Strategy for calibration of On-board Diagnostics to meet future Indian Emission Regulations

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ABSTRACT

In view of the emission regulations becoming more stringent year by year, control and functionality of ECM is also becoming more and more complex. In future, regulations such as BS-VI, RDE, IUPR and CAFC etc. are coming. OBD being a part of emission regulation monitors the health of emission related components in the vehicle. Also, scope of OBD is expanding through introduction of OBD-I, OBD-II and IUPR.

Considering the future regulations, challenge is to minimize the risk of misdetection with minimum impact on emissions. Both misdetection and emissions are complementary to each other. So, a trade-off has to be optimized between them.

This paper describes how changes were made in the EMS calibration to ensure the robustness of catalyst diagnosis function with minimum effect on emissions. It also explains how this calibration was able to successfully distinguish between a deteriorated catalyst and a new catalyst.

INTRODUCTION

The rising global demand for reduction in air pollution has prompted the Indian government to enforce different emission regulations such as BS-VI, RDE, and IUPR etc. for the automobile industry. Progression of emission regulations in India is shown in Fig. 1.

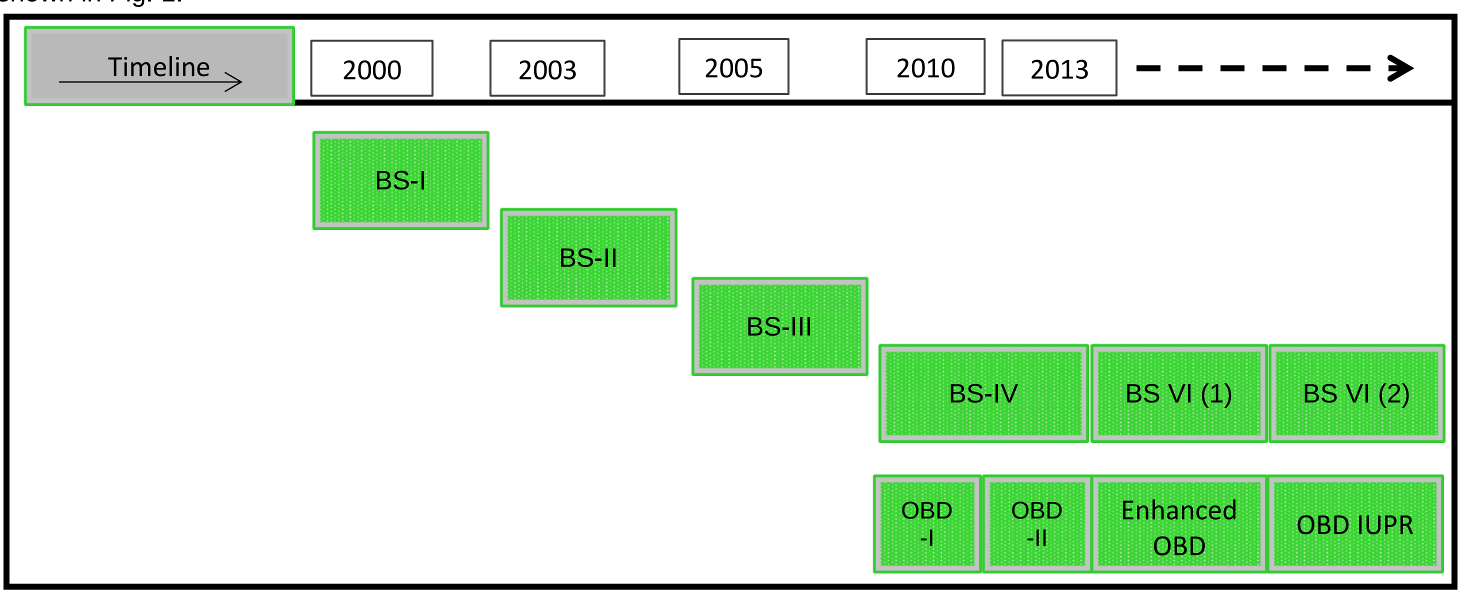

Figure 1: Progression of Emission Regulation in India

OBD-I came into effect in India in 2010. In OBD-I, only circuit discontinuity of sensors and actuators was monitored. In 2013, OBD-II was introduced in which monitoring of emission related components like catalyst, oxygen sensor was made mandatory.BS-VI (Bharat Stage Emission Standard) aims at drastic reduction in the emission limits. Also, RDE will be monitored. IUPR is coming after BS-VI, in which a certain minimum monitor ratio of 0.1 will be necessary for all emission related functions.

In sync with the upcoming regulations, a robust monitoring system is required which has minimum risk of misdetection. While minimizing the risk of misdetection, the emissions of the vehicle should not get impacted as there is a trade-off between them. Since engine & after-treatment devices work independently, the task of optimizing this trade-off becomes even more challenging. For this, a thorough understanding of both ECM logic and emission related components is required.

