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In-cylinder Oxygen Concentration Estimation for Diesel Engines Via Transport Delay Modeling

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Abstract— **In addition to the main injection, current diesel engines often use one or more pilot injections and one or more post injections to better control the combustion process. The mass of fuel delivered and the timing of these injections has a strong affect on the combustion temperature, the heat release rate, the torque production and the formation of harmful emissions. As the cylinder conditions change and in particular as the in-cylinder oxygen concentration changes, the fuel injection masses and timings must be adjusted to achieve a desired trade-off between emissions production and fuel consumption. Alternative combustion modes are particularly sensitive to the cylinder conditions. Incorrectly estimating the cylinder contents can cause inefficient combustion and can increase the emissions produced during transient operations.**

Current in-cylinder oxygen concentration estimators do not account for the transport delay of the recirculated exhaust gas and are therefore less accurate during transients. By incorporating the effects of the time-varying transport delay, the plug flow based oxygen concentration model presented in this paper is able to dynamically predict the in-cylinder oxygen concentration of every induction event. The robust performance of the proposed model is demonstrated through comparisons to a high-fidelity GT-Power engine model.

I. INTRODUCTION

For a diesel engine to produce combustion which provides the optimal trade-off between performance, fuel economy and emissions, both the cylinder contents and the injected fuel must be precisely controlled. The air path controller must ensure that the cylinders contain the correct masses of fresh air and residual gases, while the fueling controller must determine the optimal injection timings and injection quantities for the given cylinder contents. As variable geometry turbochargers (VGT) have become more prevalent, a significant research thrust in coordinated air path control has emerged. Having both an exhaust gas recirculation (EGR) valve and VGT allows for both the total trapped cylinder mass and the composition inside the cylinders to be simultaneously controlled. Many different approaches, including model based control [1],[2], Lyapunov based control [3], linear parameter varying control [4], gain-scheduled PI control [5] and adaptive control [6], have been applied to this type of two degree-of-freedom air path control system. Typically, these air path controllers try to regulate a pair of air path variables to a desired setpoint which is scheduled as a function of the engine speed and the desired torque/fueling. As shown in [7], the choice of the controlled air path variable pair does not have a significant effect on emissions when the fuel injection strategy is based on the target setpoint rather than the actual instantaneous conditions.

During a transient, the cylinder contents deviate from their desired steady-state values. Delivering fueling based on the desired cylinder contents produces suboptimal combustion which frequently produces larger concentrations of harmful emissions. When the fueling strategy is scheduled as a function of the instantaneous cylinder contents, noticeable performance improvements can be achieved. For the simple load transient tested in [8], an active fueling strategy based on an estimate of the in-cylinder oxygen concentration reduced the NO_x emission by 12% and reduced the particulate matter produced (PM) by 19% when compared to a conventional controller. This control strategy has the potential to reduce the cumulative emission produced during an actual driving cycle, but only if the in-cylinder oxygen concentration can be predicted accurately for all transient conditions.

For alternative combustion modes such as homogeneous charge compression ignition (HCCI) and low temperature combustion (LTC) estimating the cylinder contents is not only important for producing low emissions during combustion but also for maintaining combustion stability. To achieve the desired lower combustion temperatures, these combustion modes become susceptible to combustion instability. As demonstrated in [9], an estimate of the cylinder contents which has a 5% error can cause misfires in an HCCI engine. The chemical kinetics and computational fluid dynamics studies in [10] and [11] showed that the in-cylinder oxygen concentration has a strong effect on HCCI combustion. In particular, decreasing the in-cylinder oxygen concentration was found to significantly increase the ignition delay as well as decrease the heat release rate. These effects have also been observed in experimental data and can be captured using simple empirical models. In [12], for example, the effect of the in-cylinder oxygen concentration on the start of combustion was modeled using a polynomial function.

