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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, $\boldsymbol{\tau}$ 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 wash-coat, 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 NOx 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 NOx 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 O_2 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.

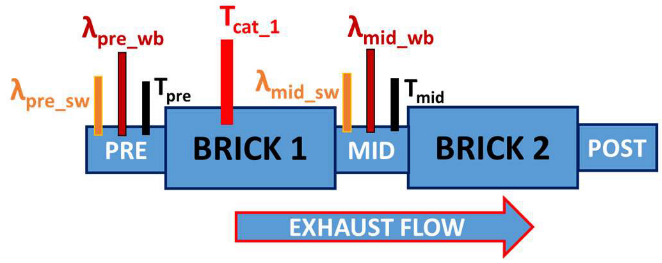

Figure 1. TWC lambda and temperature sensor layout

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).

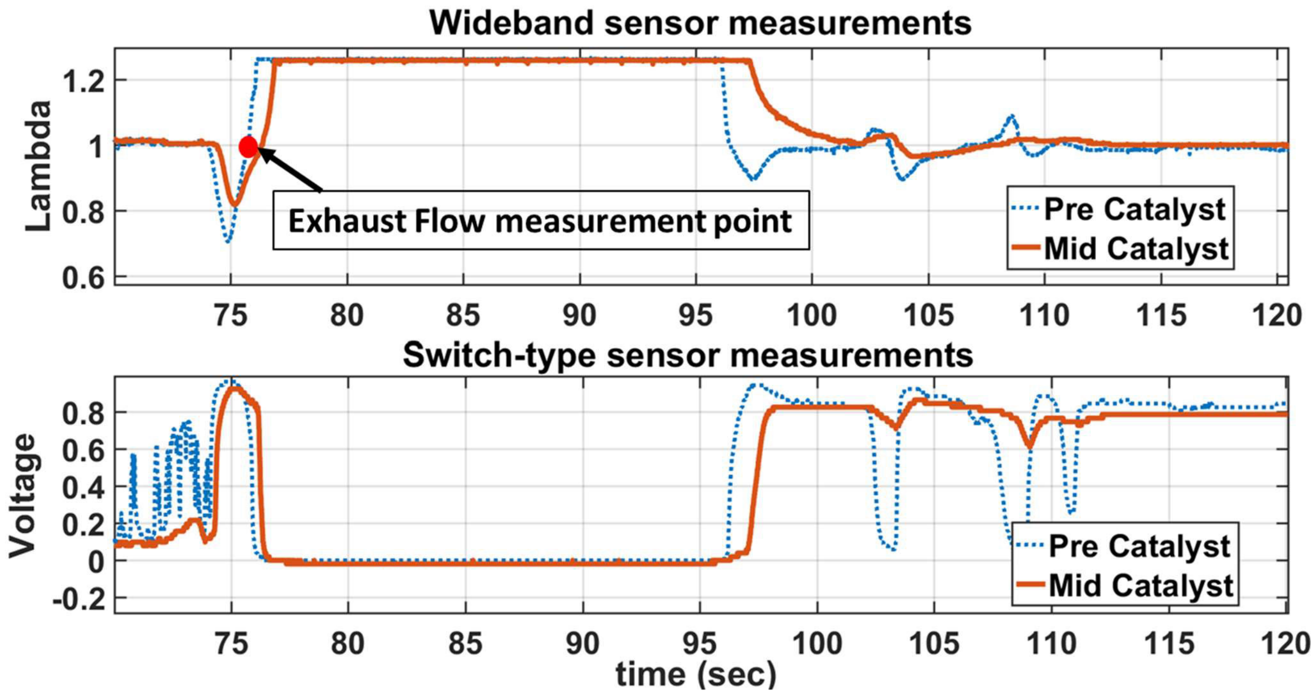

Figure 2. Response of wideband (top) and switch type (bottom) O_2 sensors to a fuel cut event at 60 mph for the “Stock” Catalyst