This paper illustrates the strategies of catalyst monitoring for three-way catalytic converters, challenges associated with it and optimization of the necessary trade-offs while doing calibration using case study of a bi-fuel vehicle.

THREE-WAY CATALYTIC CONVERTER FOR AUTOMOBILES

The automobile industry today is highly dependent on catalyst-based after-treatment technology due to tighter exhaust emission regulations.

Inside the three way converter, the following reactions take place:-

- Oxides of nitrogen are reduced into simple nitrogen and carbon-dioxide
- Hydrocarbons and carbon monoxide are oxidized to form water and carbon-dioxide

Catalyst operating efficiency is greatly affected by two factors:-

- Operating temperature
- Exhaust gas composition

The catalyst requires certain favorable conditions in order to perform its catalytic action. One of the most important of them is high temperature inside catalyst of up to 750 Fahrenheit.
In order for a catalyst to best clean up NOx, the A/F ratio must be richer than 14.7:1.However, NOx emissions from the engine are highest when the engine is lean. For the catalyst to best clean up CO & HC, the A/F ratio must be lean, but CO and HC is created when the mixture is rich. Three way catalysts overcome this problem by using cerium for oxygen storage. If the oxygen level is cycling slightly rich and slightly lean, cerium stores oxygen during lean phase and uses the same oxygen in rich phase for oxidizing harmful gases. As a result, HC, CO and NOx can be purified at the same time. In order to ensure controlled oxygen cycling, oxygen sensor feedback is used.

NEED TO DIAGNOSE THE CATALYTIC CONVERTER

The catalyst has a limited life as its efficiency decreases with age and use. The catalytic efficiency reduction occurs due to the following reasons:-

- Exposure of catalyst to high temperatures
- Presence of impurities such as lead compounds, sulfur and phosphorous in the fuel
- Physical damage by fracturing causing leaks to the atmosphere
- Thermal shocks

Hence, the harmful exhaust gases may enter the atmosphere without any treatment in a deteriorated catalyst. So, it becomes important to diagnose catalyst health throughout its lifecycle.

CHALLENGES TO CORRECTLY DIAGNOSE CATALYST HEALTH

1. LOW CATALYST TEMPERATURE- The catalyst needs to attain a certain minimum temperature viz. light-off temperature to reach its maximum efficiency as shown in Fig. 2 below. In India, infrastructure limitations such as poor road conditions, high traffic density etc. has led to a decrease in the average speed of the vehicle. So, the exhaust gas temperatures generally remain low. Low exhaust gas temperatures lead to more time in reaching the catalyst light-off temperature. Hence, the catalyst works at its full efficiency only after achieving its activation temperature under cold engine start conditions.

2. STEADY STATE OPERATION OF THE VEHICLE **–** In field, as running conditions for the vehicle are very dynamic, there is a continuous variation in the oxygen storage capacity of the catalyst. This is the reason why acceleration zone

has to be removed from the diagnosis area as shown below in Fig. 3. This leaves a very small diagnosis area for catalyst monitoring.