Because the combustion properties are so strongly dependent on the in-cylinder oxygen concentration, designing a more accurate oxygen concentration estimator is a cost effective method of reducing emissions. To estimate the in-cylinder oxygen concentration, a wide range of models have been used including models derived from the first law of thermodynamics [6],[7],[12], linear parameter varying models [4],[13],[14], steady-state relationships [5] and empirical models [1],[2],[8]. None of these approaches, however, account for the time-varying transport delay. By ignoring the transport delay, the predicted in-cylinder oxygen concentration often leads the actual oxygen concentration.

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This positive phase error can be significant especially during rapid transients.

Using a physically based plug flow model, the transport delay of a fluid system can be predicted well. Plug flow modeling has been previously used to account for the characteristic delay of the air to fuel ratio measurement system of a gasoline engine [15]. For this type of gasoline application, a plug flow approximation enables better dynamic prediction of the pre-catalyst air to fuel ratio. For diesel engines, estimating the transport delay with this type of model allows the in-cylinder oxygen concentration to be predicted with a much higher degree of accuracy, particularly during transients. Because the in-cylinder oxygen concentration can be easily measured experimentally, the plug flow based oxygen concentration prediction model presented in this paper has been validated using a high-fidelity GT-Power model. For a realistic driving simulation, the in-cylinder oxygen concentration percentage predicted by the plug flow based model agrees with the GT-Power prediction to within 0.22% in a root mean squared (RMS) sense.

II. Plug flow based oxygen concentration prediction model

A plug flow model can be used to approximate the motion of the exhausted combustion gases as flow back into the intake system through the EGR loop. This type of model accounts for the fixed delay between injecting fuel and exhausting the combustion products, the mixing phenomena within the piping systems and the transport delay. Because this model relies predominately on physically based approximations, it is able to predict the time-varying delay resulting from these effects exceptionally well both in steady-state and during transients. This model operates in the engine event domain which a subset of the crank angle domain where the number of events per engine cycle is equal to the number of cylinders. At each event one cylinder is exhausting its combustion products, while another cylinder is inducting new air charge (fresh air and EGR).

The oxygen concentration at any point in the EGR loop can be predicted by tracking small "packets" of gas (combustion gas and/or fresh air) as they move through the exhaust, EGR and intake systems. This is realized by individually discretizing these systems into many cells of constant volume. Each of these constant volume cells holds a packet of fresh/burned gas with a uniform oxygen concentration. Every event when a cylinder exhausts its combustion products the gas packets downstream from the exhaust ports are pushed further downstream. Depending on the EGR flow rate, some fraction of the gas packets that leave the exhaust manifold will enter the EGR system. The gas packets that enter the EGR system displace the same number of packets into the intake system. This mass of displaced combustion gas combines with fresh air and is eventually inducted into the engine. Modeling the system in this manner inherently captures the time-varying transport delay.

At each event, the volume occupied by the newly exhausted gas mass is calculated using the ideal gas law. The ceiling function $\lceil\ \rceil : \Re \mapsto \mathbb{Z}$ defined as

$$\lceil y \rceil = \min\{m \in \mathbb{Z} \mid m \geq y\}, \tag{1}$$

is used to convert the this volume into a discrete number of cells according to

$$x_{exh}(k) = \left\lceil \frac{\dot{m}_{exh}(k) T_{exh}(k) R}{P_{exh}(k)} \times \frac{n_{exh}}{V_{exh}} \right\rceil \tag{2}$$

where x_{exh} is the total number of cells that the new exhaust gas will occupy, $\dot{m}_{exh}$ is the exhaust gas mass flow rate on a per event basis, T_{exh} is the characteristic temperature of the exhaust manifold, R is the universal gas constant, P_{exh} is the pressure of the exhaust manifold, n_{exh} is the total number of cells used to model the exhaust manifold, V_{exh} is the total volume of the exhaust manifold system and k is the time index in engine events.

