

Determining Three-Way Catalyst Age Using Differential Lambda Signal Response

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ABSTRACT

The duration over which a three way catalyst (TWC) maintains proper functionality during lambda excursions is critically impacted by aging, which affects its oxygen storage capacity (OSC). As such, emissions control strategies, which strive to maintain post TWC air-to-fuel ratios at the stoichiometric value, will benefit from an accurate estimation of TWC age. To this end, this investigation examines a method of TWC age estimation suitable for real-world transient operation. Experimental results are harvested from an instrumented test vehicle equipped with a two-brick TWC during operation on a chassis dynamometer. Four differently aged TWCs are instrumented with wideband and switch-type Lambda sensors upstream (Pre TWC location), and downstream (Mid location) of first catalyst brick. The lambda measurements are utilized to create an age dependent time parameter, τ which is found to be predominantly a function of exhaust flow with lesser dependencies on both exhaust gas and catalyst brick temperatures. The proposed method for age estimation can distinguish between TWC of different ages during fuel cut events within a defined range of exhaust flows. Future compensation of exhaust gas temperature impacts on τ is expected to increase the confidence level of the TWC age estimation.

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INTRODUCTION

Increasingly stringent vehicle emission and fuel economy targets are a major stimulant in the development of innovative vehicle technology. The predominant emissions control device from gasoline combustion is the three way catalyst (TWC), which is most effective when the engine is operated at air-fuel ratios (λ) near stoichiometry. Current control strategies modulate λ about the stoichiometric point to selectively store and release oxygen from the ceria based washcoat, facilitating both the reduction and oxidation reactions necessary for complete emissions control. However, it is not desirable for the TWC to be either saturated or devoid of oxygen as some reaction pathways are selectively extinguish. Therefore, closed-loop control systems are necessary to maintain an internal TWC oxygen level for effective NO_x reduction and HC oxidation.

The ability of the catalyst to store and release oxygen is critical to proper TWC functionality. Oxygen storage capacity changes as the TWC ages [1]. Therefore, optimizing the commanded lambda profile to maximize fuel efficiency while maintaining emissions compliance requires accurate TWC age estimation. Several investigations have attempted to estimate TWC age [1, 2, 3, 4, 5, 6, 7]. Beulertz et al. [2] studied TWC aging with a microwave cavity perturbation. In this

study, electrical properties of the catalyst washcoat material were captured by microwave antennas and the resonance frequency was used as a direct index of catalyst aging. In [3, 4], the difference between CO-adsorbed and O₂-adsorbed, as measured by gas analyzer equipment, was used to calculate OSC. These methods are expensive, time-consuming and involve laboratory grade equipment. Hence, they cannot be used for on-vehicle OSC estimation.

Ingram and Surnilla [5], successfully estimated oxygen storage capacity by using the response of wideband lambda sensors at pre and post TWC locations. However their study was limited by sensor characteristics as the water gas shift reaction affected the lambda sensor readings and had to be corrected before estimating the oxygen storage capacity. A similar approach was used in [6] where the oxygen storage capacity was found to be independent of the gas stream oxygen concentration and the efficiencies for NO_x and HC reduction decreased with both age and fuel sulphur level. Miyamoto et al. [7], showed that OSC: i) depends on catalyst type, ii) is drastically reduced by excessive heat and chemical poisoning, and iii) varies substantially depending on catalyst temperature.

In the present study, a technique is developed to estimate the catalyst age without explicitly calculating the actual oxygen storage capacity, but by utilizing the differential response of lambda sensors mounted upstream and downstream of the TWC. The newly proposed method can be deployed on a vehicle as a map-based algorithm relying on exhaust flow, exhaust temperature and catalyst temperature measurement inputs and whose output is fed directly to the engine control unit. The paper first introduces the experimental setup and procedures. Next, the time parameter τ is defined along with factors affecting its values. Third, τ variation with age is shown along with TWC age estimation results.

EXPERIMENTAL TEST SETUP

Experiments are conducted on a vehicle with a 3.6L V6 port fuel injected (PFI) gasoline engine via a chassis dynamometer. Open loop and closed loop control is enacted via an ETAS INCA ETK system. Details of the catalyst and experimental instrumentation are provided in the following.

A. Aged Three Way Catalytic Converters

The TWCs used in the experiments are production-style, close-coupled two-brick catalysts. The TWCs were made of washcoated cordierite structures of different ages, as shown in [Table 1](#). The basic specifications of the TWC are listed in the [Table 2](#).

Table 1. Catalyst history with respect to miles driven

Catalyst	Aging Process	Distance (1000 Miles)
Stock	On-road driving	20
Threshold	Engine Dyno aged with rapid aging cycle	150

Table 2. Geometric and structural specifications of the TWC used in this study

Specifications	Brick 1
Length (mm)	68
Volume (L)	0.597
Cell density (cell/in ²)	400

B. Instrumentation

[Figure 1](#) shows the TWC instrumentation, including the O₂ sensors and thermocouple layout. While there are two bricks in the TWC setup, this study focuses on only Brick 1. Oxygen concentrations are measured using both wide band lambda sensors and switch-type lambda sensors before and after the first brick, denoted as “pre” and “mid” locations, respectively. Exhaust gas temperature is also measured at the pre and mid TWC locations using k-type thermocouples. Catalyst brick temperature is measured via a k-type thermocouple inserted into the brick such that its measurement junction is located along the exhaust flow center-line.

