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A control oriented diesel engine NO_x emission model for on board diagnostics and engine control with sensor feedback

Masoud Aliramezani*, Armin Norouzi, Charles Robert Koch, Robert E Hayes

Department of Mechanical Engineering, University of Alberta, Edmonton, Canada T6G 1H9 Department of Chemical and Materials Engineering, University of Alberta, Edmonton, Canada T6G 1H9

Abstract

Based on experimental data, a Multi-Input Multi-Output (MIMO) control oriented diesel engine model is developed to predict engine NO_x emission and brake mean effective pressure (BMEP). The experimental tests were carried out on a 4.5L medium duty diesel engine at different engine operating conditions with engine speed between 1000 rpm to 2500 rpm and normalized engine output, BMEP, between 1.8931 [bar] and 17.04 [bar]. The engine NO_x emission is measured with a fast response electrochemical NO_x sensor. The steady state engine NO_x is modeled as a function of the injected fuel amount, the injection rail pressure and the engine speed. While, the BMEP is assumed to be a function of the injected fuel amount and engine speed. Then, an engine dynamic model was developed by adding first order lags to the static NO_x and BMEP models. This two-state control oriented model is used to represent the dynamic model. Finally, the engine response to step changes of injection pressure and injected fuel amount are examined and compared with the experimental data. The developed control oriented model can be used for both engine and NO_x sensor on board diagnostics and for engine control with NO_x sensor feedback.

1 Introduction

The high combustion temperatures and the lean air-fuel mixture of Diesel engines leads to a relatively high NO_x emission. The NO_x emission in Diesel engines mainly consists of Nitrogen monoxide (NO) and Nitrogen dioxide (NO_2). Typically, the engine exhaust contains 70%-90% NO and 10%-30% NO_2 [1]. Downstream of a Diesel Oxidation Catalyst (DOC) the NO_2/NO ratio increases after the DOC to approximately one [2]. Vehicle emission regulations have become increasingly stringent and new engine control strategies and after treatment systems are needed to meet these regulations [3–5]. According to the latest emission regulations [6, 7], any fault in any emission-relevant device must be detected through on-board diagnostics (OBD) strategies [8, 9]. The updated OBD standard (OBD II) mandates monitoring any power-train component that provides input to, or receives commands from the electronic control unit (ECU) [8]. One effective technique of detecting and isolating faults in a dynamical system such as diesel engine is developing a reliable control oriented model and then using it for model-based fault detection and fault isolation.

In addition, fast and accurate emission measurement facilitates improving engine performance and reducing engine emissions by providing real-time feedback for use in engine closed-loop control. Solid-state electrochemical gas sensors have many remarkable properties that make them ideal for real-time engine emission measurement [10]. The reliability, small size, fast response and low price of solid-state electrochemical sensors make them ideal for engine emission measurement [11, 12]. An electrochemical fast response NO_x sensor is used in this work to measure NO_x concentration in the exhaust gas.

A steady state diesel engine NO_x emission and BMEP model is first developed based on the experimental data carried out on a medium duty diesel engine. The steady state engine NO_x is modeled as a function of the engine speed, the amount of injected fuel and the injection rail pressure. The BMEP is assumed to be a function of the injected fuel and engine speed. Then, a control oriented model is developed by adding low-pass filters to the static NO_x and BMEP models. The engine response to step changes of injection pressure and injected fuel amount is then examined.

*Corresponding author: aliramez@ualberta.ca

2 Experimental setup

To study the engine NO_x emission at different engine operating conditions, an electrochemical NO_x sensor was mounted in the exhaust pipe of a four cylinder medium duty Tier III diesel engine (Cummins QSB4.5 160 - Tier 3/Stage IIIA). The Engine characteristics are listed in Table 1.

Table 1: Diesel engine characteristics [13]

Engine type	In-Line, 4-Cylinder
Displacement	4.5 L
Peak BMEP	17.4163 bar (@ 1500 rpm)
Aspiration	Turbocharged and Charge Air Cooled
Certification Level	Tier 3 / Stage IIIA

The Cummmins Engine Control Unit (ECU) controls the Diesel engine by reading all the stock sensors mounted on the production Cummins engine including the intake manifold temperature, intake manifold pressure, injection rail pressure, coolant temperature, and controlling all of the engine main actuators and operating parameters, including the injection timing(s), turbocharge boost pressure, injection amount, etc. To read the engine main variables and operating parameters, the ECU is connected to a computer using J1939 connector and a hardware interface (INLINE 6).

