

A Zero-Dimensional Intake Dilution Tracking Algorithm for Real-Time Feedback on Exhaust Gas Recirculation

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ABSTRACT

This study describes a zero-dimensional algorithm for tracking the intake dilution in real-time. The inputs to the model are the oxygen concentration from the exhaust oxygen sensor, the manifold air pressure and temperature (MAP/MAT), the mass air flow (MAF) and the estimated fuel injected per cycle from the engine control module. The intake manifold, the exhaust manifold and EGR system are discretized into 3 volumes and the detailed concentrations of the gas species comprising the exhaust, EGR and intake streams are tracked at each time step (on a cycle-by-cycle basis). The model does not need the EGR ratio to be known in advance and is also applicable to oxygenated fuels such as ethanol. The model response is tuned to a multi-cylinder engine and the model output is empirically validated against a wide range of engine operations including load and EGR transients. This research is part of an effort to develop a systematic combustion and emission control strategy for advanced combustion cycles.

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INTRODUCTION

Exhaust gas recirculation (EGR) is the most widely used and effective in-cylinder NO_x control strategy in modern diesel engines [1, 2, 3, 4]. In combination with high boost/injection pressures and multiple injection strategies, the application of EGR can reduce NO_x to very low levels, without incurring a large soot penalty during steady-state engine operation [5, 6, 7, 8]. However, the significantly disproportionate response times of the combustion and the air-path systems imply the need for a reliable feedback on EGR, if it is to be used during transient operation. The lack of such a robust feedback on the amount of recycled gases has necessitated the use of a number of exhaust aftertreatment devices for NO_x emissions to meet the legislated NO_x emission limits (0.2 g/bhp-hr in North America and 0.4-0.46 g/kW-hr in Europe).

The common NO_x aftertreatment technologies (LNT or SCR) require a reducing agent for converting NO_x to N₂; the LNT needs to periodically operate rich either through an in-cylinder late-post injection or an external fuel injection [9, 10], while an SCR requires a continuous injection of urea in the exhaust system as the reducing agent [11, 12]. Since these reducing agents do not provide any useful work per se, the amount consumed can be considered equivalent to a decrease in the fuel efficiency or additional fuel consumption. To reduce the size of the aftertreatment systems (cost and packaging implications) as well as the regeneration frequency (fatigue failure, fuel efficiency penalty), EGR is aggressively employed to limit the engine-out NO_x quantity to 50-200 ppm during steady-state operation for efficient use of these devices.

A representative test result for the hot start phase of the US Federal Test Procedure 75 (FTP-75) for a small, high-speed diesel engine is shown in Figure 1. An analysis of the vehicle data indicates that

changes in the torque demand (especially during tip-in events) are accompanied by the EGR valve being clamped shut to avoid excessive smoke or unstable engine operation. As a result, large spikes in the engine-out NO_x are observed corresponding to these valve closing events.