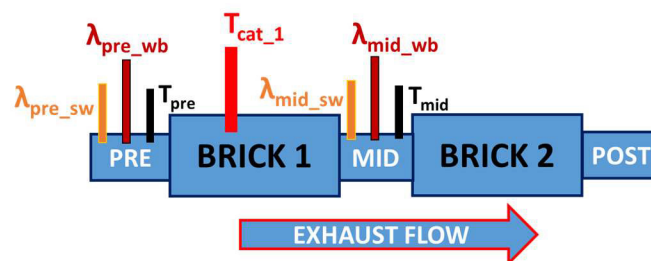


Figure 1. TWC lambda and temperature sensor layout

C. Design of Experiments

The mid-location wide band lambda sensor (λ_{mid_wb}) fluctuations increase in frequency with increasing age [1, 5] due to reducing OSC. As such, the time differential between upstream and downstream lambda responses holds potential for real time TWC age adjustment and subsequent operational alteration.

During real-world operation, rich to lean lambda excursions are achieved during throttle tip-out fuel-cuts; whereas lean to rich excursions occur as the vehicle rewets the oxygen-saturated TWC via rich fueling prior to expediently resume normal operation when the fuel cut terminates. To induce these lambda excursions for this study, a steady cruising speed corresponding to the desired exhaust mass flow rate is obtained prior to cancellation of the cruise control. Fuel cut engine operation followed as the vehicle coasts to idle while remaining in gear. [Figure 2](#) exemplifies the response of lambda sensors during these fuel-cut events. This procedure was utilized at several exhaust mass flow rates during the fuel-cutoff coast events, as shown in [Table 3](#). The measurement location of the tabulated values is indicated on subsequent figures with a red dot.

Table 3. Engine test conditions

Vehicle Cruise Speed [MPH]	Exhaust Mass Flow Rate [g/s]
50	3.48
60	3.85
70	4.12
80	5.10
90	5.56

As seen in the upper plot of [Figure 2](#), during a fuel cut event, the wide band lambda sensors first swing rich of stoichiometry because the engine throttle cuts air flow before the PFI injection strategy reacts and demands a fuel cut-off. In this engine, the fuel cut-off coast is executed in a stepwise fashion. As such, fuel injection is sequentially ceased two cylinders at a time. In this manner, the lambda control system attempts prevent TWC oxygen saturation during the initial phase of the fuel shutoff event and either avoid or reduce the magnitude of subsequent TWC rewetting enrichment. Once a complete fuel cut is observed, defined as the deactivation of all cylinders, the wide band lambda sensors saturate at a value of 1.25 ([Figure 2](#) upper plot) and switch type sensors reads 0.0 volts ([Figure 2](#) lower plot).