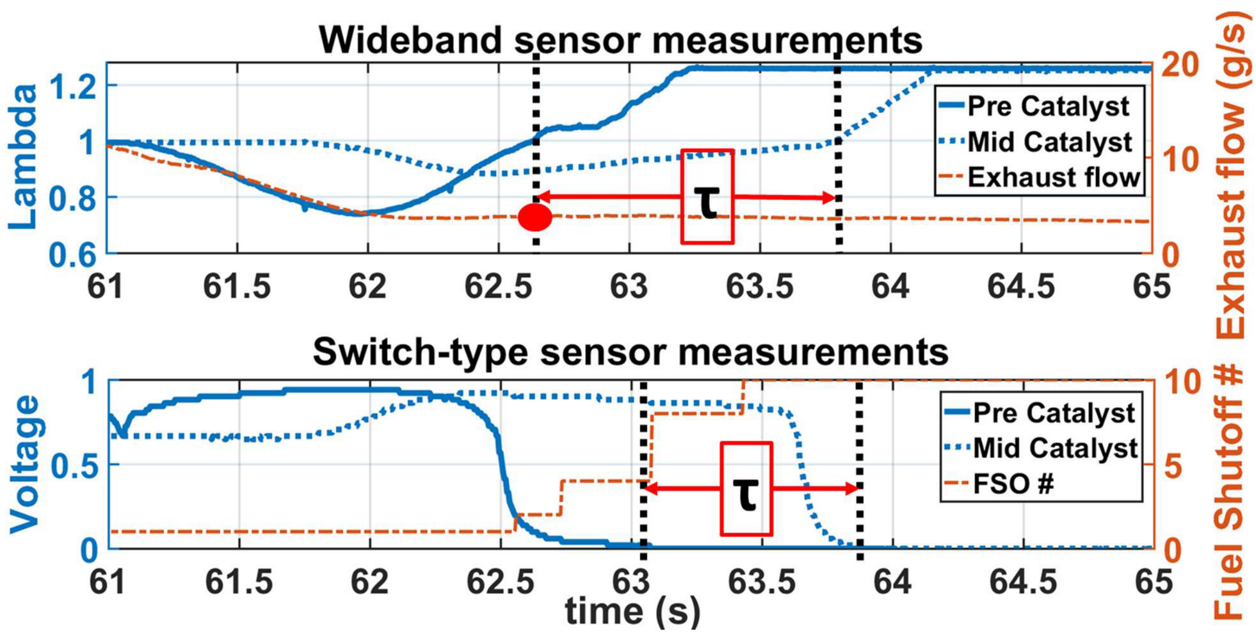

Figure 3. Response of wideband (top) and switch type (bottom) O_2 sensors and ECU variables to a fuel cut event @60 mph for a Stock Catalyst

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.

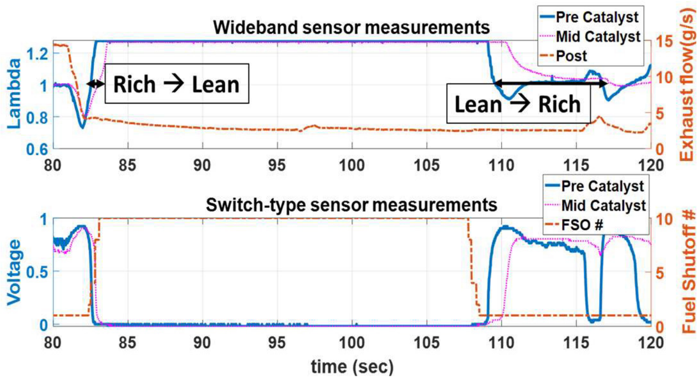

Figure 4. Response of wideband (top) O_2 sensors showing possible τ methodology and switch type (bottom) O_2 sensors with ECU variables to a fuel cut event @ 60mph utilizing the “Stock” Catlayst

As seen from the top graph in figure 4, exhaust mass flow can vary during the lean to rich transition due to gear shifts, complicating the τ calculation in practical applications. However, during the rich to lean transition, the exhaust mass flow remains relatively constant. Therefore, the rich to lean transition is the focus of the τ calculation herein.

