

Adaptive NO_x Soft Sensor for Aftertreatment of Diesel Engines

Shinichi Ishizuka^{1,a}, Itsuro Kajiwara¹, Junichi Sato², Yoshifumi Hanamura²

¹ Hokkaido University in St. Louis, Japan
² ISUZU Motors Limited, Japan

Abstract. As environmental regulations become stricter, diesel engines must become cleaner. Hence, in addition to combustion control, aftertreatment of the exhaust is important to reduce emissions involving NO_x and diesel particulate matter (DPM). NO_x is eliminated by a chemical reaction with ammonia, which is generated by hydrolysis of injected urea. Although the NO_x concentration must be accurately detected to ensure the appropriate quantity of urea is used, the response speed of the current NO_x sensor is too slow to follow transient operations. In this paper, a new NO_x adaptive soft sensor for aftertreatment of diesel engines is described, and its basic characteristics are confirmed via an engine bench test.

1 Introduction

Diesel engines are becoming cleaner in order to adapt to the increasingly stringent environmental requirements. Both combustion control and aftertreatment of the exhaust are critical to reduce emissions involving NO_x and diesel particulate matter (DPM). NO_x is eliminated via a chemical reaction with ammonia, which is generated by hydrolysis of urea. To adequately control the urea concentration, the NO_x concentration must be precisely measured. Because the response speed of the typical NO_x sensor is insufficient to follow transient operations, the NO_x concentration is estimated by a soft sensor, which calculates the variables that affect NO_x. However, the calculated and actual NO_x concentrations may differ. In this paper, an overview of the aftertreatment of diesel engines is provided at first. Then our adaptive soft sensor is described. Finally, the basic characteristics of the proposed sensor are confirmed via a bench experiment.

2 Aftertreatment of a diesel engine

Figure 1 shows the aftertreatment system of a diesel engine where blue and red indicate the air intake and exhaust systems, respectively. DPM is trapped and accumulated by a diesel particulate filter (DPF) and can be burned off when the accumulation reaches a certain level. NO_x is decomposed into water and nitrogen by selective catalytic reduction (SCR) at the appropriate temperature to accelerate the chemical reaction. In SCR, urea is injected and is subsequently hydrolyzed into ammonia and carbon dioxide. The ammonia then renders NO_x harmless by reducing it to water and nitrogen via the following chemical reactions

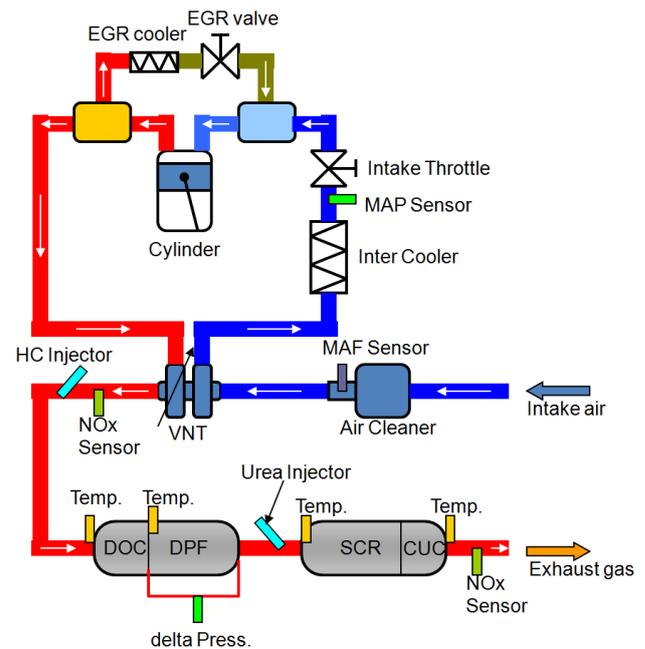
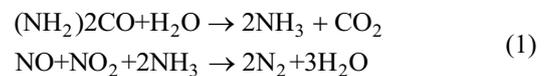


Figure 1. Aftertreatment system of a diesel engine.

The amount of injected urea must be controlled to correspond to the NO_x concentration. An insufficient urea concentration results in incomplete NO_x processing, whereas too much urea causes harmful ammonia to leak to the outside. Because the NO_x sensor response is too slow to detect the NO_x concentration transiently, it is estimated by a calculation. Herein a NO_x sensor device that measures the actual NO_x concentration is called a

^a Corresponding author: ishizuka@cybernet.co.jp

"NO_x hard sensor", while a sensor that calculates the NO_x concentration from other factors is called a "NO_x soft sensor". In the conventional method, a NO_x hard sensor is used during stationary operations, but it is switched to a NO_x soft sensor during transient operations. In this paper, an adaptive NO_x soft sensor method, which is compensated by a NO_x hard sensor, is proposed.

