controlling the AFR under steady state conditions. The remainder of the intake charge is comprised of external EGR. The mass fraction and flow rate of EGR therefore vary as the intake charge density or engine volumetric efficiency change. This basic EGR control strategy is unchanged when LP EGR is added. The ECU does not quantify the LP EGR rate but continues to control the HP EGR valve based on the desired fresh air flow rate. As LP EGR is added, fresh air entering the compressor is displaced and the ECU compensates by incrementally closing the HP EGR valve to maintain the desired fresh air flow rate. This type of mixed-source EGR strategy allows the benefits of LP EGR to be utilized while maintaining fast, precise control over the fresh air flow rate by feedback control of the shorter, faster HP loop [16, 19]. Although this control strategy is relatively simplistic by modern standards it is sufficient to maintain safe, reliable operation of the engine under transient conditions and allows the fundamental response characteristics of the LP EGR hardware components to be observed and quantified more easily. This information is requisite for development of more accurate models and control strategies. Additional information on the specific hardware and control system used in this work is available in [18] and [18].

INSTRUMENTATION

In order to maintain precise time resolution, all data acquisition is hardware triggered based on the engine crankshaft encoder. This ensures that data from all systems is recorded at precisely the same point during a given cycle, providing a comprehensive data set describing the condition of the engine at a specific instant in time. Cylinder and manifold pressures, injection current, and Combustion fast emissions analyzers are sampled at 1024 points per crankshaft revolution while other instruments are sampled once per crankshaft revolution. Data is presented as a function of engine cycles rather than seconds because many transient processes such as gas exchange in the air system occur as a function of the number of engine cycles completed

as opposed to elapsed time. Using engine cycles as the independent variable effectively normalizes elapsed time with respect to engine speed and provides a more fundamental indication of transient rates of change.

Cylinder pressure measured in cylinder number two is used to calculate the apparent rate of heat release as well as certain combustion metrics such as the location of 50% mass fraction burned. The combustion ringing intensity is calculated according to the correlation proposed by Eng [20]. This correlation provides a more accurate indication of combustion noise by including the influence of cylinder bulk gas temperature, pressure, and engine speed in addition to the maximum rate of pressure rise per crank angle degree.

High speed measurements of NO and UHC are provided by Cambustion CLD 400 and HFR 500 fast response emissions analyzers, respectively. The 10-90% response time of these instruments is just a few milliseconds, so near-crank-angle time resolution is possible. For this work, data points collected during one engine cycle are averaged to obtain a single average NO or UHC concentration for each cycle. Each instrument provides two independent measurement channels, allowing simultaneous measurement at two different locations. All emissions reported in this work are engine out measurements made directly downstream of the turbine and before any after-treatment devices.

Transient exhaust smoke opacity is measured using an AVL 439 Opacimeter and can be converted to an approximate mass value using existing correlations [21,22]. The mass correlations are not believed to be quantitatively accurate for LTC PM emissions, but can reliably indicate cycle-to-cycle trends and offer the benefit of intuitive, physically meaningful units for PM emissions. Oxygen concentration is measured in the intake near cylinder 2, in the intercooler, and in the exhaust. These three measurements allow the fractions of HP and LP EGR to be calculated independently. Pressure and temperature measurements are made at critical locations in the air system including the intake and exhaust manifolds, EGR system, and charge air cooler. An HBM T-40 in-line torque transducer measures crankshaft torque. The combination of available instrumentation provides a comprehensive view of the engine system state during each individual combustion cycle.

PROCEDURE

The engine is coupled to a hydrostatic dynamometer capable of rapid speed and load transients [23, 24]. Transient events were initiated by changing the accelerator pedal command to the ECU. The ECU interprets the pedal command as a desired torque output and adjusts the injected fuel quantity accordingly. The current study was conducted for tip-in transitions, i.e. increasing load at constant engine speed, 1500 rpm in this case.

During each transition the ETVM (LP EGR valve) was kept in a fixed position corresponding to 10-20% of the total EGR via the LP loop at the initial condition. This relatively small amount of LP EGR does not significantly increase the

potential boost pressure, especially at low loads and exhaust temperatures, but does reduce the intake temperature by transferring part of the EGR cooling load from the relatively small HP EGR cooler to the LP EGR cooler and intercooler. The small LP EGR fraction also has a measurable effect on the rate at which the concentration of combustion products in the EGR changes during a transient due to the much longer loop length.