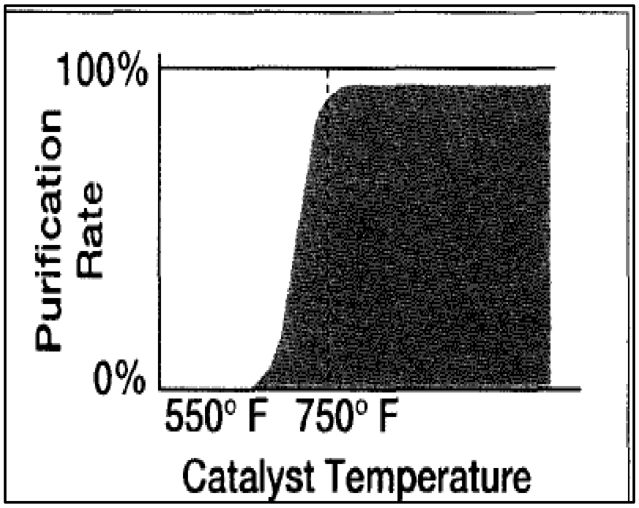

Figure 2: Catalyst efficiency variation with temperature

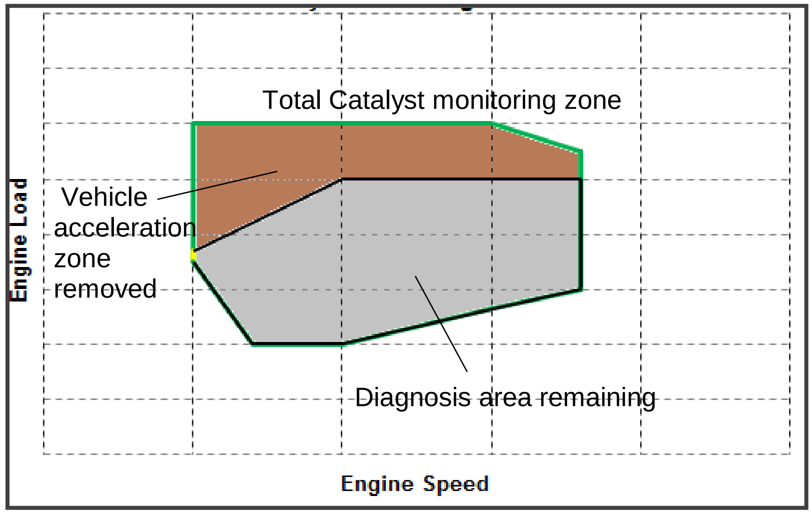

Figure 3: Identifying Catalyst Monitoring Area

3. BI-FUEL VEHICLE – As different fuels have different characteristics, the base engine emissions will be different. Hence, the catalyst configuration may differ which results in different OBD calibration.

4. CATALYST SIZE - With deterioration factors and emission limits getting more stringent, the size of the catalyst may need to be increased to get optimum emission performance with minimum cost impact. However, increase in catalyst size will require shift in strategy from passive to active as shown in Fig. 4

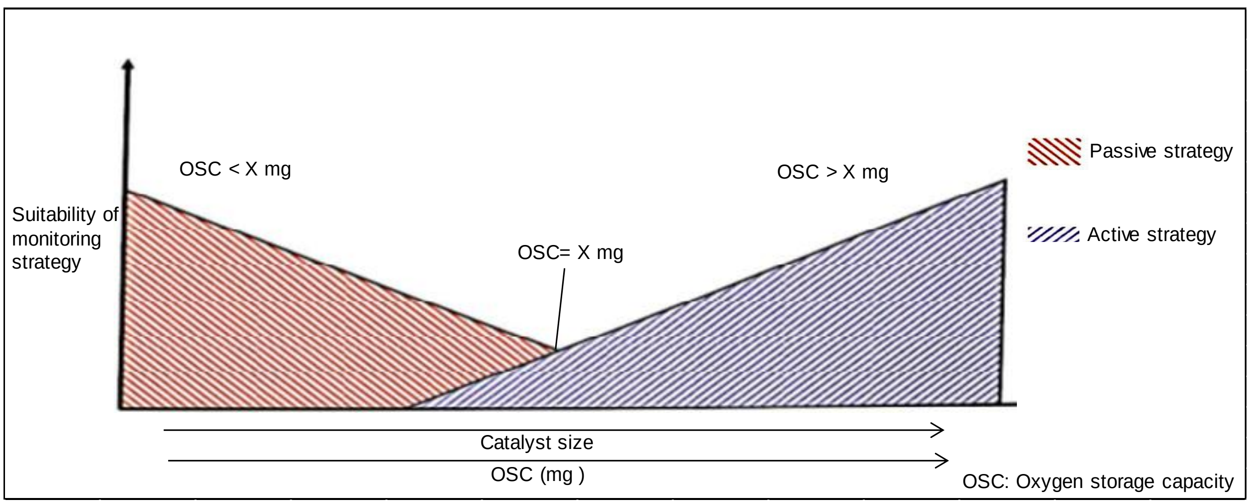

Figure 4: Suitability of monitoring strategy on the basis of catalyst size

USING OXYGEN SENSORS FOR DIAGNOSING CATALYST HEALTH

The OBDII system does not have the ability to measure CO, HC or NOx directly. The system uses oxygen sensors to measure the oxygen level before and after the converter. The difference between the before and after oxygen sensors is used during catalyst monitoring to get an indication of catalyst efficiency.

Ideally, a catalytic converter should promote complete conversion of harmful exhaust products into carbon-dioxide and water by using free oxygen available in the exhaust. Therefore, a very less amount of oxygen will be available at the oxygen sensor fixed after the catalytic converter, referred to as the rear oxygen sensor. In such conditions, the voltage output of rear oxygen sensor under steady state conditions tend to stabilize with little fluctuations in its output pattern. As the efficiency of the catalyst decreases, oxygen passes through the converter without any reaction leading to high fluctuations in rear oxygen sensor voltage. When the catalyst gets completely deteriorated the response pattern of the front oxygen sensor and rear oxygen sensor becomes almost similar. The difference in the voltage pattern of the two sensors between normal and deteriorated catalyst is shown in Fig. 5.