Each cell represents a physical location in the exhaust system, so the newly exhausted cells enter the model at the cell corresponding to the exhaust ports of the engine, EXH_1, according to

$$EXH_1^{q_{exh}}(k) = [O_2]_{comb}(k - d_{fuel,exh}) \tag{3}$$

where $[O_2]_{comb}$ is the oxygen concentration of the gases within the cylinders after combustion occurs, q_{exh} is the flow index of the exhaust system and $d_{fuel,exh}$ is the fixed delay between the fueling and exhausting events. The general notation $EXH_i^{q_{exh}}$ represents the oxygen concentration of the i^{th} cell of the exhaust system after the $q_{exh}{}^{\text{th}}$ cell has been exhausted. To make room for this new cell, each cell in the fluid path must move downstream one cell. The propagation of the cells within the exhaust manifold is modeled as

$$EXH_i^{q_{exh}}(k) = (1-\beta_f) EXH_i^{q_{exh}-1}(k) + \beta_f EXH_{i-1}^{q_{exh}-1}(k) \tag{4}$$

$\forall\ i \in \{2,\ 3,\ ...,\ n_{exh}\}$ where $\beta_f \in (0.5,\ 1.0]$ captures the mixing effects of the diffusion process. To model the effect of each new cell entering the exhaust system, the calculations in (3) and (4) must be repeated for all integer values q_{exh} from 1 to $x_{exh}(k)$.

Part of the exhaust gases that leave the exhaust manifold enter the EGR loop while most of the exhaust gases continue down the exhaust system through the turbocharger. The number of cells in the EGR system occupied by these gases, x_{egr}, is governed by

$$x_{egr}(k) = \left\lceil \frac{\dot{m}_{egr}(k) T_{egr}(k) R}{P_{egr}(k)} \times \frac{n_{egr}}{V_{egr}} \right\rceil \tag{5}$$

where $\dot{m}_{egr}$ is the mass flow rate of EGR on a per event basis, T_{egr} is the characteristic temperature of the EGR system, P_{egr} is the pressure of the EGR system, n_{egr} is the total number of cells used to model the EGR system and V_{egr} is the total volume of the EGR system. Define r_{egr} as the ratio described by

$$r_{egr}(k) = \frac{x_{exh}(k)}{x_{egr}(k)}. \tag{6}$$

To determine the oxygen concentration of the cells entering the EGR system, the incoming x_{exh} cells are split into x_{egr}

groups of r_{egr} exhaust cells. If $r_{egr}(k) > 1$, then each group will contain two fractional cells and may contain multiple whole cells. If instead $r_{egr}(k) \leq 1$, then each group will contain either two fractional cells or a single factional cell. The oxygen concentration of each new EGR cell entering the EGR system is the weighted average of the oxygen concentrations of the exhaust cells in that grouping.

For the case where $r_{egr}(k) > 1$, each grouping of exhaust cells can be split into the following three partitions: a first partition which contains a fractional cell, a middle partition which contains multiple whole cells and a last partition which contains a fractional cell. The contribution from the first partition of the j^{th} group of exhaust cells, F_{egr}^j, is calculated according to

$$F_{egr}^j = EXH_{n_{exh}}^{\lceil r_{egr}\times(j-1)\rceil^\star}\left(\lceil r_{egr}\times(j-1)\rceil^\star - r_{egr}\times(j-1)\right) \tag{7}$$

$\forall\ j \in \{1, 2, ..., x_{egr}\}$ where $\lceil\ \rceil^\star : \Re \mapsto \mathbb{Z}$ represents the strictly ceiling function defined as

$$\lceil y\rceil^\star = \min\{m \in \mathbb{Z} \mid m > y\}. \tag{8}$$

Similarly, the contribution from the last partition of the j^{th} group of exhaust cells, L_{egr}^j, is calculated with

$$\begin{aligned} L_{egr}^j \quad = \quad & EXH_{n_{exh}}^{\left\lceil r_{egr}\times j\right\rceil} \times \\ & \left(r_{egr}\times j - \left\lfloor r_{egr}\times j\right\rfloor^\star\right) \end{aligned} \tag{9}$$

$\forall\ j \in \{1, 2, ..., x_{egr}\}$ where $\lfloor\ \rfloor^\star : \Re \mapsto \mathbb{Z}$ represents the strictly floor function defined as

$$\lfloor y\rfloor^\star = \max\{m \in \mathbb{Z} \mid m < y\}. \tag{10}$$

Lastly, the contribution from the middle partition of the j^{th} group of exhaust cells, M_{egr}^j, is defined as

$$M_{egr}^j = \sum_{c\ =\left\lceil (j-1)\times r_{egr}(k)\right\rceil^\star}^{\left\lfloor j\times r_{egr}(k)\right\rfloor^\star - 1} EXH_{n_{exh}}^{c+1}(k) \tag{11}$$