B. Sensitivity of τ to Vehicle Lambda Control

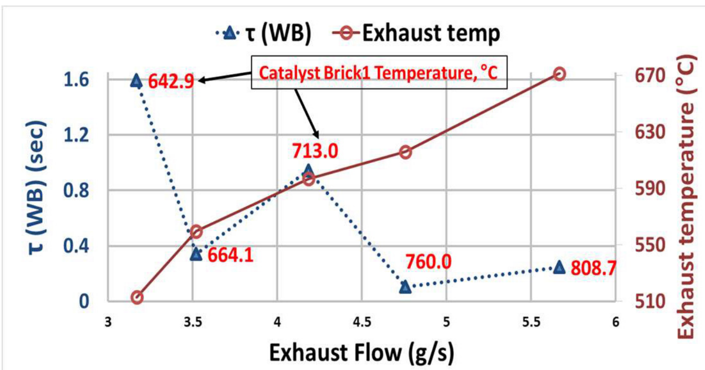

Figure 5. Closed loop test results for Wideband O_2 Sensor of a Stock catalyst at different exhaust flow as defined in table 3

Since τ represents the time until the TWC becomes saturated with oxygen, it is expected to vary inversely with the mass flow rate of oxygen. In addition, since TWC reactivity increases with exhaust and catalyst brick temperatures, τ will vary directly with these temperature impacts. The dominant τ trend is expected to follow the raw supply of oxygen to the brick via the exhaust mass flow during the tip-out event. As seen from figure 5, τ (blue triangles) does not monotonically decrease as exhaust mass flow rate increases.

In order to investigate this behavior, “fuel cutoff-coast” experiments were conducted with the vehicle’s lambda control in both open and closed loop modes, as shown in Figure 6. After the fuel cut event, lambda upstream of the TWC, “Lambda Pre”, swings from rich to lean in both control scenarios. However, the slope of the lambda response in closed loop control plateaus near stoichiometry. This behavior was attributed to the control system attempting to maintain stoichiometry during this fuel cut event. This closed loop behavior was found to create discrepancies in τ calculations at different vehicle speeds as the ability of the closed-loop control to maintain stoichiometric lambda during the tip-out varied across the testing matrix.

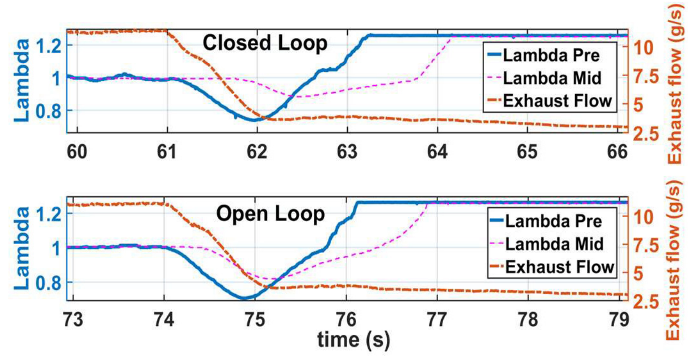

Figure 6. Wideband O2 sensor response comparison with closed loop (top) and open loop (bottom) lambda control during a tip out fuel cut event @ 60 mph utilizing the “Stock” Catalyst

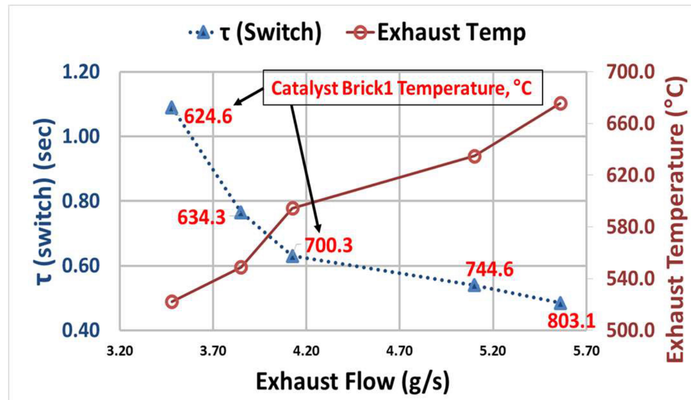

Figure 7. τ variation with Open Loop lambda control for Wideband O_2 sensors and the “Stock” catalyst

Figure 7 shows τ results from tip out fuel cut tests conducted at the same exhaust flow operating points during open loop operation (lambda control turned off). Note that the open loop experiments produce a τ trend which more closely follows intuition - a monotonic decrease of τ as exhaust mass flow rate (the flow rate of oxygen during the tip-out) is increased. Figure 8 shows τ calculated with switch type O2 sensors during the same tests. Note that the same τ trend persists regardless of the chosen lambda sensor type.