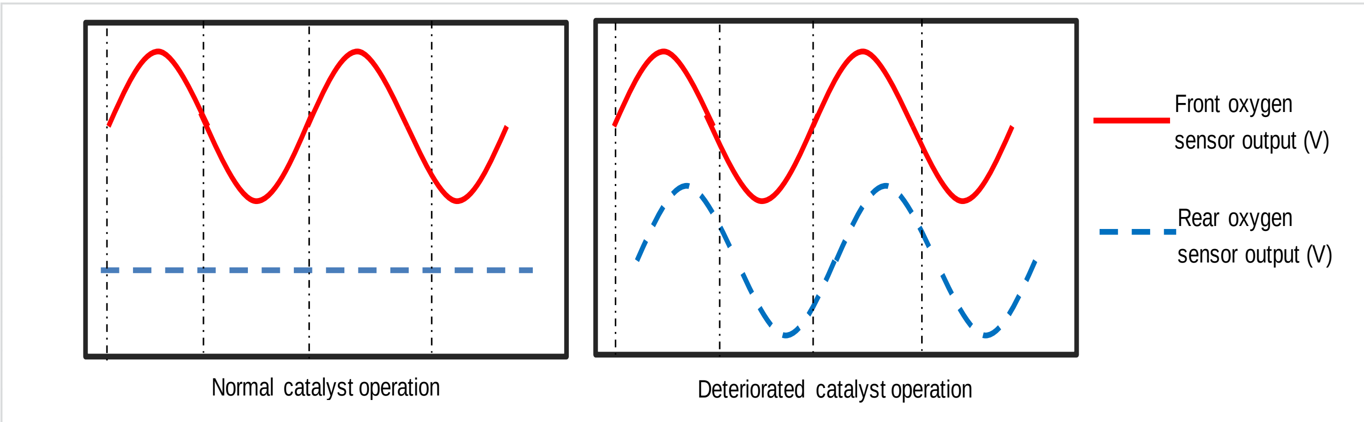

Figure 5: Variation of front and rear oxygen sensors

Although there are a number of methods for diagnosing catalyst health using oxygen sensors, two of the most commonly used methods are-

1. Active Method
2. Passive Method

Active method – It uses one lambda sensor upstream of the catalytic converter and one switching oxygen sensor downstream of the catalytic converter to calculate oxygen storage capacity of catalyst.

In this method, oxygen storage capacity (OSC) of the catalyst is measured during transition from rich to lean mixture. The lambda sensor helps in precise measurement of the air-fuel mixture. Although the methodology followed by different manufacturers for oxygen storage calculation may vary, the basic concept remains the same. One example of this method for catalyst monitoring is explained below in Fig. 6:-

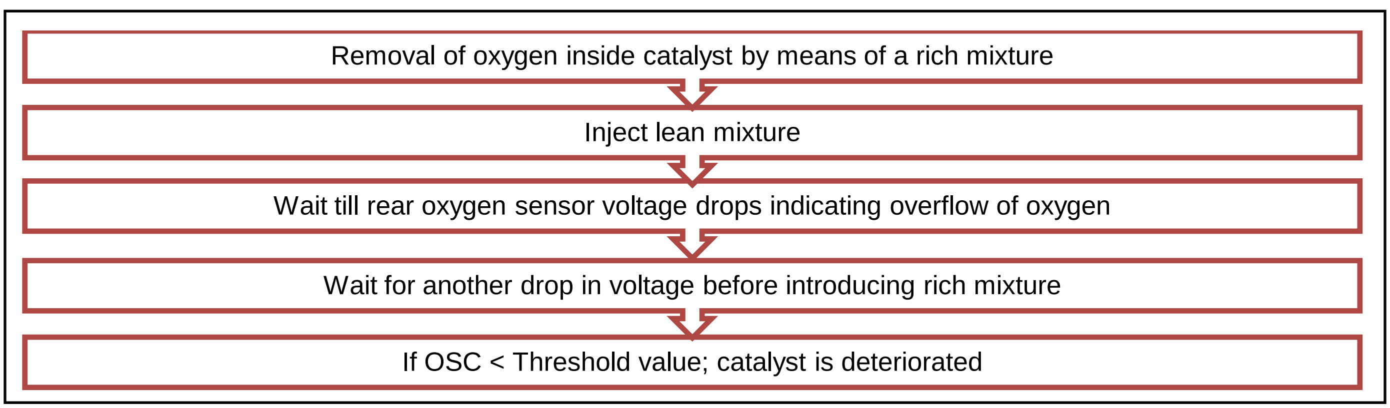

Figure 6: Catalyst Monitoring using active method

Passive method – It uses two switching oxygen sensors upstream and downstream of the catalytic converter to calculate oxygen storage time.