The NO_x sensor used in the experiments was a production ECM NO_x sensor (P/N: 06-05). The sensor output for NO_x was measured and logged using the corresponding control module (*ECM-NOxCANt* P/N: 02-07) connected to a computer via *Kvaser Light HS* CAN interface.

3 Model

The BMEP and engine-out NO_x emission are considered the main outputs of the model. The steady state experimental data is used to develop the steady state NO_x and BMEP model. For simplification, the dynamics NO_x and BMEP models are obtained by adding a first order low pass filter to the steady state models.

3.1 Steady state NO_x *emission model*

The steady state NO_x emissions of a diesel engine are a strong function of the local in-cylinder temperature and local oxygen concentration [14, 15]. Based on the available experimental data of the engine operating parameters that have a direct effect on engine NO_x emission [16], the following polynomial equation is found for the steady-state engine NO_x emission the steady-state engine NO_x emission:

$$NO_{x,ss} = a_o + a_1 mf_i + a_2 mf_i^2 + a_3 mf_i^3 + a_4 P_r + a_5 P_r^2 + a_6 n + a_7 n^2 \tag{1}$$

where, $NO_{x,ss}$ is the steady state NO_x concentration [ppm], mf_i is the injected fuel [mg/stroke], P_r is the injection rail pressure [bar] and n is the engine speed [rpm]. Parameters a_o to a_8 are found through fitting to experimental data using a trust-region algorithm [17] with squared correlation coefficient (R^2) of 0.989. The experiments were carried out at 14 engine operating conditions with the engine speed of 1000 to 2500 rpm and output torque of 50 to 450 ft.lb. Parameters a_o to a_8 are listed in Table A1. The predicted vs experimental NO_x concentration is shown in Fig. 1.

3.2 Steady state BMEP model

A simple model is also developed for the steady state BMEP. The BMEP is assumed to be a function of the injected fuel [mg/stroke] and the engine speed [rpm] [18], as follows:

$$BMEP_{ss} = b_o N^{b_1} mf_i^{b_2} \tag{2}$$

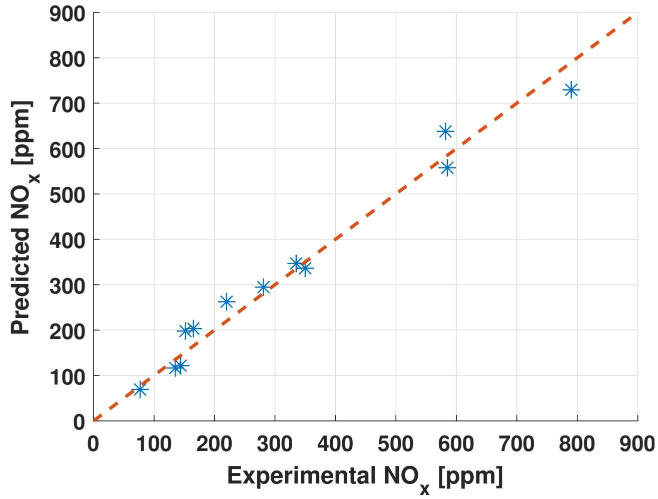

Fig. 1: Predicted vs Experimental NO_x concentration

where, $BMEP_{ss}$ is the steady state BMEP. Parameters b_o to b_2 are found through fitting to experimental data using a trust-region algorithm with squared correlation coefficient (R^2) of 0.9914. The model parameters are listed in Table A2. The predicted vs experimental BMEP is shown in Fig. 2.

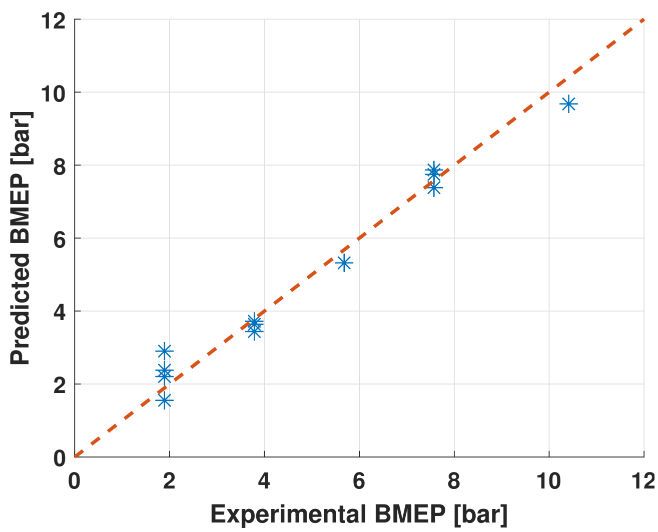

Fig. 2: Predicted vs Experimental BMEP

3.3 Dynamic models

The effect of engine dynamics on the transient NO_x and BMEP are approximated by two first order lags as follows:

