

OBD Diagnostic Strategies for LEV_{III} Exhaust Gas Aftertreatment Concepts

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ABSTRACT

Upcoming motor vehicle emission regulations, such as California's LEV_{III}, continue to tighten emission limitations in diesel vehicles. These increasingly challenging emission requirements will be met by improving the combustion process (reducing engine-out emissions), as well as improving the exhaust gas aftertreatment efficiency.

Furthermore, intricate On-Board Diagnostics (OBD) systems are required to properly diagnose and meet OBD regulation requirements for complex aftertreatment systems. Under these conditions, current monitoring strategies are unable to guarantee reliable detection of partially failed systems. Additionally, new OBD regulations require aftertreatment systems to be diagnosed as a whole.

This paper covers potential OBD strategies for LEV_{III} aftertreatment concepts with regard to regulation compliance and robustness, while striving to use existing sensor concepts.

CITATION: Nanjundaswamy, H., Deussen, J., Van Sickel, R., Tomazic, D. et al., "OBd Diagnostic Strategies for LEV_{III} Exhaust Gas Aftertreatment Concepts," *SAE Int. J. Passeng. Cars - Mech. Syst.* 8(1):2015, doi:10.4271/2015-01-1040.

INTRODUCTION

With the intention to improve the local air quality, more stringent emission regulations are released worldwide to require further reduction of motor vehicle air pollution. Notably, this paper will focus on the California Air Resources Board's (CARB) LEV_{III} program which takes effect starting in 2015. This imposes massive challenges for passenger cars and forces manufacturers to reduce motor vehicle emissions to extremely low levels. Major challenges for fulfillment of the next US emission legislation are the upcoming combination of conflicting NO_x and NMOG limits and a yearly decreasing NO_x+NMOG fleet-average to 30 mg/mile in 2025, as shown in Figure 1.

In addition to these ultra-low emission standards in North-America, the parallel introduction of fleet-average fuel consumption limits in 2017, known as CAFE standards, represents a conflicting development target for motor vehicles in terms of emissions and fuel consumption [8]. In this context, an increased market share of modern efficient diesel engines in North America can offer the opportunity to meet these upcoming regulations with regard to both, emissions and efficiency.

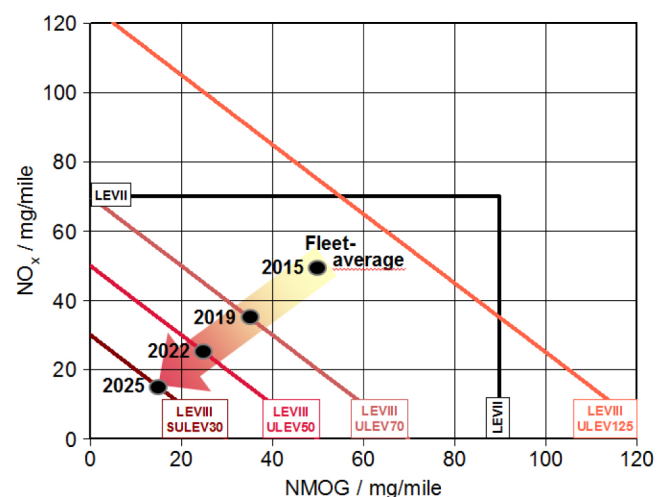


Figure 1. Combined NO_x+NMOG threshold and yearly decreasing NO_x+NMOG fleet-average for passenger cars with introduction of LEV_{III}

Avoidance of NO_x formation in modern diesel engines can be achieved to a certain extent using internal measures e.g. optimized operation of low pressure and high pressure exhaust gas recirculation.

(EGR). However, higher EGR rates result in increased hydro carbons (HC), decreased fuel efficiency, and degraded acceleration performance. Therefore, an optimized combination of advanced internal engine measures and new high-efficiency aftertreatment systems are needed to NOx meet future requirements without sacrificing engine system complexity, cost and durability.