In this method, the catalyst uses the delay time between front and rear oxygen sensor signal to calculate its oxygen storage time in milliseconds. Larger delay time indicates good condition of catalytic converter (high oxygen storage capacity) and small delay time indicates vice versa. During catalyst diagnosis, a feedback period adjustment delay is introduced to increase the target feedback period calculated from front oxygen sensor response. This feedback period adjustment delay is calibrated such that the normal and deteriorated catalyst gets differentiated by EMS. The value of this adjustment delay is added in rich/lean judgment delay time so that the feedback period is increased. The introduction of feedback delay and calculation of the oxygen storage time has been explained in the Fig. 7:-

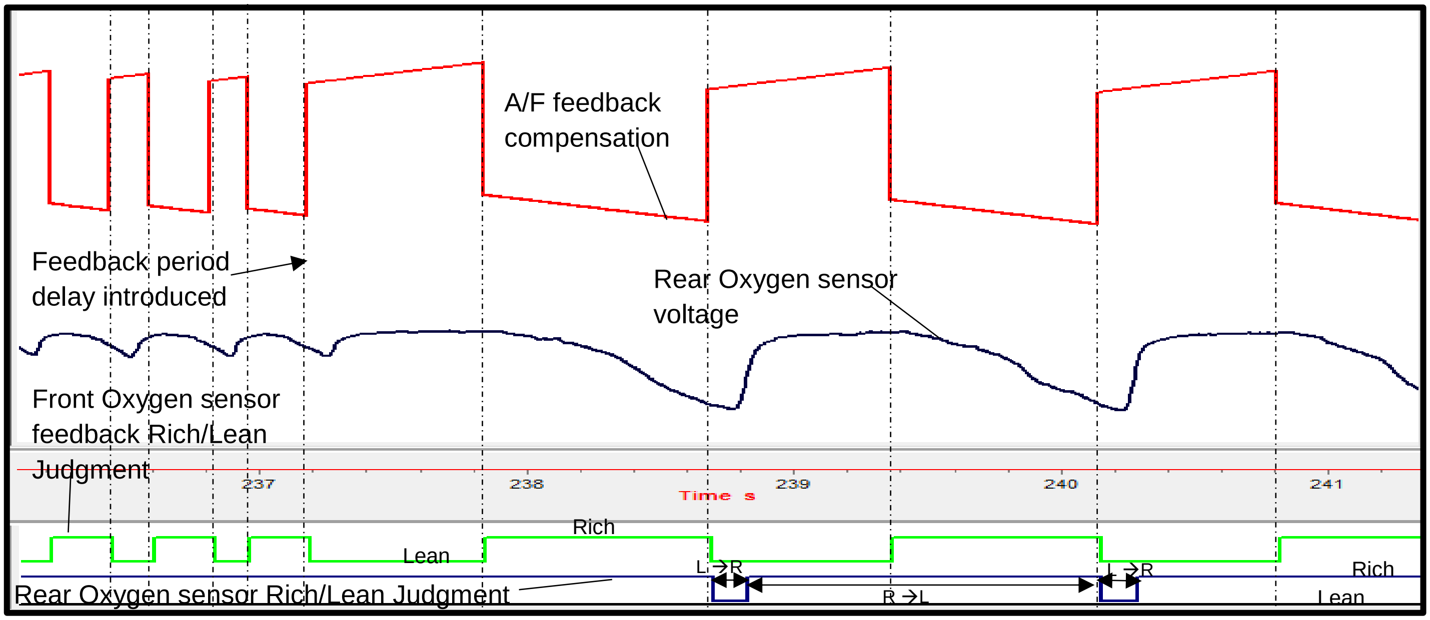

Figure 7: Introduction of feedback delay for catalyst monitoring

Oxygen storage time is calculated as the sum of following two parameters:-

- The moment lean mixture is injected in the cylinder (indicated by air fuel feedback) to the moment rear oxygen sensor indicates lean mixture (R→L time)
- The moment rich mixture is injected in the cylinder (indicated by air fuel feedback) to the moment rear oxygen sensor indicates rich mixture. (L→R time)

This time taken is divided by 2 to get the final time in milliseconds. If this value is less than the threshold value, then the catalyst is detected as deteriorated.

CATALYST MONITORING CALIBRATION FOR A BI-FUEL VEHICLE USING PASSIVE METHOD

One of the most important calibrations for catalyst monitoring is air-fuel ratio feedback calibration.
At any point during feedback execution condition, the A/F ratio feedback compensation amount is calculated as:
Total feedback compensation = Proportional gain (P-gain) + Integral gain (I-gain)
For catalyst deterioration monitoring, both these terms are different from normal feedback operation and hence needs to be calibrated. The variation of P-gain and I-gain for rich-lean variation is explained in Fig. 8.