$\forall\ j \in \{1, 2, ..., x_{egr}\}$. The same definitions for F_{egr}^j, M_{egr}^j and L_{egr}^j can be used for the case when $r_{egr}(k) < 1$. In this situation, M_{egr}^j will always be identically zero. The diagram presented in Figure 1 demonstrates how cells are divided for the case when seven exhaust cells are converted into three EGR cells.

Once each of the three contributions has been calculated, the oxygen concentration of the cells entering the EGR system can be calculated. Define q_{egr} as the flow index of the EGR system in the same way that q_{exh} represents the flow index of the exhaust system. Let the general notation $EGR_i^{q_{egr}}$ represent the oxygen concentration of the i^{th} cell of the EGR system after the $q_{egr}{}^{\text{th}}$ cell has entered the EGR system. If $\lceil (q_{egr}-1)\times r_{egr}(k)\rceil^\star \leq \lfloor q_{egr}\times r_{egr}(k)\rfloor^\star$, then

$$EGR_1^{q_{egr}}(k) = \frac{1}{r_{egr}(k)}\left(F_{egr}^{q_{egr}} + L_{egr}^{q_{egr}} + M_{egr}^{q_{egr}}\right), \tag{12}$$

otherwise

$$EGR_1^{q_{egr}}(k) = EXH_{n_{exh}}^{\lceil (q_{egr}-1)\times r_{egr}(k)\rceil^\star}(k). \tag{13}$$

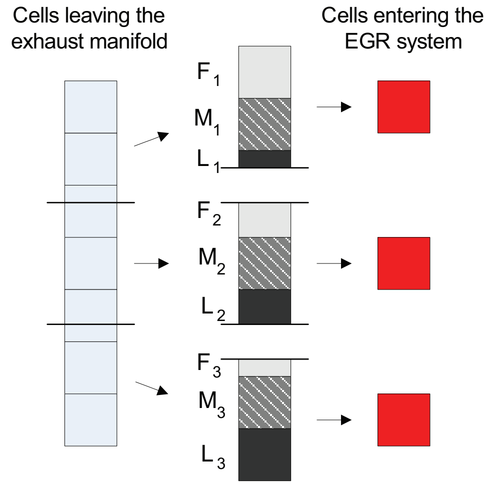

Fig. 1. Cell splitting diagram

The second equation corresponds to the case when $r_{egr}(k) < 1$ and only a fraction of a single cell is contained within the $q_{egr}{}^{\text{th}}$ grouping of exhaust cells. The propagation of the downstream cells within the EGR loop is exactly the same as the exhaust manifold. This process is modeled as

$$EGR_i^{q_{egr}}(k) = (1-\beta_f)EGR_i^{q_{egr}-1}(k) + \beta_f EGR_{i-1}^{q_{egr}-1}(k) \tag{14}$$

$\forall\ i \in \{2, 3, ..., n_{egr}\}$ and $\forall\ q_{egr} \in \{1, 2, ..., x_{egr}\}$.

Each cell that exits the EGR system mixes with fresh air and enters the intake system. The number of cells occupied by this mixture of EGR and fresh air, x_{int}, is governed by

$$x_{int}(k) = \left\lceil \frac{\dot{m}_{charge}(k)T_{int}(k)R}{P_{int}(k)} \times \frac{n_{int}}{V_{int}} \right\rceil \tag{15}$$

where $\dot{m}_{charge}$ is the mass flow rate or air charge on a per event basis, T_{int} is the characteristic temperature of the intake system, P_{int} is the pressure of the intake system, n_{int} is the total number of cells used to model the intake system and V_{int} is the total volume of the intake system. Define r_{int} as the ratio described by

$$r_{int}(k) = \frac{x_{int}(k)}{x_{egr}(k)}. \tag{16}$$

As with the EGR system, this ratio will be used to separate the x_{egr} EGR cells into x_{int} groups of r_{int} intake cells. The contribution from the first partition of the j^{th} group of EGR cells, F_{int}^j, is calculated according to

$$F_{int}^j = EGR_{n_{int}}^{\lceil r_{int}\times(j-1)\rceil^\star}\left(\lceil r_{int}\times(j-1)\rceil^\star - r_{int}\times(j-1)\right) \tag{17}$$