3 NO_x soft sensor

3.1 Basic composition

A typical soft sensor employs either a just-in-time model [1] or a neural network-based [2] method. However, these methods are not model based and the factors that influence NO_x are indistinct. From the viewpoint of practical calibrations, a soft sensor should be structured so that the effect of each factor can be tuned independently and simultaneously. In this study, an experiment-based soft sensor model is used. Figure 2 shows the NO_x soft sensor scheme where the dashed red and solid blue lines denote parameters and variables, respectively. The NO_x soft sensor calculates the NO_x concentration as shown in Equation 2:

$$\psi_{NO_x} = \psi_{NO_x,ref} \cdot C_{O_2} \cdot C_{SOI} \cdot C_{RP} \cdot C_{T_{cool}} \cdot C_{T_{inm}} \quad (2)$$

where ψ_{NO_x} is the NO_x concentration as a mole fraction. The terms on the right-hand side affect NO_x, and the subscripts denote

- O₂*: O₂ concentration
- SOI*: Main injection timing
- RP*: Rail pressure
- T_{cool}*: Temperature of the cooling water
- T_{inm}*: Temperature of the intake manifold

Each term is described as

$$\begin{cases} C_{O_2} = \left(\frac{\psi_{O_2,cyl}}{\psi_{O_2,cyl,ref}} \right)^{\alpha_{O_2}} \\ C_{SOI} = e^{\alpha_{SOI} \cdot (\theta_{SOI} - \theta_{SOI,ref})} \\ C_{RP} = \{ \alpha_{RP} \cdot (p_{rail} - p_{rail,ref}) + 1 \} \\ C_{T_{cool}} = \{ \alpha_{T_{cool}} \cdot (T_{cool} - T_{cool,ref}) + 1 \} \\ C_{T_{inm}} = \left(\frac{T_{inm}}{T_{inm,ref}} \right)^{\alpha_{T_{inm}}} \end{cases} \quad (3)$$

In Equations (1) and (2), the variables with subscript the *ref* denote the nominal values under normal atmospheric conditions, while the variables with *a** indicate calibration factors when the operation condition differs from the standard condition (i.e., the variable does not affect the calculated value when the state is the same as the normal condition). Each nominal value (*ref*) and calibration factor (*a**) can be plotted to form a 2D map using engine speed and fuel injection quantity as the parameters.

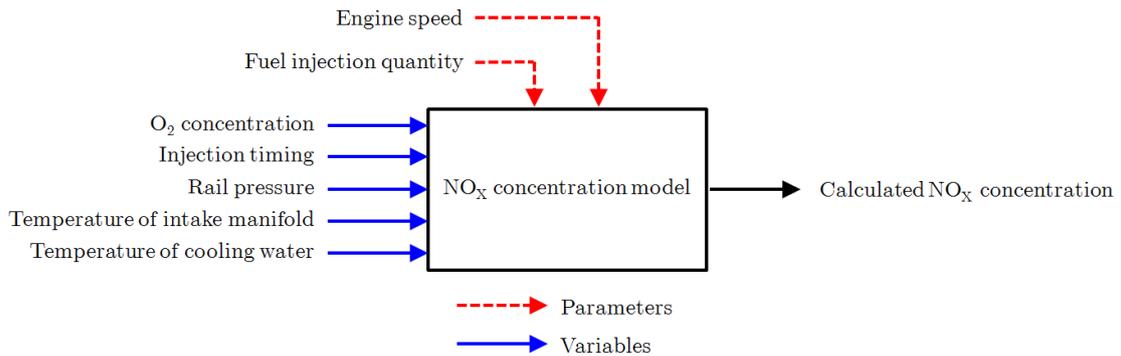


Figure 2. Scheme of the NO_x soft sensor.

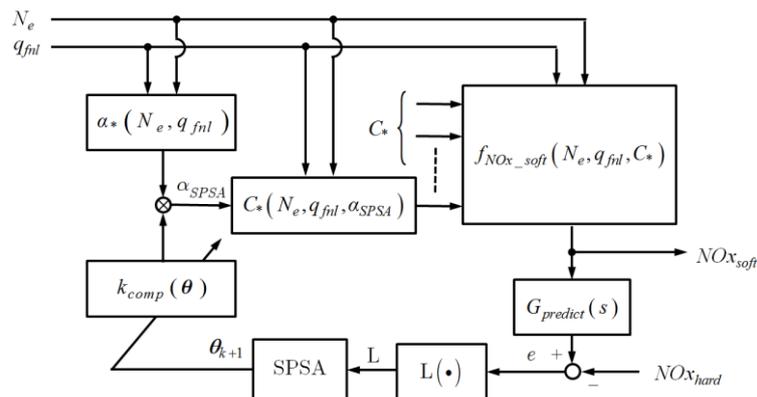


Figure 3. Composition of the adaptive NO_x soft sensor.