At the same time, CARB's legislation dictates the most stringent regulations for on-board diagnostic (OBD) in terms of in-use-performance and mileage conformity and forces multiple monitors to work reliably in a wide operation range under extended environmental conditions [1]. Furthermore, higher demanded system efficiencies will reduce the margin between full useful life (FUL) and OBD limit parts indicating that even more complex monitoring functionalities are needed to ensure robust and reliable malfunction detection. Monitoring of aftertreatment components are especially tied to the respective conversion efficiency. With this in mind OBD can make a big impact into the tailored selection of future exhaust aftertreatment systems for all manufactures.

The target of this paper is to point out possible promising LEV III / Tier 3 aftertreatment variants for diesel passenger vehicles and their impact on OBD. To do this, existing in-series aftertreatment applications are intensively analysed, investigated and discussed in terms of feasibility for LEV III / Tier 3. Additionally, novel advanced NOx aftertreatment architectures for enhanced system performance and robustness are proposed and evaluated with regard to emission and OBD compliance. In addition, new exhaust architectures directly imply adaption of existing OBD strategies and sensor layouts. This paper outlines benefits as well as challenges of advanced NOx aftertreatment layouts and mentions methods to deal with issues that may arise.

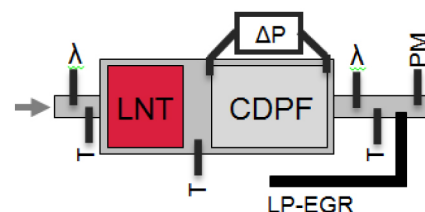
POTENTIAL OF LEVII APPLICATIONS FOR FUTURE US EMISSION LEGISLATIONS

At the beginning of this paper, the restricted potential of common diesel exhaust systems for the future US legislation is briefly discussed with the focus on diesel engines with a displacement of 2 to 3 liters for passenger car applications up to 5000 lbs. In general, the definition of engine concept and exhaust aftertreatment system strongly depends on the vehicle as well as on the pollutant regulation of the respective market. Especially, the choice of the NOx aftertreatment system represents a characteristic distinction. For California air Resources Board's LEVII program NOx aftertreatment systems, shown in Figure 2, are the common solution for diesel passenger cars. Generally, lean NOx traps (LNT) are preferred for comparably low NOx conversion needs, whereas SCR technology is used at high conversion requirements, most likely for larger vehicles.

The first example shows an exhaust system layout in the form of LNT followed by a coated DPF (CDPF) and low pressure EGR. The second example shows the mainstream layout for US diesel passenger cars consisting of diesel oxidation catalyst (DOC), CDPF and SCR. Both single NOx aftertreatment systems are briefly analyzed by means of model-based aftertreatment simulation and measurement data of two serial vehicles. A 1-D aftertreatment simulation tool was

used, which was developed by the FEV Group and represents a useful routine for development and evaluation of exhaust systems. With regard to the yearly decreasing NOx+NMOG fleet-average the emission categories, ULEV70 and ULEV50 represent the engineering targets to achieve LEV III / Tier 3 emission scenario within this investigation. Figure 3 illustrates the performance of a single LNT system for a small passenger car (3500lbs) with a 2 liter diesel engine including "state-of-the-art" internal measures for NOx reduction (low pressure EGR and LNT-CDPF).