$\forall\ j \in \{1, 2, ..., x_{int}\}$. Similarly, the contribution from the last partition of the j^{th} group of EGR cells, L_{int}^j, can be calculated with

$$\begin{aligned} L_{int}^j \quad = \quad & EGR_{n_{int}}^{\left\lceil r_{int}\times j\right\rceil} \times \\ & \left(r_{int}\times j + - \left\lfloor r_{int}\times j\right\rfloor^\star\right) \end{aligned} \tag{18}$$

$\forall\ j \in \{1, 2, ..., x_{int}\}$. Lastly, the contribution from the middle partition of the j^{th} group of EGR cells, M_{int}^j, is defined as

$$M_{int}^{j} = \sum_{c\ =\lceil (j-1)\times r_{int}(k)\rceil^{\star}}^{\lfloor j\times r_{int}(k)\rfloor^{\star}-1} EGR_{n_{int}}^{c+1}(k) \tag{19}$$

$\forall\ j \in \{1,\ 2,\ ...,\ x_{int}\}$.

Because both fresh air and EGR enter the intake system, the oxygen concentration of the cells entering the intake depends on both the oxygen concentration of the ambient air and the cells leaving the EGR system. Define q_{int} as the flow index of the intake system. If $\lceil (q_{int}-1)\times r_{int}(k)\rceil^{\star} \leq \lfloor q_{int} \times r_{int}(k)\rfloor^{\star}$, then the effect of the EGR gases on the oxygen concentration of the $q_{int}{}^{\text{th}}$ cell entering the intake system, $\Gamma^{q_{int}}$, is

$$\Gamma^{q_{int}}(k) = \frac{1}{r_{int}(k)}\Big(F_{int}^{q_{int}} + L_{int}^{q_{int}} + M_{int}^{q_{int}}\Big), \tag{20}$$

otherwise

$$\Gamma^{q_{int}}(k) = EGR_{n_{egr}}^{\lceil (q_{int}-1)\times r_{int}(k)\rceil^{\star}}(k). \tag{21}$$

The second equation corresponds to the case when $r_{int}(k) < 1$ and only a fraction of a single cell is contained within the $q_{int}{}^{\text{th}}$ grouping of EGR cells. The oxygen concentration of the first cell in the intake system after the $q_{int}{}^{\text{th}}$ cell has entered the intake system can be predicted using

$$INT_{1}^{q_{int}}(k) = \frac{\dot{m}_{egr}(k)\Gamma^{q_{int}}(k) + \dot{m}_{fresh}(k)[O_2]_{amb}(k)}{\dot{m}_{charge}(k)} \tag{22}$$

where $\dot{m}_{fresh}$ is the mass flow rate of fresh air on a per event basis and the general notation $INT_{i}^{q_{int}}$ refers to the oxygen concentration of the i^{th} cell of the intake system after the $q_{int}{}^{\text{th}}$ cell has entered the intake system. The propagation of the downstream cells within the intake manifold is modeled as

$$INT_{i}^{q_{int}}(k) = (1-\beta_f)INT_{i}^{q_{int}-1}(k) + \beta_f INT_{i-1}^{q_{int}-1}(k) \tag{23}$$

$\forall\ i \in \{2,\ 3,\ ...,\ n_{int}\}$ and $\forall\ q_{int} \in \{1,\ 2,\ ...,\ x_{int}\}$.

