

Model Predictive Control Approach for AFR Control during Lean NO_x Trap Regenerations

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ABSTRACT

This paper describes a diesel engine lean NO_x trap (LNT) regeneration air to fuel ratio (AFR) control system using a nonlinear model predictive control (NMPC) technique for simultaneous regeneration fuel penalty and overall tailpipe-out NO_x reductions. A physics-based and experimentally validated nonlinear LNT dynamic model was employed to construct the NMPC control algorithm, which dictates the AFR value during regenerations. Different choices of NMPC cost function were examined in terms of the impact on fuel penalty and total tailpipe NO_x slip amount. The cost function to achieve the best tradeoff between fuel penalty and tailpipe-out NO_x was selected based on physical insights into the LNT system NO_x and oxygen storage dynamics. The NMPC regeneration AFR control system was evaluated on a vehicle simulator cX-Emissions¹ with a 1.9L diesel engine model through the FTP75 driving cycle. Compared with the conventional LNT regeneration AFR control strategies such as a PID controller, 23.7% of regeneration fuel penalty reduction and 16% of tailpipe NO_x mass reduction were observed.

INTRODUCTION

Diesel engines possess noticeable advantages in terms of efficiency, reliability, and power density compared with gasoline counterparts. However, on the other hand,

diesel engine emission control, especially NO_x reduction, is much more challenging than that for gasoline engines. The lean burn characteristic of diesel engines is notably of higher NO_x emissions compared with gasoline stoichiometric engines. It is often difficult to achieve the increasingly stringent NO_x emission regulations by engine control and combustion improvement only. Catalytic aftertreatment systems have been introduced to significantly reduce the tailpipe emissions. Among a variety of selections, the most promising and commonly used NO_x aftertreatment systems are lean NO_x traps (LNT) for light-duty vehicles and selective catalytic reduction (SCR) for medium- and heavy-duty vehicles. In order to maintain the NO_x conversion efficiency for LNTs, rich exhaust gas so far is necessary to intermittently purge the stored NO_x in LNTs [1, 2].

The main LNT operation process can be described by two steps. The first step, named NO_x absorption, is where the LNT traps the emitted NO_x from the engine and stores it in solid state. Because the LNT storage capacity is finite, it has to be purged when the storage is full. The second step process is NO_x desorption, in which the stored NO_x is released to gaseous state, at the same time it is converted to N₂ by the available reductants (CO and HC). In this step, extra amounts of fuel is dosed upstream of LNT in order to generate a rich environment that is conducive to regeneration. After the regeneration is finished, LNT regains the NO_x adsorption capacity and starts trapping NO_x. The LNTs were demonstrated to be able to convert more than 90% of NO_x emissions from the engine. However, a common concern about LNTs is the associated fuel penalty during

¹ cX-Emission is a vehicle emission simulator developed by Center for Automotive Research at OSU. The simulator was validated by experimental data.

regeneration that can lead to higher overall vehicle fuel consumption. The tradeoff between LNT regeneration fuel penalty and tailpipe NO_x slip has been a major challenge for LNT control.

Different LNT regeneration control strategies aimed at fuel penalty and emission reductions have been studied by researchers in both industry and academia [2-7]. For instance, in [2], the author developed an in-cylinder no-post-injection rich-lean combustion switching control for LNT regeneration purpose for fuel penalty reduction. Nakagawa et al. proposed a model-based approach to control the rich pulse timing and its duration for LNT regeneration [3]. A LNT model adaptation mechanism was used to adjust the rich pulse timing and duration to reduce tailpipe emissions. In [5], the authors studied an adaptive LNT purge control strategy, in which on-line adaptation for the LNT capacity and LNT-in NO_x flow rate models was conducted with the assistance provided by an exhaust gas oxygen sensor. The estimated LNT capacity usage percentage was then used to trigger the LNT regeneration events. Due to the highly nonlinear LNT regeneration efficiency, the AFR profile during regeneration is also of importance for fuel penalty and emission reductions. However, less attention has been devoted to this aspect. In this paper, we specifically study the near-optimal AFR control during LNT regeneration using a nonlinear model predictive control approach. Based on a simulated case study using an experimentally validated LNT model, it was observed that the NMPC AFR controller can reduce the regeneration fuel penalty up to 23.7% and the tailpipe NO_x by 16% compared with a conventional LNT regeneration AFR control strategy such as PID control.

The rest of this paper is organized as follows. In Section II, a physics-based LNT model and its experimental validation are briefly described. The NMPC regeneration AFR control approach is presented in Section III followed by simulation results and analyses. Conclusive remarks and future research directions are summarized in Section V.