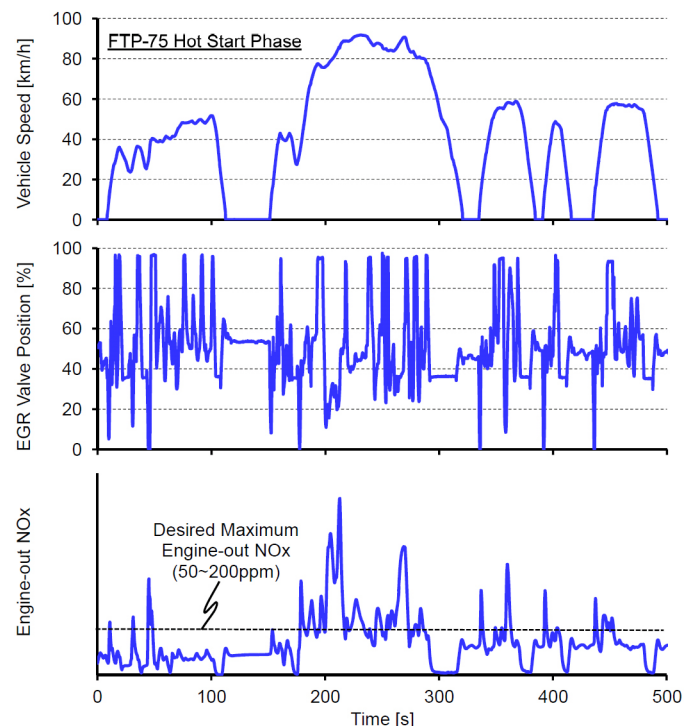


Figure 1. EGR Valve Actuation and NO_x Time-history during Hot Start Phase of FTP-75 Test Cycle



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It is evident that any major improvement in the efficiency of the exhaust aftertreatment system or a reduction in the size/cost while meeting the legislative emission levels would require the extension of the EGR implementation regime to the transient engine operation.

EGR is usually quantified with an *EGR Ratio* which is defined either as the ratio of the recycled mass flow to the total exhaust mass flow, or as the ratio of the carbon dioxide (or oxygen) concentration in the intake to that in the exhaust stream [1, 13]. However, EGR ratio is not a suitable feedback parameter for control since additional information about the engine load and excess-air ratio (a function of both the fuelling and intake pressure) is required to fully quantify the engine operation. Previous work by the authors has demonstrated that the *intake charge dilution* (intake oxygen concentration) provides a reliable, quantitative and platform-independent measure of the EGR effectiveness in reducing NO_x emissions [1, 14]. At any given EGR ratio, the intake charge dilution accounts for the effects of engine load and intake pressure on the recycled gas composition. A representative test result for the effect of engine load on EGR is shown in Figure 2. At the same intake pressure, a higher engine load (7.2 bar BMEP) results in a reduced intake oxygen concentration (higher intake charge dilution) at the same EGR ratio. Conversely, to achieve the same intake dilution at a lower load (4.3 bar BMEP), a larger amount of EGR is required.

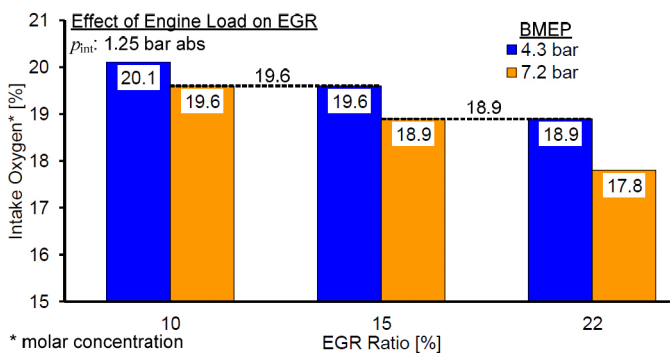


Figure 2. EGR Ratio vs Intake Charge Dilution as Feedback Parameter for EGR

With highly boosted (turbocharged) diesel engines and the lean nature of diesel combustion, the real-time estimation of the intake dilution becomes a challenging task since the established relationship between the intake dilution and the EGR rate for naturally aspirated engines is no longer valid. The need for a precise control on the intake charge dilution (as a result of EGR) is also paramount for enabling alternate combustion modes that operate close to the combustion stability limits. Small fluctuations in the intake charge dilution at high EGR rates may cause larger than acceptable spikes in NO_x/soot emissions or a deterioration in the combustion efficiency, especially at low to mid-engine loads. The control problem becomes more pronounced during transient engine operations; currently the trend is to momentarily close the EGR valve during tip-in or tip-out events.

Therefore, there is a need to track the intake dilution level on-the-fly to enable closed-loop control for minimizing the NO_x emissions during transient engine operation.