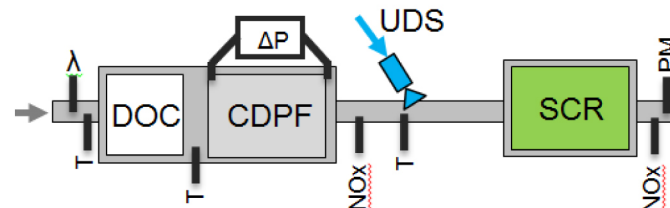
LNT based aftertreatment layout



LNT: Lean NOx Trap

CDPF: Coated DPF

SCR based aftertreatment layout



DOC: Diesel Oxidation Catalyst

SCR: Selective Catalytic Reduction

UDS: Urea Dosing System

Figure 2. Common exhaust aftertreatment layouts for CARB's LEVII program

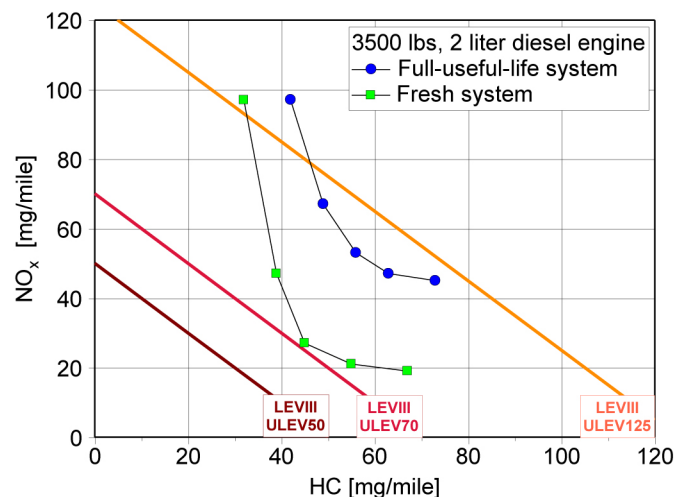


Figure 3. Simulated FTP-75 tailpipe potential for a 2 liter diesel engine with LP-EGR in a 3500 lbs passenger car with close-coupled LNT-CDPF

Even with lowest NO_x raw emissions around 90 mg/mile in the FTP-75 at medium HC emissions, this diesel vehicle equipped with LNT cannot meet LEV_{III} emission thresholds in a robust way. The typical trade-off between NO_x emissions and HC emissions by LNT enrichment is challenging regarding the future combined NO_x and HC limits. With an increasing number of LNT regeneration events per cycle, triggered at decreasing NO_x storage levels, the NO_x conversion can be enhanced up to more than 80%. But at the same time, an increase in HC emissions leads to exceedance of the combined limit. In addition, due to critical aging behavior or sulfurization maintenance of high LNT performance over lifetime is extremely challenging. According to this example and assuming no significant raw emission decrease by advanced fuel-neutral internal measures within the near future, single LNT applications may be capable to meet ULEV₁₂₅ for lighter vehicle applications, but do not appear to be an option for ULEV₇₀ or ULEV₅₀. This conclusion is confirmed by already published strategy changes of OEM's for US Diesel applications.

Since tailpipe emissions are directly related to the emissions immediately after cold-start, a quick warm-up behavior of the exhaust system during the first seconds of the FTP-75 is mandatory to achieve with the overall emission norm. In contrast, low specific load for passenger cars in the FTP-75 and improved combustion efficiency as well as reduced friction result in considerably lower exhaust gas temperatures. Regarding this, conventional SCR systems show obvious drawbacks due to their positioning. At sufficient temperatures, NO_x conversion efficiencies of SCR catalysts are already as high as they can be. For further NO_x reduction additional heat-up strategies, e.g. intake mass flow throttling or late post-injection, are needed to expand the active timeframe of SCR systems towards cold-start. However, these measures lead as well to increased HC and undesired drawbacks in fuel consumption.

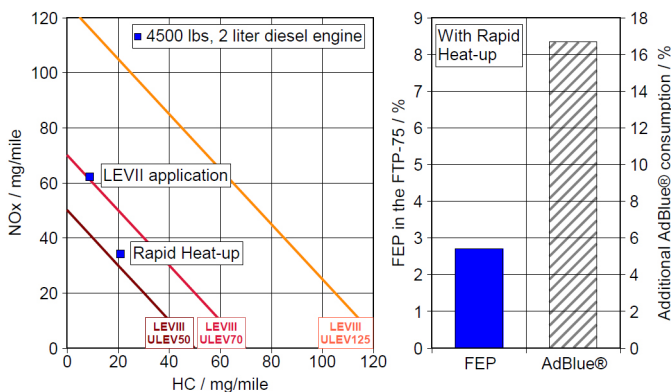


Figure 4. Simulated NO_x and HC tailpipe emissions in the FTP-75 for a 2 liter engine in a 4500 lbs passenger car with DOC-CDPF-SCR configuration