Once a particular load transition has been run, the engine is operated under steady state conditions at the speed and fuel injection quantity reported by the ECU at a specific selected instant during the transient. The engine is allowed to reach the target system state defined in the ECU calibration tables for that particular speed and fueling rate. This process is repeated for a series of speed-fueling coordinates recorded at regular intervals during the transient, and data is collected at each operating condition. These data are referred to as the “steady state” measurement series and are compared to the transient data to indicate the deviation in performance between steady state and transient operation, and to serve as a baseline for comparison of other transient reconstruction methods. Although more precise measurement tools are available for steady state measurements, the same transient instrumentation is used in all cases to avoid the uncertainty caused by comparing data obtained using different instruments or measurement techniques.

A second reconstruction of the transient event is created by repeating the above procedure, but additionally altering the mass flow rate of fresh air into the engine and the intake manifold absolute pressure at each speed-fuel point to match the conditions measured at the same instant during the transient event. MAF and MAP are controlled by adjusting the EGR valve and VGT vane position, respectively. This is referred to as the “MAF-MAP” approximation.

In order to obtain a closer representation of transient engine operation and determine which additional variables may be important in determining transient engine performance, a third method was tested in which these two factors as well as variations in fuel rail pressure were included. In addition, the MAF constraint was replaced by an intake oxygen concentration constraint in order to account for the excess oxygen in the EGR. This combination of variable constraints accounts for the thermodynamic conditions, flow rates, and major species fractions of both reactant streams (fuel and gaseous charge) entering the cylinder. This was referred to as the “quasi-transient” approximation since it provides the closest approximation of the actual transient event.

The variables that were adjusted to match the transient data in each reconstruction method are summarized in Table 2. In comparing these methods it should be noted that the injection timing and variable swirl vane position are matched to the transient event by default in all cases since there is no delay in actuation for these controls and therefore no deviation from the desired values during the transient. Other variables are not intentionally or directly altered and may or

may not show agreement with the transient data depending on the magnitude of transient effects for a given case.

Table 2. Variables matched to the transient data in each reconstruction method

	Steady State	MAF-MAP	Quasi-Transient
Speed	X	X	X
Fuel Mass	X	X	X
MAP		X	X
MAF		X	
Intake O2 [%]			X
Intake Temp			X
Rail Pressure			X

Two separate combustion strategies were studied in order to understand how the mechanisms by which transient operation affects performance may vary for different combustion regimes. The first strategy uses a single early injection and very high EGR (55-60%) to allow extensive ignition delay and premixing, a strategy often referred to as early injection premixed charge compression ignition (PCCI). In this strategy all control targets including VGT vane position, fresh air mass flow, variable swirl actuator position, fuel rail pressure, and injection timing are held constant. This control strategy is not optimal from a performance standpoint, but it is useful for identifying and understanding the engine's fundamental transient response behaviors since the complexity of the engine system is greatly reduced by eliminating many of the variables. In addition, inherent transient properties of the engine system can be isolated from effects of the actuator control strategy, an important distinction. Understanding the fundamental engine behaviors is a necessary prerequisite to properly analyzing the complex interactions between controls and hardware that affect transient processes when more complex control strategies are applied.

The other strategy is based on the EURO 4 production calibration and utilizes moderate to high EGR rates (20-50%) with near top-dead-center (TDC) main injection timing and a pilot injection. Physical controls and actuators such as injection pressure and timing, VGT position, and variable swirl actuator are continuously adjusted to the optimal conditions based on the current engine speed and injection quantity. Of particular importance to this study are the EGR or fresh air maps.

Selected steady state measurements for each combustion strategy are provided for reference in Table 3. It is important to note that these combustion modes are not meant to represent ideal or optimized combustion strategies, but are simply two unique modes selected to encompass a large range of operational parameters.

Table 3. Selected steady-state performance metrics for two low-temperature combustion modes.

	Early-Injection PCCI	Euro 4
Speed [rpm]	1500	
BMEP [bar]	2.0	
Main Inj Timing [deg ATDC]	-27	-0.4
Pilot Inj Timing [deg ATDC]	n/a	-14.5
EGR Fraction [%]	59	44
Air/Fuel Ratio	22.3	34.7
Intake Oxygen [%]	11.8	16.9
50% Mass Burned [deg ATDC]	6.2	14.7
Max Pressure Rise [bar/deg]	3.4	1.7
Ring Intensity [MW/m ²]	0.95	0.29
BSFC [g/bkWh]	348	315
NO [g/kg fuel]	0.217	1.37
UHC [g/kg fuel]	20.8	8.19
Soot [g/kg fuel]	0.002	0.165

RESULTS

EARLY INJECTION PCCI LOW LOAD TRANSITION

A load change from 0.5-2 bar was conducted at a constant speed of 1500 RPM using the early injection PCCI combustion strategy. The three reconstruction methods were then implemented in an effort to reproduce the emissions from this transient. In order to once again illustrate the parameters that have been adjusted for each reconstruction method, the variables have been plotted in two groups: those that characterize the intake charge (Figure 2) and those that characterize the injected fuel (Figure 3).