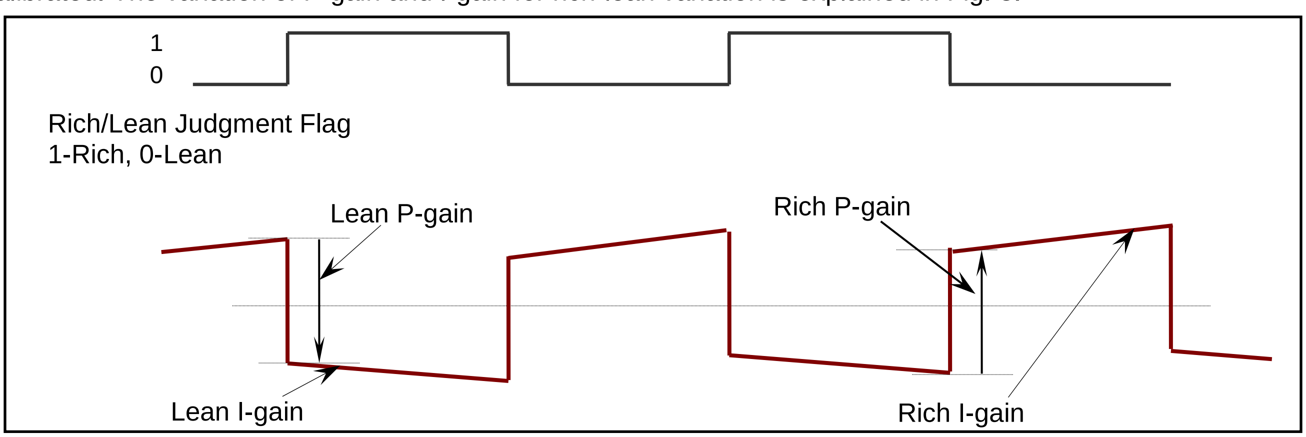

Figure 8: Variation of P & I gains

During catalyst monitoring, these gains are calibrated depending on the vehicle base emissions. Depending on the emissions, this pattern can be asymmetric also. When catalyst monitoring starts, the flowing changes take place in A/F feedback:-

- Rich side (gain) is made richer, rich compensation increased from X to (X+ Δ X)
- Lean side (gain) is made leaner, lean compensation increased from Y to (Y+ Δ Y)

If base emissions are on leaner side, the amount of lean feedback gain is reduced. Similarly, if base emissions are on richer side, the amount of rich feedback gain is reduced. So depending upon rich or lean emissions, either of these two maps should be calibrated.

CALIBRATION OF PROPORTIONAL AND INTEGRAL GAINS - OPTIMIZING THE TRADE- OFF BETWEEN OXYGEN STORAGE TIME CALCULATION FOR DETERIORATED AND NORMAL CATALYST WITH MINIMUM EMISSIONS-The air-fuel ratio feedback calibration has to be performed so that the following conditions get satisfied:-

1. Oxygen storage time calculation criteria - The ECU should clearly differentiate between a deteriorated catalyst and a new catalyst with sufficient margin available in the oxygen storage time calculated by the ECU for the two catalysts. If this margin (1) between the deteriorated and new catalyst is small, chances of misdiagnosis will be higher. In such cases, issues from market with MIL illumination due to wrong diagnosis may also come. Also, the value of threshold time should be set a little higher than the storage time for a deteriorated catalyst. This is just a safety margin (2). This condition is explained below in Fig. 9.

2. Emission criteria - While catalyst monitoring takes place, there should not be any abnormal emission peaks for CO, THC or NOx.