$$NO_{x,t}(s) = \frac{1}{\tau_{NOx}s + 1} NO_{x,ss}(s) \tag{3}$$

$$BMEP(s) = \frac{1}{\tau_{BMEP}s + 1} BMEP_{ss}(s) \tag{4}$$

where, $NO_{x,t}(s)$ and $BMEP(s)$ are the transient NO_x emission and BMEP respectively while $NO_{x,ss}(s)$ and $BMEP_{ss}(s)$ are the steady state NO_x and BMEP respectively, all in Laplace domain. The first order lag time constant for NO_x, τ_{NOx}, is larger than the time constant for the BMEP τ_{BMEP} due to the lag associated with the flow of the exhaust gas through the engine exhaust manifold and exhaust pipe [19] and the lag associated with diffusion of species through the NO_x sensor. The time constant parameters for NO_x and BMEP are estimated based on the experimental data and are found to be 1 seconds and 0.2 seconds respectively [19].

3.4 Control oriented model

To derive the discrete control oriented model, first the first order lags are written in discrete form. For a sampling interval of T, the NO_x concentration at step k+1 is calculated as follows:

$$NO_x(k+1) = (1 - \frac{T}{\tau_{NOx} + T})NO_x(k) + \frac{T}{\tau_{NOx} + T}NO_{x,ss}(k+1) \tag{5}$$

and the BMEP at step k+1 is calculated using the following equation:

$$BMEP(k+1) = (1 - \frac{T}{\tau_{BMEP} + T})T(k) + \frac{T}{\tau_{BMEP} + T}BMEP_{ss}(k+1) \tag{6}$$

where $NO_{x,ss}(k+1)$ and $BMEP_{ss}(k+1)$ are the steady state NO_x and output BMEP calculated using Eqn. (1) and Eqn. (2) respectively.

The model inputs, states, parameters and outputs are classified as vectors. The vector $\mathbf{x}$ contains two model states:

$$\mathbf{x(k)} = \begin{bmatrix} NO_x(k) & \tau(k) \end{bmatrix} \tag{7}$$

The vector $\mathbf{u}$ contains three model inputs:

$$\mathbf{u(k)} = \begin{bmatrix} N(k) & mf_i(k) & P_r(k) \end{bmatrix} \tag{8}$$

The vector $\boldsymbol{\zeta}$ contains 14 model parameters:

$$\boldsymbol{\zeta} = \begin{bmatrix} \tau_{NOx} & \tau_{BMEP} & a_o & a_1 & a_2 & a_3 & a_4 & a_5 & a_6 & a_7 & b_o & b_1 & b_2 \end{bmatrix} \tag{9}$$

The vector $\mathbf{y}$ contains two model outputs:

$$\mathbf{y(k)} = \begin{bmatrix} x_1(k) & x_2(k) \end{bmatrix} \tag{10}$$

The control oriented model states result from combining Eqn. (1 to 2) with Eqn. (5 to 9) and is:

$$\begin{aligned} \mathbf{x_1}(k+1) = \left(1 - \frac{\zeta_1}{\zeta_2 + \zeta_1}\right)x_1(k) + \frac{\zeta_1}{\zeta_2 + \zeta_1}\Big(\zeta_4 + \zeta_5 u_2(k+1) + \zeta_6\Big[u_2(k+1)\Big]^2 + \zeta_7\Big[u_2(k+1)\Big]^3 \\ + \zeta_8 u_3(k+1) + \zeta_9\Big[u_3(k+1)\Big]^2 + \zeta_{10}u_1(k+1) + \zeta_{11}\Big[u_1(k+1)\Big]^2\Big) \end{aligned} \tag{11}$$

$$\mathbf{x_2}(k+1) = \left(1 - \frac{\zeta_1}{\zeta_3 + \zeta_1}\right)x_2(k) + \frac{\zeta_1}{\zeta_3 + \zeta_1}\zeta_{12}\left(\Big[u_1(k+1)\Big]^{\zeta_{13}}\Big[u_2(k+1)\Big]^{\zeta_{14}}\right) \tag{12}$$