There has been extensive research, both theoretical and empirical, on the use of EGR in diesel engines under steady-state engine operation [2, 3, 4, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27]. Zheng et al. [4] outlined the requirements and limitations for the physical implementation of EGR on diesel engines using high-pressure loop and low-pressure loop systems, and also highlighted the need for real-time EGR feedback for enabling transient EGR operation. Zhao et al. [15] developed an engine simulation model with detailed chemical kinetics to analyse the effects of the recycled gases on HCCI combustion. Aithal [16] reported the development of a 0-D modelling tool to quantify the impact of EGR on diesel combustion parameters under steady-state conditions. Xue and Caton [17] demonstrated a 6-zone model for diesel combustion based on Dec's conceptual spray jet model. Although they included the effects of EGR, they did not account for the in-cylinder residuals and the model only dealt with stabilized, steady state operation.

The primary use of these above mentioned models is in desktop applications as the numerical complexity and computational resources required, make them unsuitable for real-time estimation of EGR and the intake parameters. For example, an engine running at 6000 rpm completes 1 combustion cycle (2 revolutions) in 20 ms. To implement a control system on a cycle-by-cycle basis, the model calculations must complete by the end of the exhaust stroke so that suitable control actions can be applied at the start of the next cycle. Therefore, the time window available for the calculations is usually around 0.5 ms @ 6000 rpm (last 20°CA of the exhaust stroke).

In this work, a zero-dimensional algorithm for tracking the intake dilution in real-time (on a cycle-by-cycle basis) has been described. The air-path system is discretized into 3 volumes and the individual concentrations of the gas species in the exhaust, EGR and intake streams are tracked at each time step. The inputs to the model are the oxygen concentration from the exhaust oxygen sensor, the manifold air pressure (MAP) and temperature (MAT), the mass air flow (MAF) and the estimated fuel injected per cycle from the engine control module. The EGR ratio is estimated from the MAF measurement and the speed-density equation. The model is implemented on a controller running a real-time operating system and the model response is tuned to a multi-cylinder engine. The model output is empirically validated against a wide range of engine operations including load and EGR transients. The model is also applicable to any fuel that can be represented by $C_\alpha H_\beta O_\gamma$ (such as oxygenated fuels like ethanol).

INTAKE DILUTION ALGORITHM DEVELOPMENT

The intake dilution tracking algorithm described here is based on the authors' previously published EGR sub-model that can be integrated with zero-dimensional engine cycle simulations to provide both

steady-state and transient EGR assessment capability within the cycle simulation code [14, 28]. To accurately model the intake charge dilution, the build-up of EGR and the exhaust gas flow across the manifolds as well as the EGR loop (cooler, valve, piping) needs to be accounted for, since the oxygen concentration can vary across the EGR system during transient operation. The location of the wide-band oxygen sensor (UEGO), typically downstream of the turbine also needs to be considered. The EGR sub-model has therefore been modified by including the EGR path dynamics to allow the tracking of the intake dilution in real-time.

The flowchart for the zero-dimensional intake dilution tracking algorithm is shown in Figure 3. The air-path system is modelled by 3 lumped control volumes (cv) that combine sections of the exhaust, EGR and intake piping. The model employs a global combustion reaction for a quick assessment of the EGR metrics. The analysis only considers the complete products of combustion for a lean-burn engine, i.e. oxygen, nitrogen, carbon dioxide and water.