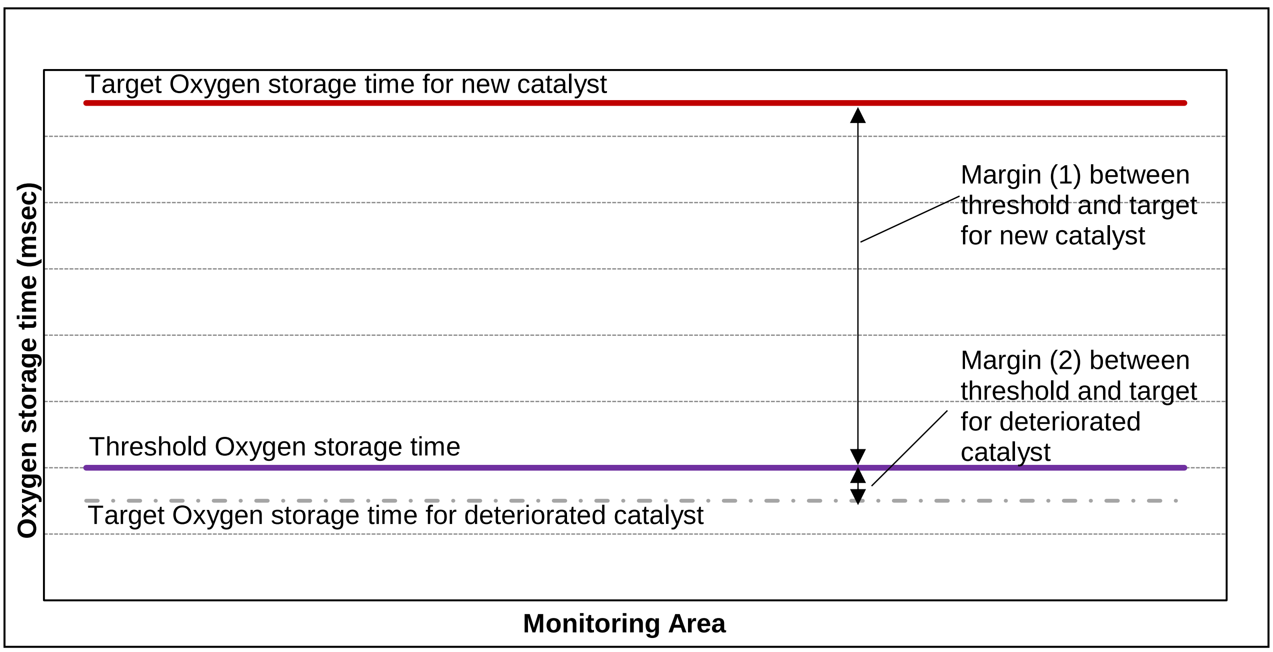

Figure 9: Oxygen storage time margins setting for deteriorated and new catalyst

If the air-fuel ratio feedback is kept more towards the rich side (High Δ X value) during catalyst monitoring, then the following phenomenon may occur:-

a) Sudden increase in CO, THC formation
b) Rear oxygen sensor voltage may not fluctuate in case of deteriorated catalyst causing storage time calculation to increase.

If the air-fuel ratio feedback is kept more towards the lean side(High Δ Y value) during catalyst monitoring, then the following phenomenon may occur:-

a) Sudden increase in NOx formation (especially observed in CNG mode)
b) Rear oxygen sensor voltage may fluctuate even with a new catalyst causing decrease in storage time calculation.

Air-fuel ratio feedback calibration for catalyst monitoring in Petrol mode for a bi-fuel vehicle- Petrol being a primary fuel for a bi-fuel vehicle, first air-fuel feedback calibration is done in petrol mode. After calibration in petrol mode, the ECU was able to clearly differentiate between deteriorated and new catalyst and with minimum emissions. Hence, the calibration was judged as okay.

Air-fuel ratio feedback calibration for catalyst monitoring in CNG mode for a bi-fuel vehicle- Using A/F calibration done in petrol mode for CNG mode as well.
Using same catalyst monitoring calibration for both Petrol and CNG helps in better dataset management. Also, time required in testing and validation activities gets reduced.

Results Obtained after validation in CNG mode:-

1. Fluctuations observed in rear oxygen sensor voltage during catalyst monitoring
2. Oxygen storage time decreased for new catalyst leading to reduction in margins between deteriorated and new catalyst
3. NOx peak observed during catalyst monitoring

Conclusion from the above results- Re-calibration required for CNG mode.

Reasons for calibrating air-fuel ratio feedback separately for CNG-

- From emission point of view:-
  The two fuels- Petrol and CNG have different properties. With CNG, controlling nitrogen oxides is a big challenge as compared to petrol. This is because of high temperatures produced inside the cylinder in CNG engines favoring NOx formation. Petrol being a liquid fuel has cooling effects; hence temperatures inside the cylinder tend to be less than CNG, which is a gaseous fuel.
  Also, A/F for CNG is 17.4:1 and for Petrol it is 14.7:1. Hence, more amount of nitrogen enters the engine in CNG as compared to petrol, leading to more NOx formation.

- From diagnosis point of view:-
  The proportional and integral gains for catalyst monitoring were kept same for both Petrol and CNG. However, the base emission calibration which is done before the start of catalyst monitoring calibration was found to be different for Petrol and CNG. Further, on a close observation it was found that the rich and lean proportional / integral gains before and during catalyst monitoring had significant differences in CNG mode (High Δ X, Δ Y). Continuously dynamic working of the system added with significant change in A/F compensation resulted in incorrect storage time calculation in this case.

Hence, it is essential that only tweaking is done to the existing emissions P/I gains in the monitoring area to ensure correct diagnosis.