4 Results and discussion

To evaluate the effect of transient inputs on the model outputs, the model response to step changes in fuel rail pressure and injection amount are simulated and compared to the measured experimental results in Fig. 3. The control oriented model transient response matches the experiments with maximum error of 18.1 % for NO_x and 10.3 % for BMEP. The engine speed is kept constant (1500 rpm) for the simulations. The engine NO_x emission and BMEP both increase as the amount of injected fuel increases. By increasing the injection amount, the overall in-cylinder heat release increases which will increase the indicated engine power and therefore the BMEP at a constant engine speed. This also increases the maximum in-cylinder temperature and consequently increases the NO_x production. On the other hand, the engine NO_x emission decreases by decreasing the injected fuel rail pressure as shown in Fig. 3. Reducing the injection rail pressure can reduce the the heat release rate and consequently reduces the maximum in-cylinder temperature [20], and therefore reduces the NO_x production rate [21]. This effect may vary at different engine operating conditions and injection timings including multiple injections, which are not captured by the control oriented model proposed.

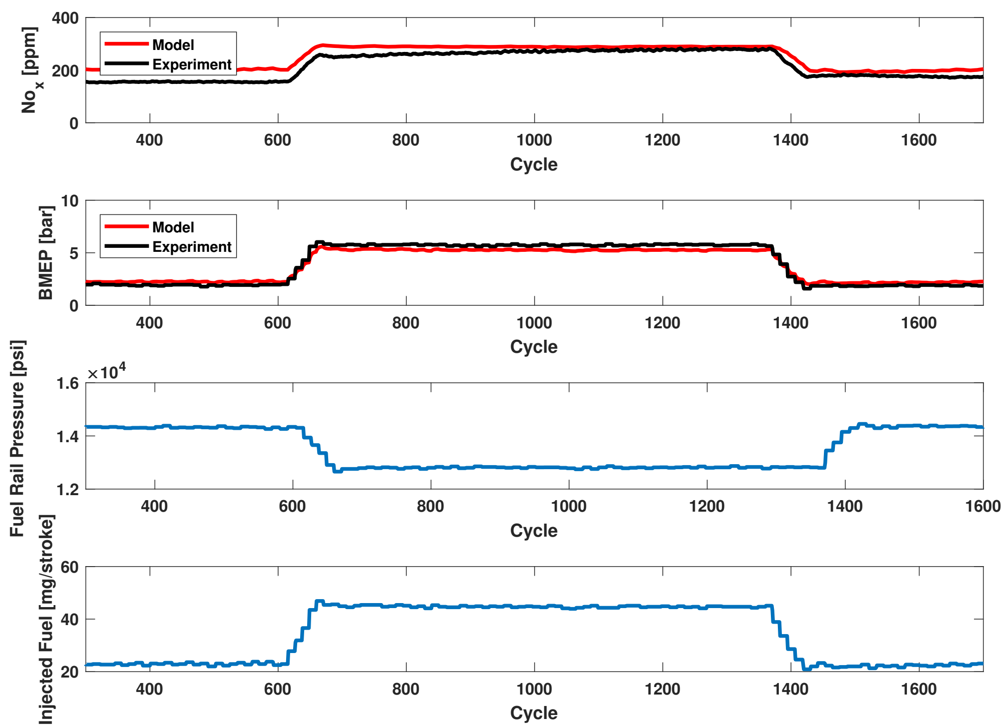

Fig. 3: NO_x and BMEP transient response of the engine control oriented model compared to measurement for input of injected fuel amount and rail pressure and measured NO_x and BMEP. Engine speed = 1500 rpm

5 Conclusions

A MIMO control oriented diesel engine NO_x emission and output BMEP model is developed based on the experimental data carried out on a on a 4.5L medium duty diesel engine. The engine NO_x emission is measured with a fast response electrochemical NO_x sensor at different engine operating conditions with engine speed between 1000 rpm to 2500 rpm and BMEP between 1.89 bar and 17.42 bar. The injected fuel amount, the injection rail pressure and the engine speed are considered as the model inputs. The model transient response to step changes of injection pressure and injected fuel amount is also studied in this work and the model accuracy is compared to the experimental engine transient response. The control oriented model transient response matches the experiments with maximum error of 16 % for NO_x and 17.5 % for BMEP.

The control oriented model is suitable for on board diagnostics and engine control with a fast-response NO_x sensor feedback [22].

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A Appendix

Table A1: Steady state NO_x model parameters

a_0	a_1	a_2	a_3
708.498	19.41075	- 1.627061	0.08590996
a_4	a_5	a_6	a_7
0.2677758	-3.494× 10^{-4}	- 1.925 × 10^{-6}	1.413 × 10^{-3}

Table A2: Steady state BMEP model parameters

b_0	b_1	b_2
0.1755	-0.1982	1.277