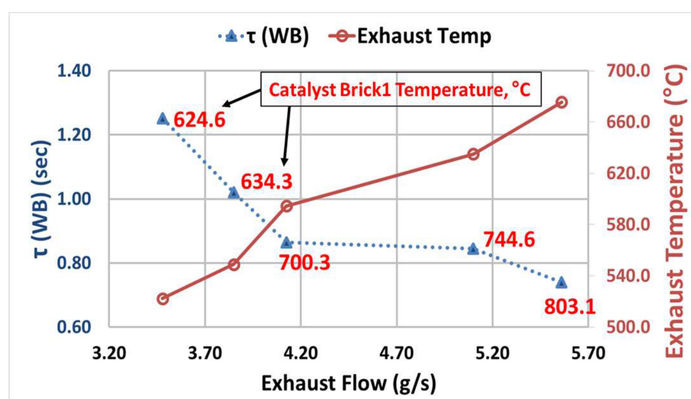

Figure 8. τ variation with Open Loop lambda control for Switch-type O2 sensor for a Stock Catalyst

C. τ Performance with Switch-type vs Wideband Lambda Sensors

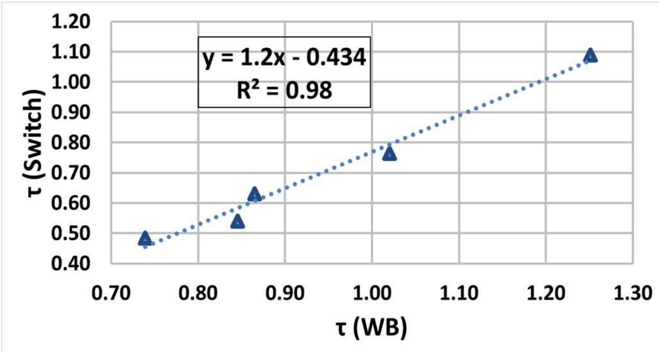

Figure 9. A linear transform exists between τ calculated through switch type lambda sensors and τ calculated via wide band lambda sensors during open loop control of Stock Catalyst

τ was simultaneously calculated based on the response of both wide-band and switch-type lambda sensors during each fuel-cut tip-out. The linear relationship between τ calculated from switch-type lambda sensors and τ calculated from wide band lambda sensors is shown in Figure 9. This result reveals that the two lambda sensor types are interchangeable for this analysis, adding to the real-world applicability of the τ methodology. A simple linear relationship can be used to transpose τ values between sensor types.

SENSITIVITY OF T TO OPERATIONAL PARAMETERS

Identical experimental tests were carried out with catalysts of two different ages. For this study, the two catalysts chosen span nearly the entire useful life spectrum. One catalyst has 20k miles (Stock) and the other is a 150k mile (Threshold) aged catalyst provided by the project's industrial partner. The pre tip-out cruise speeds in Table 3 were utilized to conduct testing at multiple exhaust (oxygen) mass flow rates. For each exhaust mass flow rate point, the tip-outs procedure was conducted three times. Although the tip-outs were conducted at the same vehicle speed, the three test repetitions produced slightly different oxygen mass flow rates, exhaust temperatures and catalyst brick temperatures during the fuel cut event.

A. τ vs Oxygen Mass Flow Rate

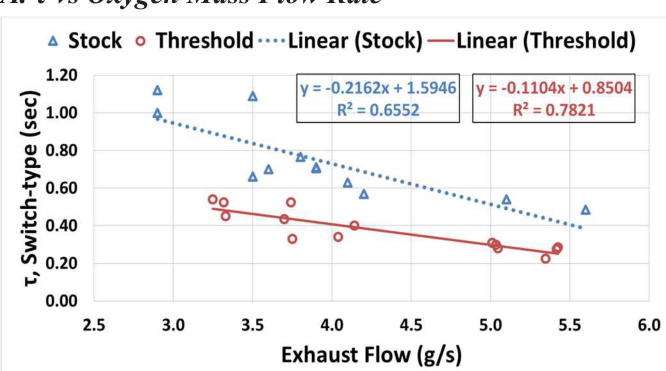

Figure 10. τ for two differently aged catalysts with respect to Oxygen mass flow rate. Also shown is the linear fit equation with its R-squared value.

The temperature and mass flow rate discrepancies were primarily attributed to the throttle's PID control gains which are a function of engine coolant temperature in addition to engine speed. While the test repetitions produced similar oxygen mass flow rates, dispersion in τ during these repetitions was attributed to the sensitivity of τ to exhaust gas and catalyst brick temperatures. Overall, with increasing oxygen mass flow rate, τ decreases, which was the expected behavior as shown in Figure 10.