The in-cylinder oxygen concentration depends on both the air charge inducted from the intake system and the residual gases that remained in the cylinders. The contribution from the air charge, $[O_2]_{int}$, can be calculated using

$$[O_2]_{int}(k) = \frac{1}{x_{int}(k)} \sum_{c=1}^{x_{int}(k)} INT_{n_{int}}^{c}(k). \tag{24}$$

Define the trapped residual fraction γ as the ratio of the trapped residual mass m_{res} to the total trapped mass $m_{trapped}$ as in

$$\gamma(k) = \frac{m_{res}(k)}{m_{trapped}(k)}. \tag{25}$$

Using this definition, the total trapped mass can be related to the charge flow rate with

$$m_{trapped}(k) = \frac{\dot{m}_{charge}(k)}{1-\gamma(k)}. \tag{26}$$

In steady-state, the in-cylinder oxygen concentration is the mass weighted average of the oxygen concentration of the inducted air charge and the oxygen concentration of the residual gases from the previous combustion cycle. In terms of the trapped residual fraction,

$$\begin{aligned}[O_2]_{cyl}(k) \quad = \quad & \big(1-\gamma(k)\big)[O_2]_{int}(k) + \\ & [O_2]_{comb}(k-d_{fuel,int})\gamma(k)\end{aligned} \tag{27}$$

where $[O_2]_{cyl}$ is the in-cylinder oxygen concentration and $d_{fuel,int}$ is the fixed delay between the fueling and intake events. The mass of oxygen trapped in the cylinder is therefore

$$m_{[O_2]_{cyl}}(k) = [O_2]_{cyl}(k)m_{trapped}(k). \tag{28}$$

During combustion much of the oxygen within the cylinders is expended. The remaining oxygen concentration after combustion $[O_2]_{comb}$ can be predicted using

$$[O_2]_{comb}(k) = \frac{m_{[O_2]_{cyl}}(k-d_{int,fuel}) - \frac{AFR_s}{[O_2]_{air}}m_{fuel}(k)}{m_{trapped}(k-d_{int,fuel}) + m_{fuel}(k)} \tag{29}$$

where $d_{int,fuel}$ is the fixed delay between the induction and fueling events, AFR_s is the stoichiometric air-to-fuel ratio, $[O_2]_{air}$ is the concentration of oxygen in fresh air and m_{fuel} is the total injected fuel mass. Before beginning the calculations for the next event, the initial conditions for each of the subsystems must be defined according to

$$\begin{aligned} EXH_i^0(k+1) &= EXH_i^{x_{exh}}(k) \quad \forall\ i \in \{1,\ 2,\ ...,\ n_{exh}\}, \\ EGR_i^0(k+1) &= EGR_i^{x_{egr}}(k) \quad \forall\ i \in \{1,\ 2,\ ...,\ n_{egr}\}, \\ INT_i^0(k+1) &= INT_i^{x_{int}}(k) \quad \forall\ i \in \{1,\ 2,\ ...,\ n_{int}\}. \end{aligned} \tag{30}$$

Unlike most models, this plug flow model does not predict the thermodynamic conditions of the system. Instead, the temperatures, pressures and mass flow rates within the exhaust, EGR and intake systems (all of which are readily measured and/or estimated in current production engines) are considered as inputs. The commanded fuel injection mass is also an input. In addition to these inputs, the trapped residual fraction must also be estimated. As will be demonstrated in the next section, a plug flow based oxygen concentration model is still able to produce quality estimates even when the inputs are not perfectly known.

III. Performance Evaluation

Experimentally measuring the in-cylinder oxygen concentration is very difficult and not feasible in a production setting. Using a high fidelity engine model such as GT-Power, the oxygen concentration can be readily estimated. GT-Power is a commercially available software package which is capable of accurately predicting the one-dimensional gas dynamics within an engine. The performance of the plug flow based oxygen concentration model has been quantified using a high-fidelity GT-Power model of a six cylinder heavy-duty diesel engine with a VGT. This GT-Power model was previously calibrated and experimentally validated. This model was also used to construct an operating condition indexed look-up table for the trapped residual fraction.