Catalyst monitoring results in CNG mode after re-calibration-

1. No fluctuations observed in rear oxygen sensor voltage during monitoring after re-calibration as shown in Fig. 10.

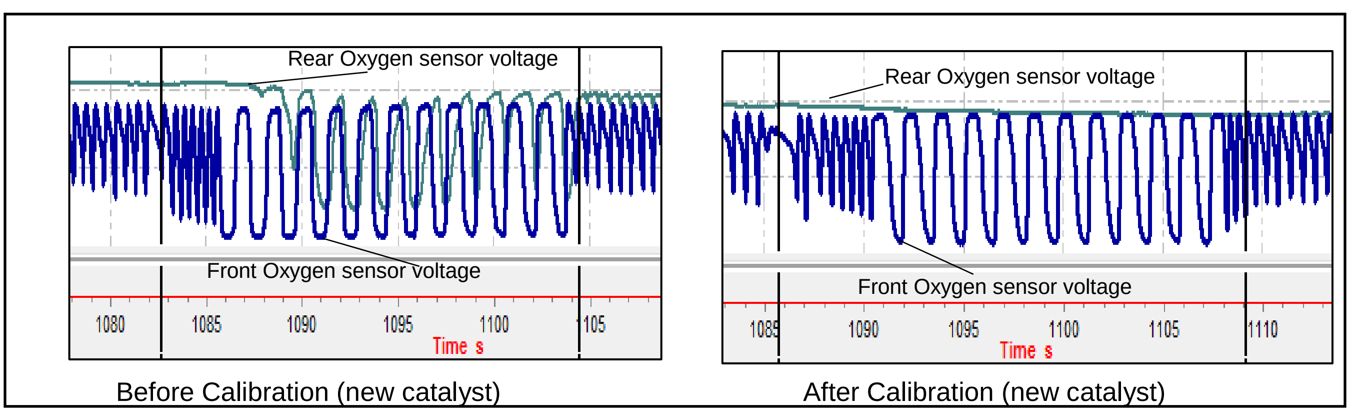

Figure 10: No fluctuations in rear oxygen sensor voltage after re-calibration in CNG mode

2. Enough oxygen storage time (milliseconds) margin obtained between deteriorated and new catalyst- the oxygen storage time for new catalyst was near the target value and for deteriorated catalyst, the storage time had sufficient margin below the threshold value

3. NOx emission peak issue solved as shown in Fig. 11

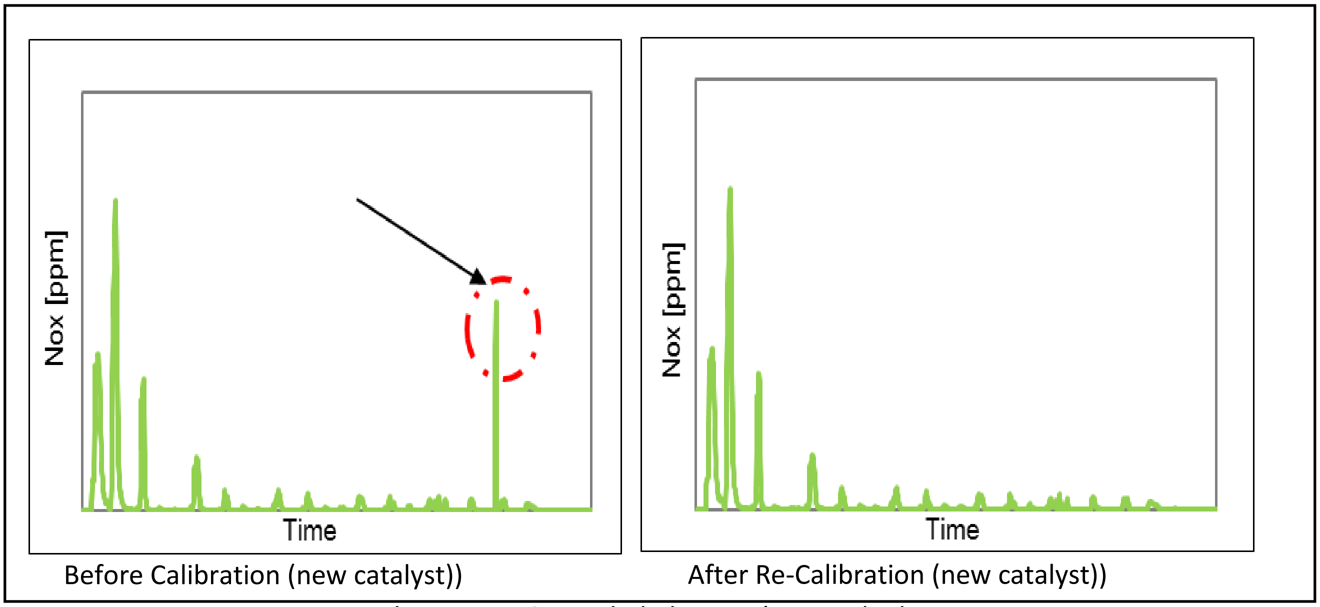

Figure 11: NOx peak during catalyst monitoring

CONCLUSION

With so many emission regulations coming in India, the process of vehicle calibration is set to become difficult as trade-offs have to be optimized for all ECM functionalities. Also, the margin area for these trade-offs may reduce in future, making calibration an uphill task. One example of this challenge was described in this paper for catalyst diagnosis function.
From the results obtained after re-calibration of catalyst function in CNG mode, it was concluded that both the criteria of oxygen storage time and emissions were met. Hence, the new calibration is okay.
Hence, we were able to achieve the following targets-

1. Increase in robustness of catalyst diagnosis
2. Reduction in emission while OBD monitoring
3. Reduction in chances of misdetection

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ABBREVIATIONS

OBD On-Board Diagnosis

RDE Real Driving Emissions

IUPR In-use Performance Ratio

CAFC Corporate Average Fuel Consumption

A/F Air-fuel ratio

ECM Engine Control Module

EMS Engine Management System

MIL Malfunction Indicator Lamp

CNG Compressed Natural Gas

CO Carbon-monoxide

THC Total Hydrocarbons

NOx Nitrogen oxides