B. τ vs Exhaust Gas and Catalyst Brick Temperature

Calculated τ results were also examined for sensitivity to both exhaust gas and catalyst brick temperatures as shown in Figures 11 and 12, respectively. While τ does exhibit weak inverse correlations to both exhaust gas and catalyst brick temperatures, τ is two orders of magnitude more sensitive to exhaust flow than either exhaust or catalyst temperature. However, τ loses sensitivity to all factors, (oxygen flow, exhaust temperature and brick temperature) as the catalyst ages. It should also be noted that the catalyst temperature in this study are well above the light-off temperatures and hence the impact of temperature is less significant compared to the oxygen flow.

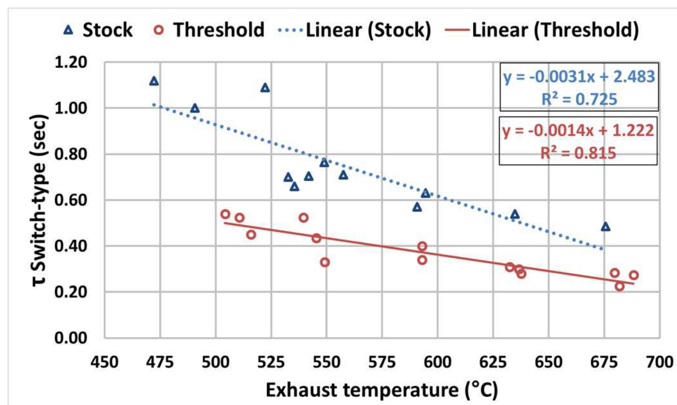

Figure 11. Variation of τ with respect to exhaust temperature. Also shown is the linear fit equation with its R-squared value.

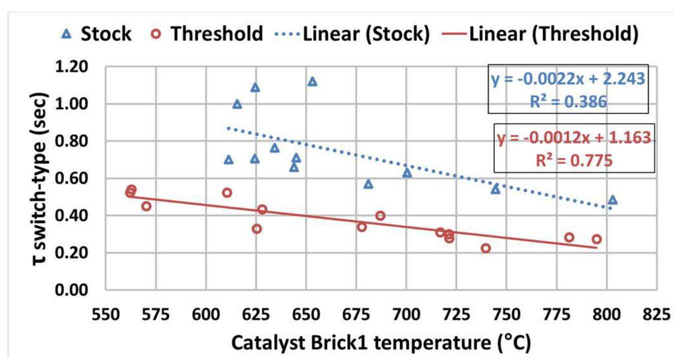

Figure 12. Variation of τ with respect to Catalyst brick1 Temperature. Also shown is the linear fit equation with its R-squared value.

TWC AGE ESTIMATION

In this study of catalyst age estimation, it is proposed that a linear model of τ can be defined which is a function of exhaust mass flow rate. Catalyst temperature and exhaust temperature are recognized as variables that may influence the fidelity of the age estimation results.

Statistically, catalyst brick and exhaust temperatures are the degrees of freedom that will define the margin of error for our proposed model. This margin of error is also dependent on the standard deviation of the collected data samples. Increased data sampling creates more accuracy and confidence in the fit. In this paper, for each exhaust flow, three sets of data were collected and the results are shown below.

Confidence Bound Calculations

To obtain the confidence boundaries on τ-based TWC age estimation, residuals between the trendline model and raw data points (delta between experimental and the trendline) were calculated as shown in the Figure 13.

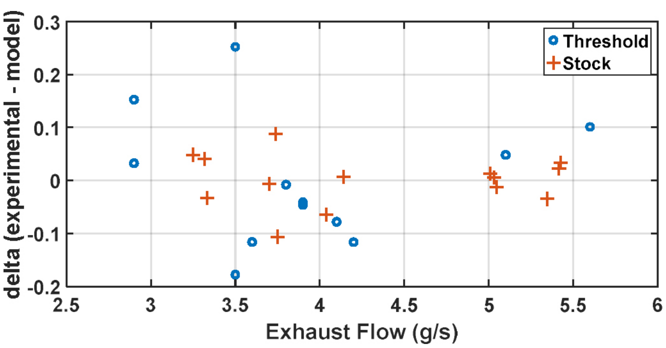

Figure 13. Residual (delta) between experimental values and the trendline

The overall standard deviation (STD) of the residuals were calculated to be 0.0493 and 0.124 for the threshold and stock TWC, respectively. If we assume that τ varies in a normal distribution about the trendline we can define