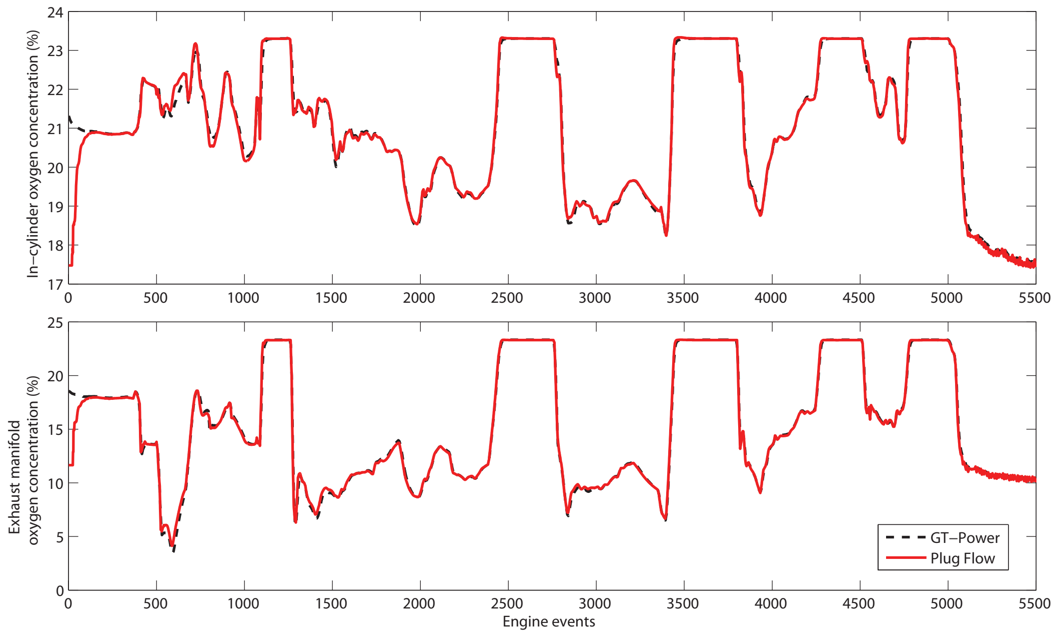

Fig. 2. Oxygen concentration prediction comparison with ideal temperature, pressure and mass flow rate measurements

Because most of the parameters within a plug flow based oxygen concentration model depend on the geometry of the system being modeled, only the mixing parameter (β_f) and the number of cells used to model each subsystem (n_{exh}, n_{egr} and n_{int}) must be calibrated. As the value of β_f approaches zero, the predicted in-cylinder oxygen concentration response becomes more filtered. For the engine under investigation, a value of 0.90 was found to best model the mixing effects. When selecting the number of cells for the exhaust, EGR and intakes systems, the number of cells must be chosen large enough to provide sufficient accuracy but not so large that the model becomes a computational burden. A total of 100 cells was chosen because it provides a good compromise between these two factors. The cells were distributed across the three subsystems to best capture the transport delay fluctuations (20 exhaust cells, 50 EGR cells, 30 intake cells).

To best represent real-world usage, the performance of the plug flow based oxygen concentration model was studied for the first one hundred seconds of a FTP (Federal Test Procedure) heavy-duty transient drive cycle. This drive cycle was run experimentally and the experimental trajectories for the engine speed, fueling parameters, EGR valve position and VGT position were imposed as inputs to the GT-Power model. The performance of the plug flow based model was first analyzed under ideal conditions where the input temperatures, pressures and mass flow rates were measured perfectly. Under these conditions, the plug flow based model produces excellent performance as shown in Figure 2. The top plot in Figure 2 compares the in-cylinder oxygen concentration predicted by GT-Power to the in-cylinder oxygen concentration predicted by the plug flow model, whereas the bottom plot compares the predicted oxygen concentration at the entrance to the exhaust manifold. By dynamically accounting for the transport delay, the trajectories of the two models are always in phase and almost always agree in amplitude. Overall, the RMS error between the GT-Power predicted in-cylinder oxygen concentration and the plug flow model prediction is 0.109%.