3.2 Adaptive NO_x soft sensor

To eliminate the offset in a NO_x soft sensor, the gain of the offset is compensated compared with the NO_x hard sensor value. Figure 3 diagrams the proposed adaptive NO_x soft sensor. SPSA stands for the simultaneous perturbation stochastic approximation, which was originally proposed by Spall in 1987 [3] as a very efficient optimization technique. An online adaptive tuning method using a modified SPSA is proposed by the authors [4], [5]. In this study, our modified SPSA is utilized. The NO_x soft sensor value $NO_{x,soft}$ is derived from predictor $G_{predict}$, which predicts the behavior of the NO_x hard sensor dynamics. $G_{predict}$ is calculated from loss function L and modified gain k_{comp} . Each term C_* is tuned simultaneously and continuously by the modified SPSA.

3.3 SPSA algorithm

The modified SPSA is briefly described here. For more details, refer to [4]. The estimated value of the loss function gradient is expressed as

$$\hat{\theta}_{k+1} = \hat{\theta}_k - a_k \hat{g}_k(\hat{\theta}_k) \quad (4)$$

where $\hat{\theta}_k$ is the estimated optimization parameter vector, a_k is the update gain, and $\hat{g}_k(\hat{\theta}_k)$ is the estimated value of the gradient for the parameter, which is described as

$$\hat{g}_k \hat{\theta}_k = \frac{L \hat{\theta}_k + c_k \Delta_k}{c_k} \begin{Bmatrix} \Delta_{k1}^{-1} \\ \Delta_{k2}^{-1} \\ \vdots \\ \Delta_{kp}^{-1} \end{Bmatrix} \quad (5)$$

where L is the loss function, c_k is a coefficient with a minute positive value to adjust the perturbation, and Δ_k is a bounded p -dimensional random number vector with a symmetric distribution when the expected value is 0 and no element can ever be zero (e.g., a Bernoulli distribution). For example, Equation (6) shows a random number vector expressed as a random binary sequence

$$\Delta_k = \{1, -1, -1, 1, -1, 1, 1, \dots\}^T \quad (6)$$

By choosing a_k and c_k appropriately and iterating Equation (4) recursively, the estimated optimal parameters converge to an optimal value as a stationary system. The standard SPSA evaluates the loss function twice by perturbing all the tuning parameters simultaneously. In this case, a one-time evaluation SPSA [6] is used. The sum of the squared error is used as the loss function.

4 Experiment

4.1 Engine bench

The adaptive NO_x soft sensor algorithm was modeled with Simulink and downloaded to a rapid controller prototyping environment. The diesel engine was for a

medium truck with a displacement of about 5,200 cc. Table 1 shows the specifications, and Figure 4 shows the engine bench. In Equation (3), the nominal variables with the *ref* subscript and calibration variables a_* are tuned for the experimental engine. Generally, an engine's characteristics change during operation and due to aging. To reproduce these situations, each calibration map changes 1.5 times (i.e., the calibration map contains some errors and the operation conditions are altered as shown in Table 2).

Table 1. Engine specifications.

Type	Direct injection, DOHC, IC turbo
Displacement	5193 cc
Compression ratio	15.5
Maximum power	140 kW / 2600 rpm
Maximum torque	510 Nm / 1600 rpm
Regulation	Euro 6



Figure 4. Engine bench.

Table 2. Operation conditions

Changing item	Notes
EGR valve	Half of the nominal amount
Injection timing	2 degree retard of the crank angle
Rail pressure	-30 MPa

4.2 Test pattern

The test was carried out at the middle and high engine speed points while changing the amount of fuel injection such that the load was changed stepwise. The upper plot in Figure 5 shows the test pattern. The blue and green lines indicate the engine speed trace and the change in the amount of fuel injection, respectively.