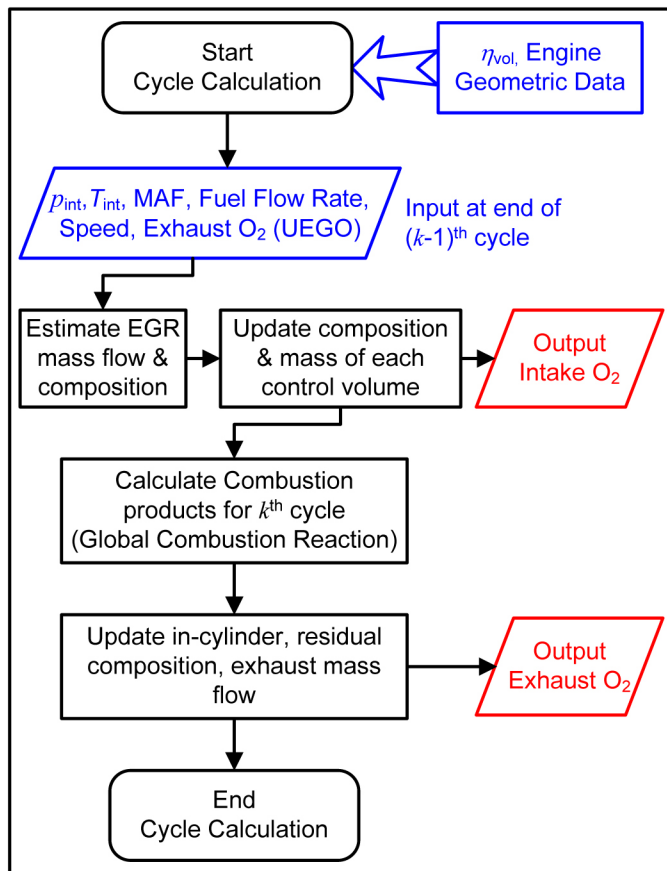


Figure 3. Flow Chart of EGR Tracking Algorithm in Cycle 'k'

The salient features and assumptions of the algorithm are based on well-established modelling practices [29, 30, 31] and are as follows:

- The air-path system is modelled by 3 lumped control volumes that combine sections of the exhaust, EGR and intake piping as shown in Figure 4.

- The pressure within each control volume is updated at the start of the cycle calculations and set equal to the measured intake manifold pressure (MAP). To reduce the computational load, the temperature and the pressure dynamics in the control volumes within one cycle are assumed to be available and constant. Both heat generation and heat loss are neglected.
- The gases within each control volume are assumed to mix perfectly so that the properties of the gases exiting the control volume can be assumed to be equal to the mass-averaged properties for the control volume. It also implies that the concentration of all the gas species (O_2 , N_2 , CO_2 , H_2O) exiting the control volume can be approximated by the mass-averaged species' concentrations in the control volume [32].
- Instead of predicting the EGR flow, typically done using the orifice flow equation (based on isentropic expansion assumption) and the mass flows across the system, the mass flow rate into the engine without EGR ($\dot{m}_{eng}$) is estimated using the speed density equation (Equation 1). The EGR mass flow rate for each cycle is then obtained by subtracting the measured MAF ($\dot{m}_{air}$) from the calculated $\dot{m}_{eng}$ (Equation 2).

$$\dot{m}_{eng} = \eta_{vol} \cdot N \cdot \frac{p_{int} V_d}{RT_{int}} \quad (1)$$

$$\dot{m}_{egr} = \dot{m}_{eng} - \dot{m}_{air} \quad (2)$$

where η_{vol} is the volumetric efficiency, N is the engine speed in revolutions per second, p_{int} is the pressure in the intake control volume, V_d is the engine displacement, T_{int} is the temperature in the intake control volume and R is the specific gas constant (287 J/kg K for air).

- The moles of the control volumes are calculated at the start of each engine cycle based on the initial conditions that include the intake pressure/temperature and engine geometric constraints.
- The EGR stream is assumed to be fully cooled and at the same temperature as the fresh air part of the intake charge, i.e. $T_{egr} = T_{int}$.
- The EGR ratio is calculated as the ratio of the recycled mass to the mass of the exhaust.
- For the residuals, the composition will be the same as that of the exhaust. The residual fraction depends on the volumetric efficiency η_{vol} , the engine speed and the exhaust back-pressure. In this work, the residual fraction r_{res} is based on empirical data for the volumetric efficiency and is estimated as follows:

$$r_{res} = 1 - \frac{m_{int}}{m_{cyl}} \approx 1 - \eta_{vol} \quad (3)$$