In practice the temperatures, pressures and mass flow rates within the exhaust, EGR and intake systems are not measured perfectly. To quantify the model performance more realistically, unique disturbance profiles which represent bias errors and sensor dynamics were added to each of the model inputs. The magnitude of the disturbances applied to each of temperature, pressure and flow rate inputs was on average 4.0% and the peak amplitude was 16.0%. To represent fuel injector errors, a disturbance with an average magnitude of 2.0% and a peak magnitude of 8.0% was applied to the injected fuel mass input. These disturbance magnitudes are meant to be representative of a typical production system. An additional disturbance was also applied to the trapped residual fraction look-up prediction to represent the uncertainty in this part of the GT-Power model. This disturbance had an average magnitude of 10.0% and a peak of 40%.

Including these disturbances did not significantly degrade the performance of the plug flow based oxygen concentration model. The in-cylinder and exhaust manifold oxygen concentration predicted by the plug flow model under these conditions are compared to the GT-Power prediction in Figure 3. The RMS in-cylinder oxygen concentration error is 0.211% which is approximately double that of the ideal

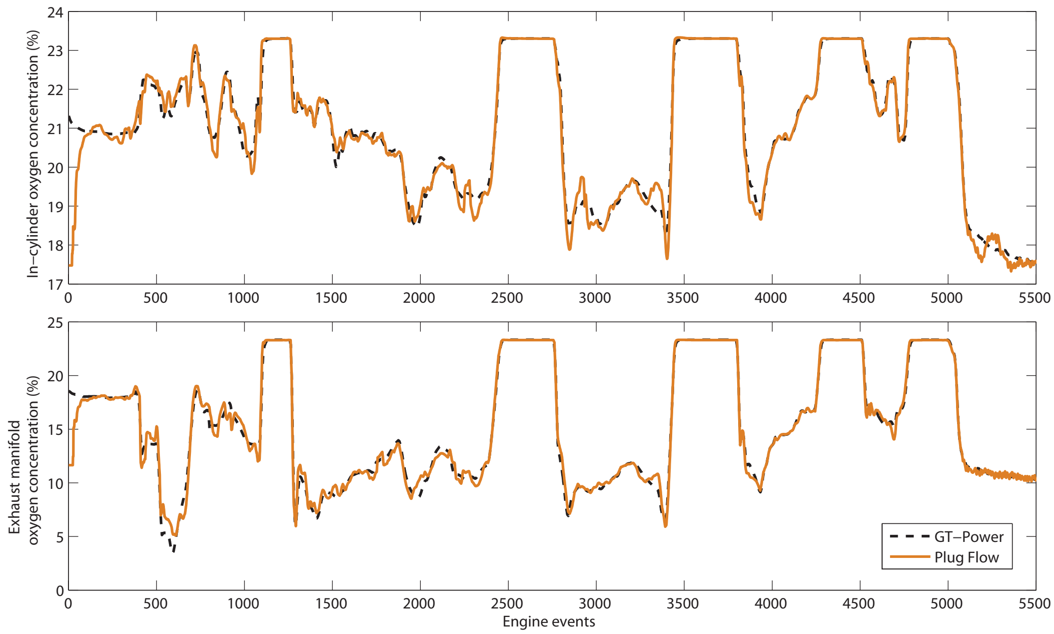

Fig. 3. Oxygen concentration prediction comparison with noisy temperature, pressure and mass flow rate measurements

case. These results compare favorably to other in-cylinder oxygen concentration prediction models.

IV. Conclusion

By capturing the effects of the time-varying transport delay, a plug flow based oxygen concentration model is able to dynamically predict the in-cylinder oxygen concentration with very high accuracy. Under realistic transient drive cycle conditions, the oxygen concentration percentage is predicted to within 0.211% of the true value on average in an RMS sense. Accurately estimating the in-cylinder oxygen concentration is a necessity for advanced combustion control techniques including alternative combustion modes. The future of this work will focus on demonstrating the improvements in emissions and fuel economy that are enabled by precisely estimating the in-cylinder oxygen concentration. To this end, the performance of an active fueling controller which schedules the fueling parameters as a function of the in-cylinder oxygen concentration will be compared to a conventional fueling controller.

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