Figure 4 illustrates the effect of a rapid heat-up strategy, which is activated as soon as the SCR temperature drops below a certain limit. Starting from a LEV application for a large diesel vehicle (4500 lbs, 2 liter engine), at constant raw emissions further NO_x reduction can be achieved in comparison to the system without significant heating measures. But not all of the additional HC can be converted by DOC and CDPF. Therefore, the desired NO_x decrease is again compensated by an increase of HC. Heating measures with lower impact on HC

emissions are available and imaginable, e.g. costly electric heater or variable exhaust valve timing [3], [4]. But in the end, for increased efficiency of single SCR higher fuel economy penalty and decisive increase of AdBlue® consumption must be accepted.

SCR efficiencies above 80% in the FTP-75 and advanced cold-start strategies have also a major impact on OBD leading to challenging requirements for the respective diagnoses. Figure 5 shows the dependency between component efficiency to reach emission limits and relative efficiency loss at OBD threshold violation for three different OBD factors, which are representing the maximum allowed deterioration in relation to the applicable standard.

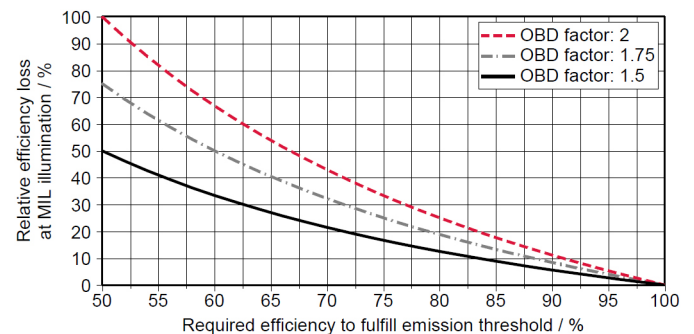


Figure 5. Dependency between component efficiency and relative efficiency loss at OBD threshold violation for three different OBD factors

With increasing conversion the distance between a full useful life (FUL) part and a limit part is shrinking to very low values.

Assuming a sufficient margin for robust failure detection this distance will be further reduced. Therefore, robust performance maintenance over lifetime appears to be challenging from the perspective of OBD, since a slight decrease in SCR performance would cause OBD threshold violation. In addition, new requirements concerning feed-gas quality (NO₂/NO_x-ratio) starting from 2015 could play a more important role since the SCR system is more sensitive at such high efficiencies. NO₂ is formed in the DOC or CDPF by oxidation of NO and delivers a positive impact on the SCR performance. Small variations in NO₂ generation due to aging of an oxidation catalyst can cause decisive loss of NO_x conversion efficiency. For instance, monitoring of feed-gas quality is legally demanded for SULEV₃₀, if an oxidation catalyst malfunction would cause an increase in NO_x emissions of only 4.5 mg/mile [1]. This does not require a completely separate diagnosis but strongly affects the limit part of an oxidation catalyst resulting in substantial challenges for a robust diagnosis. From this point of view, diagnoses accuracies and sensor tolerances set a limit for component conversion efficiencies, especially for advanced catalyst formulations.

It can be stated, that with today's in-series conventional NO_x aftertreatments systems, robust fulfillment of the upcoming US legislation becomes extremely challenging and is hardly practicable with regard to the SULEV standards of 2025. Both single LNT and SCR exhaust systems are facing restrictions due to their temperature operation window and fuel consumption. The configuration DOC-CDPF-SCR is an option for LEV_{III} ULEV₇₀, but only if significant higher fuel and AdBlue® consumption is accepted. Furthermore, it is