LNT MODEL AND VALIDATION

In order to exercise NMPC, a mathematical model that fairly accurately describes the dynamics of the physical process while still maintaining affordable computational burden is essential. Figure 1 shows the block diagram of the LNT model used in this paper [12]. The inputs are the exhaust-gas mass flow rate and temperature, together with the composition of the feed gas, for which eight species are considered (CO_2 , H_2O , O_2 , N_2 , NO , CO , C_nH_m , SO_2). The outputs are the outlet gas temperature (assumed equal to the catalyst brick temperature) as well as the outlet mixture composition.

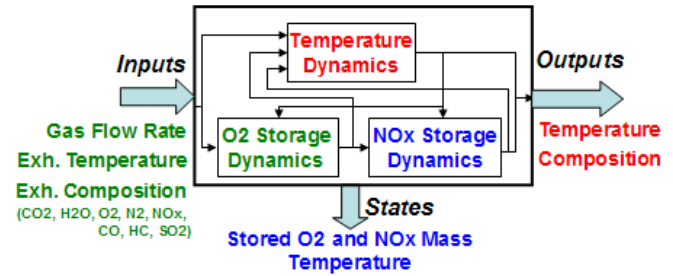


Figure 1 Structure of the LNT model

The input/output characterization of the LNT model results from the interaction of three subsystems, namely an oxygen-storage dynamics model, a NO_x -storage dynamics model, and a model for the catalyst-temperature dynamics. The equations of the above subsystems, originally derived in [11], will be briefly summarized in this section. Interested readers can refer [11, 12] for details regarding the models.

OXYGEN STORAGE/RELEASE DYNAMICS

The model characterizing the oxygen storage and release dynamics is based on application of the continuity equation to the oxygen stored (in solid state) and to the oxygen present in the exhaust stream (gas phase), as in the following:

$$\begin{aligned} \frac{dM_{O_2}}{dt} &= C_{O_2} \frac{dx_1}{dt} = r_{O_2,stor} - r_{O_2,rel}, \\ \dot{m}_{O_2,out} &= \dot{m}_{O_2,in} - r_{O_2,stor} + r_{O_2,rel}, \end{aligned} \quad (1)$$

where C_{O_2} is the oxygen storage capacity and x_1 represents the catalyst oxygen fill ratio.

The oxygen storage and release rate, $r_{O_2,stor}$ and $r_{O_2,rel}$, can be described as:

$$\begin{aligned} r_{O_2,stor} &= k_{st} \left(\frac{1-e^{\alpha x_1}}{e^{\alpha}-1} + 1 \right) \dot{m}_{O_2,in}, \\ r_{O_2,rel} &= k_{rel} \left(\frac{1-e^{\beta x_1}}{e^{\beta}-1} + 1 \right) (\dot{m}_{CO} + \dot{m}_{HC})_{in}, \end{aligned} \quad (2)$$

where k_{st} and k_{rel} are the two empirical constants, and the multipliers α and β are linear functions of the catalyst temperature T .

It is important to observe that the model assumes the O_2 storage and release phenomenon prevails over the NO_x ones. In particular, if storage sites are available in the catalyst and the engine exhaust gas is lean, the oxygen will be stored before the NO_x . Conversely, if oxygen is stored in the LNT and the feed gas is rich, the reductants present will release and combine with the oxygen first and then the NO_x .

NO_x STORAGE / RELEASE DYNAMICS

The dynamics associated with the NO_x adsorption and release are described using a similar approach. Due to the fact that various parameters depend on inputs and states such as temperature, inlet mass flow rate, and catalyst fill ratio, the model equations developed are highly nonlinear:

$$\begin{aligned} \frac{dM_{NO_x}}{dt} &= C_{NO_x} \frac{dx_2}{dt} = r_{NO_x,stor} - r_{NO_x,rel}, \\ \dot{m}_{NO_x,out} &= \dot{m}_{NO_x,in} - r_{NO_x,stor} + r_{NO_x,rel}. \end{aligned} \quad (3)$$

Here x_2 is the LNT NO_x fill ratio and C_{NO_x} is the LNT NO_x storage capacity. The NO_x storage and release rates can be expressed by:

$$\begin{aligned} r_{NO_x,stor} &= k_{st} \eta_c \left(\frac{1 - e^{\gamma x_2}}{e^{\gamma}} + 1 \right) \dot{m}_{NO_x,in}, \\ r_{NO_x,rel} &= k_{rel} \left(\frac{e^{-\phi x_2} - 1}{e^{-\phi} - 1} \right) (\dot{m}_{CO} + \dot{m}_{HC})_{in}^*, \end{aligned} \quad (4)$$

where the multiplier γ depends linearly on the catalyst temperature. The efficiency term η_c accounts for the oxygen available to promote the NO_x storage reactions.