The lower plot in Figure 5 shows the NO_x concentration where black, green, blue, and red lines indicate the values measured by a hard sensor, a soft sensor without

calibration map error, a soft sensor with calibration map error, and an adaptive soft sensor with calibration map error. To make a direct comparison of the hard and soft sensors, the dynamics of each soft sensor response is compensated by the hard sensor delay. In the case of the soft sensor with calibration map error, the value deviates

significantly from the hard sensor. Although the error is slightly smaller in the case of the soft sensor without calibration map error, the error is still large. However, the proposed adaptive soft sensor can adapt to appropriately reduce the error.

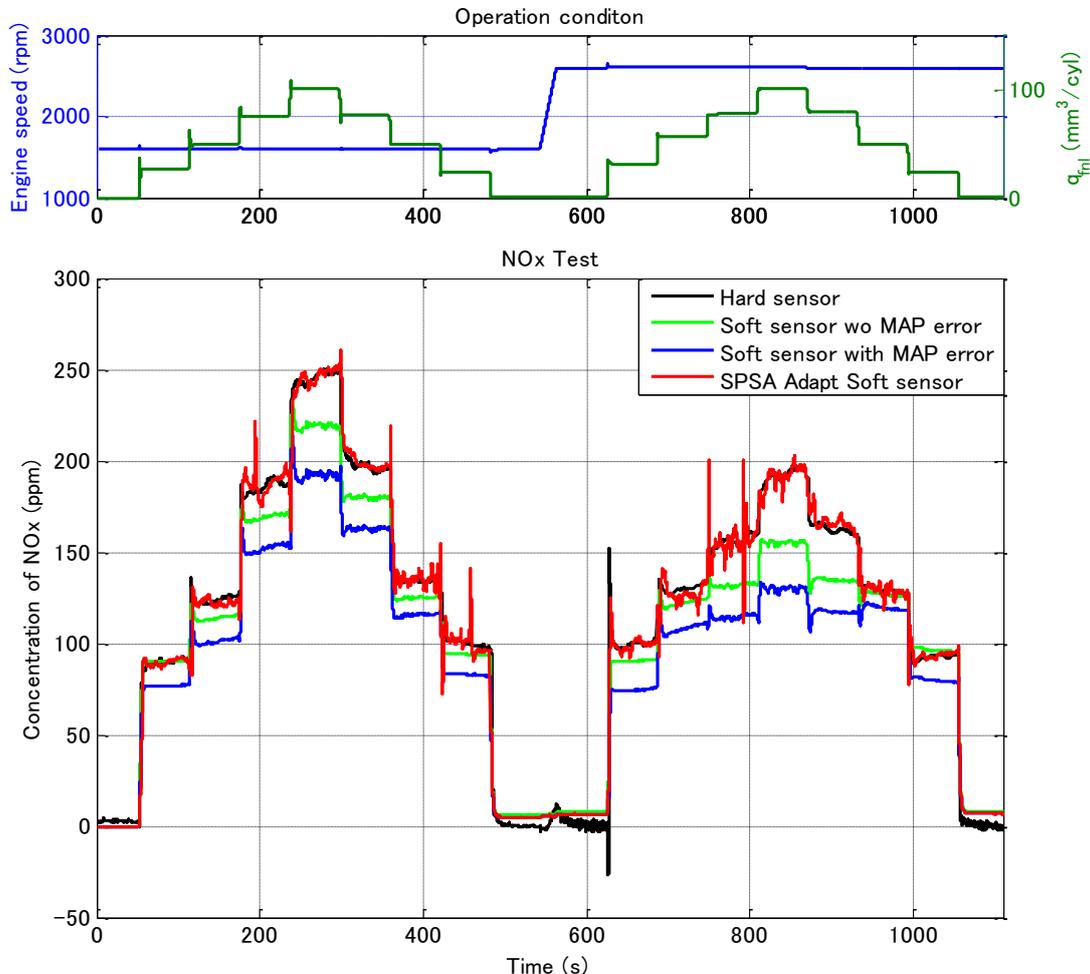


Figure 5. NO_x test results.

5 Summary

This study investigates the use of NO_x soft sensors in the aftertreatment of diesel engines. To eliminate the offset from the NO_x hard sensor, an adaptive NO_x soft sensor using SPSA is proposed. The most distinctive feature of the SPSA algorithm is that the calculation only requires that the loss function be determined once or twice per iteration regardless of the number of optimization parameters. In this study, the soft sensor model has five calibration terms, which are simultaneously updated and tuned using SPSA. The adaptability of the proposed method is confirmed using a stepwise engine bench test. Even if the condition differs significantly from the standard condition, the proposed method adapts appropriately. In the future, it is planned to investigate the proposed method under transient conditions like a world harmonized transient cycle (WHTC).

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