Margin of error = Critical value x Standard deviation of the statistic,

where the critical value is a factor used to compute the margin of error. Critical value (c) is confidence dependent [see appendix A], for a 50% confidence, c = 0.816; and for 95 %, c = 4.303

Confidence bounds = Model (trendline) +/- Margin of Error

While τ is a stronger function of oxygen flow than exhaust temperature, the trends for the TWC ages tested converge for higher exhaust flows, reducing the probability of successfully detecting TWC age. As such, a statistical evaluation of confidence was conducted to establish a range of oxygen flow conditions (during fuel cut operation) where τ can be used effectively for TWC age assessment. A possible age observation range was created as shown in Figure 14.

Also shown in Figure 14 are the 50% confidence bounds for each trend line; meaning, if a new observation is made for a given age, there is 50% chance that it will fall within the bounds. Utilizing 95% confidence bounds for the stock and threshold catalysts, shown in Figure 15, does not provide a usable region for TWC age identification with this data set.

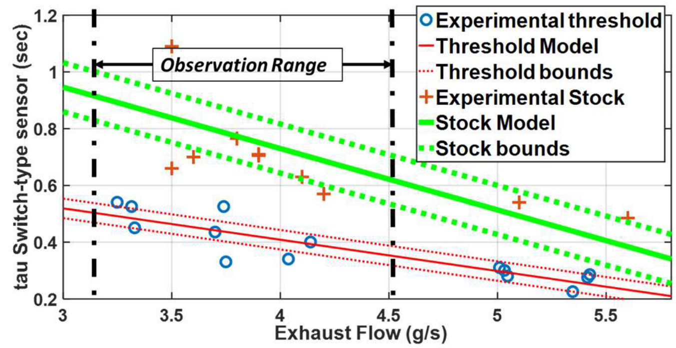

Figure 14. 50% confidence bounds for Stock Catalyst and Threshold Catalyst

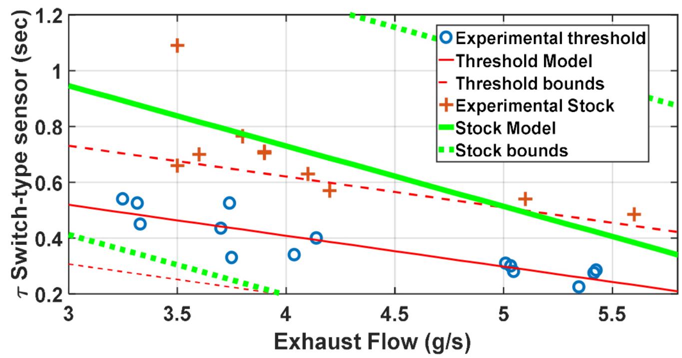

Figure 15. 95% Confidence bounds for Stock Catalyst and Threshold Catalyst

Thus, this age estimation methodology can currently determine whether the given catalyst is good (Green/Stock Catalyst) or aged (Threshold Catalyst) with 50% confidence. Currently, the method has usefulness for OBD detection of a damaged, defective, or non-functioning TWC. Implementing such a strategy for real time check would not involve a complex algorithm. Additionally, the accuracy of the τ-based age assessment method is expected to increase by isolating the age trend from the sensitivity of τ to exhaust and catalyst brick temperature trends. With these influences removed, the τ age methodology will be reassessed for discrete TWC age detection capabilities.

CONCLUSIONS

In the presented paper, a time dependent variable, τ was defined in order to estimate the aging of a TWC and following conclusions are drawn:

1. τ was found to be affected by the vehicle's lambda control and hence for practical application an open-loop event should be used for age estimation.
2. τ can be calculated via wide-band or switching lambda sensors, enhancing its utilization with cost effective sensor layouts. A linear trend was established as a transpose between switch-type and wide band lambda sensor τ calculations.

3. It was found that τ is predominantly dependent on exhaust mass flow rate (the flow of oxygen during the tipout). τ was orders of magnitude more sensitive to exhaust mass flow rate than either catalyst brick or exhaust temperature.
4. Implementation of confidence bounds to quantify between two age catalysts showed that the proposed method does provide a viable range of conditions for TWC age estimation with 50% confidence.