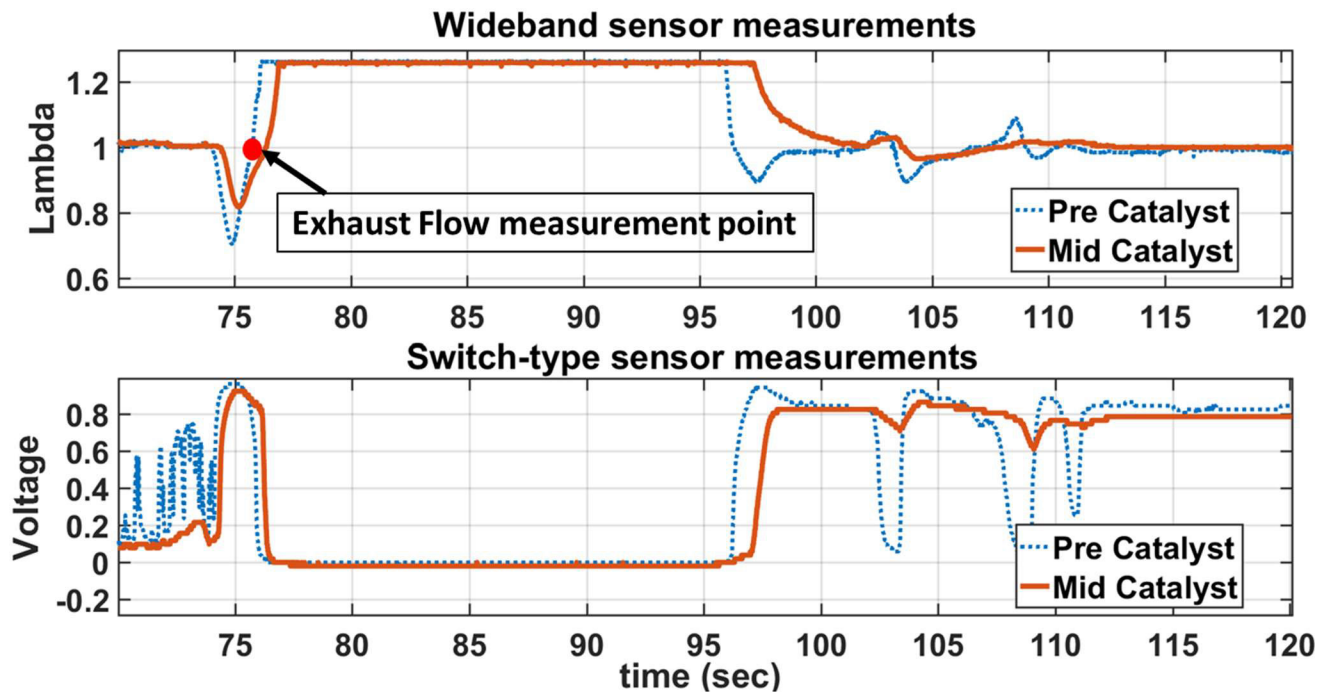


Figure 2. Response of wideband (top) and switch type (bottom) O_2 sensors to a fuel cut event at 60 mph for the "Stock" Catalyst

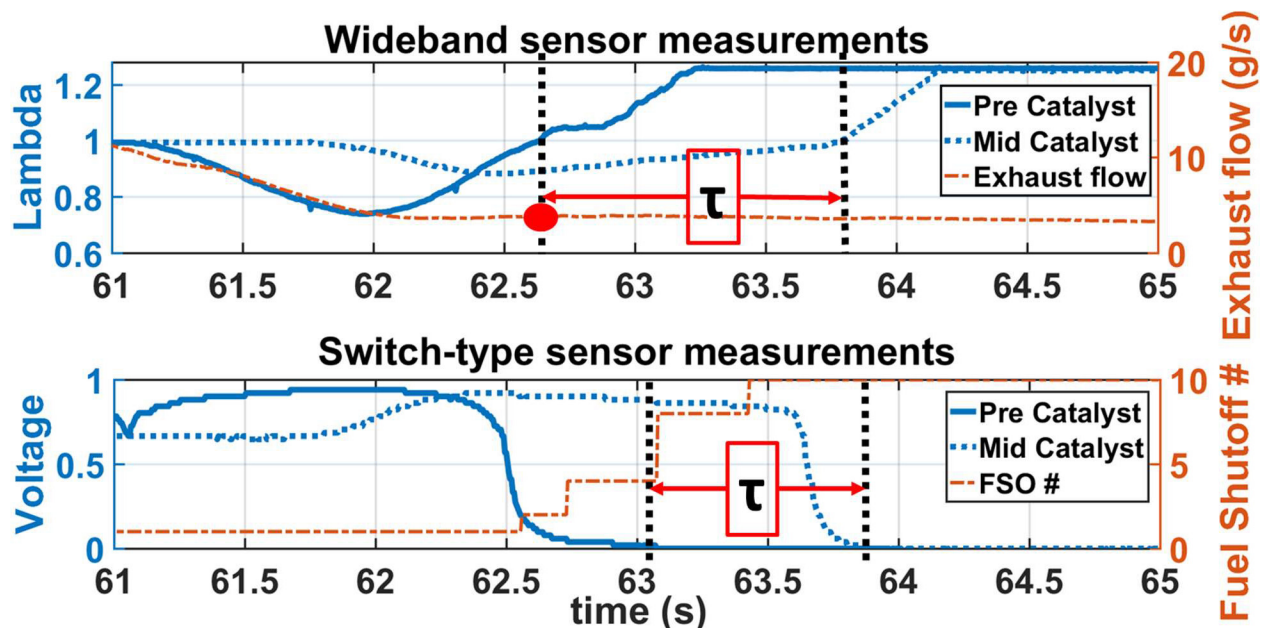


Figure 3. Response of wideband (top) and switch type (bottom) O_2 sensors and ECU variables to a fuel cut event @60 mph for a Stock Catalyst

TWC AGE INDICATION

For TWC age monitoring, a time variable, τ is defined as time difference, in seconds, between pre and mid lambda measurements, as shown in Figure 3. The nature of the time differential depends on the lambda sensor type. For wide band lambda sensors, the time difference is measured between when the respective O_2 sensors reach stoichiometry. For switch-type lambda sensors, τ is the time difference between when the pre and mid O_2 sensors read 0.0 Volts.

Since τ is a differential measurement between two lambda sensors separated by the catalyst brick, τ is a function of: the oxygen flowing in the exhaust stream; the ability of the TWC brick to absorb that oxygen (OSC); and the reactivity of the TWC, which itself is a function of brick temperature, exhaust temperature and lambda. Since age impacts TWC OSC, τ can indirectly quantify TWC age

A. τ Measurement Methodology

There are two opportunities within a fuel-cut event during which τ can be calculated, namely the rich-to-lean and subsequent lean-to-rich lambda transitions. Both transition types are shown in Figure 4