The trap regeneration is modeled considering two sequential phases. First, the stored NO_x is released from the trap in the presence of rich exhaust gas conditions. After that, the released NO_x is converted to N_2 by reductants. The conversion process depends on the catalyst temperature, fill ratio, and concentration of CO and hydrocarbons available in the mixture. Therefore, the mass rate of NO_x conversion to N_2 can be defined as:

$$r_{NO_x,conv} = k_{conv} \eta_{conv} r_{NO_x,rel}, \quad (5)$$

where the conversion efficiency is a function that includes the effects of the mentioned variables,

$$\eta_{conv} = \left(\frac{e^{\lambda x} - e^{\lambda}}{1 - e^{\lambda}} \right) \left(\frac{e^{-\sigma u} - 1}{e^{-\sigma} - 1} \right), \quad (6)$$

where λ is a linear function of the catalyst temperature and u represents the mass of equivalent reductants ($CO + C_n H_m$) that is required to convert the released NO_x , normalized to the corresponding stoichiometric value [11, 17, 23].

CATALYST TEMPERATURE DYNAMICS

The LNT temperature dynamics can be characterized by applying the energy conservation principle to the catalyst brick, assuming its temperature equal to the gas contained in the system. This simplification can be justified by the small diameter of the passages inside the catalyst, which reduces the average gas velocity. With this assumption, the energy balance yields:

$$\frac{dT}{dt} = \frac{1}{M_{cat} c_{cat}} [m_{gas} c_p (T_{in} - T) - \dot{Q}_{reac} - \dot{Q}_{ht}] \quad (7)$$

where $M_{cat} c_{cat}$ denotes the catalyst thermal capacity, c_p is the specific heat of the feed gas, and $\dot{Q}_{ht}$ is relative to the heat losses, mainly due to convection. The term $\dot{Q}_{reac}$ represents the total reaction enthalpy produced by the release and conversion of the stored O_2 and NO_x approximated from the results of an exotherm analysis of a LNT catalyst [20].

LNT MODEL VALIDATION

The LNT model developed has been validated with experimental data obtained on a 4-cylinder Diesel engine equipped with an aftertreatment system consisting of a dual lean NO_x traps and a bypass regeneration system [23].

The inputs to the model are the engine air mass flow rate, the air/fuel ratio, and the exhaust gas temperature. The inlet composition, in particular the NO_x concentration, was determined by measurements (in particular, a NO_x analyzer was available) and by elementary mass balances based on equilibrium reactions [18]. The composition of the exhaust gas (in particular, the concentrations of CO_2 , CO , O_2 and hydrocarbons) is implemented in the model as a function of the air mass flow rate and air/fuel ratio, based on the steady-state engine emission maps. The composition during rich operations was estimated from experimental data obtained on a Diesel fuel reformer for regeneration of LNT systems [13]. Figure 2 and Figure 3 show the profiles of the main model inputs, namely engine MAF, AFR and NO_x concentration in the exhaust, as obtained in the experimental tests.

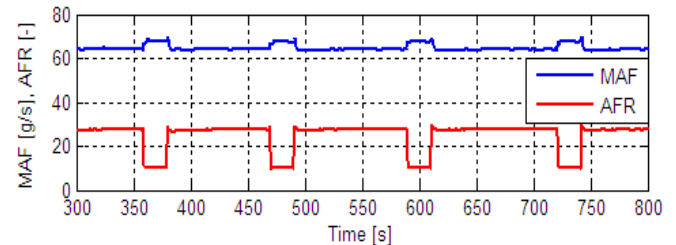


Figure 2: MAF and AFR at the LNT inlet

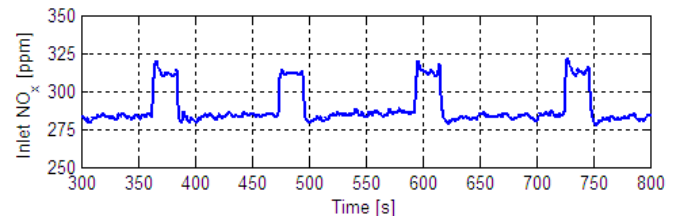


Figure 3: NO_x concentration at the LNT inlet