Future work towards the ability to eliminate the temperature dependence of τ will be useful in getting a more distinct trend with exhaust flow and catalyst age. This is expected to improve the age detection confidence interval.

REFERENCES

1. Sabatini, S., Kil, I., Hamilton, T., Wuttke, J. et al., "Characterization of Aging Effect on Three-Way Catalyst Oxygen Storage Dynamics," SAE Technical Paper 2016-01-0971, 2016, doi:10.4271/2016-01-0971
2. Beulertz, Gregor, Votsmeier Martin and Moos Ralf. “In operando detection of three-way catalyst aging by a microwave-based method: Initial studies.”Applied Sciences 5, no.3 (2015):174-186. Doi:10.3390/app5030174
3. Kallinen, Kauko, Suopanki Aslak, and Harkonen Matti.”Laboratory scale simulation of three-way catalyst engine ageing.” Catalysis today 100.3 (2005):223-228. Doi:10.1016/j.cattod.2004.09.057
4. Maunula T., Vakkilainen A., Lievonen A., Torkkell K. et al., ”Low Emission Three-way Catalyst and OSC Material Development for OBD Diagnostics,” SAE Technical Paper 1999-01-3625, 1999, doi:10.4271/19999-01-3625.
5. Ingram, G. and Surnilla, G., "On-line Oxygen Storage Capacity Estimation of a Catalyst," SAE Technical Paper 2003-01-1000, 2003, doi:10.4271/2003-01-1000.
6. Zhang Yuetao, Cheng Wai K., Massachusetts Institute of Technology. “Fuel Sulfur and Aging Effects on the Oxygen
7. Zhang, Y. and Cheng, W., "Fuel Sulfur and Aging Effects on the Oxygen Storage Capacity in Three-Way Catalytic Converters," SAE Technical Paper 2003-01-1874, 2003, doi:10.4271/2003-01-1874.
8. Miyamoto, K., Takebayashi, H., Ishihara, T., Kido, H. et al., "Measurement of Oxygen Storage Capacity of Three-Way Catalyst and Optimization of A/F Perturbation Control to Its Characteristics," SAE Technical Paper 2002-01-1094, 2002, doi:10.4271/2002-01-1094.
9. **Introduction to the Practice of Statistics** by Moore David S., McCabe George P., Craig Bruce A., Purdue University. W. H. Freeman and Company New York. 6th Edition

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DEFINITIONS/ABBREVIATIONS

TWC - Three-Way Catalytic Converter

PFI - Port Fuel Injected

τ - *tau*, age dependent time variable

WB - Wide-band

SW - Switch

STD - Standard Deviation

c - Critical Value

Appendix

In this study, we found that τ is a normal distribution with respect to oxygen flow/exhaust flow.

When the sampling distribution of the statistic is normal or nearly normal, the critical value (c) can be expressed as a t score. Table 2 was used to calculate the critical value. As shown in fig 10, 11 and 12, τ is primarily a function of exhaust flow. Therefore, in this study Catalyst temperature and Exhaust temperature are the two degrees of freedom (df) or variables that are allowed to change for the proposed τ model at a given exhaust flow.

From Table 2 (below), for confidence level of 50%, c = 0.816 and for confidence level of 95 %, c = 4.303

Table 2. *t* distribution critical values [9]

	Upper-tail probability *p*											
df	.25	.20	.15	.10	.05	.025	.02	.01	.005	.0025	.001	.0005
1	1.000	1.376	1.963	3.078	6.314	12.71	15.89	31.82	63.66	127.3	318.3	636.6
2	0.816	1.061	1.386	1.886	2.920	4.303	4.849	6.965	9.925	14.09	22.33	31.60
3	0.765	0.978	1.250	1.638	2.353	3.182	3.482	4.541	5.841	7.453	10.21	12.92
4	0.741	0.941	1.190	1.533	2.132	2.776	2.999	3.747	4.604	5.598	7.173	8.610
5	0.727	0.920	1.156	1.476	2.015	2.571	2.757	3.365	4.032	4.773	5.893	6.869
	50%	60%	70%	80%	90%	95%	96%	98%	99%	99.5%	99.8%	99.9%
	Confidence level *C*											