

In-Situ Emissions Performance of EPA2010-Compliant On-Highway Heavy-Duty Diesel Engines

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ABSTRACT

Implementation of EPA's heavy-duty engine NO_x standard of 0.20 g/bhp-hr has resulted in the introduction of a new generation of emission control systems for on-highway heavy-duty diesel engines. These new control systems are predominantly based around aftertreatment systems utilizing urea-based selective catalytic reduction (SCR) techniques, with only one manufacturer relying solely on in-cylinder NO_x emission reduction techniques. As with any new technology, EPA is interested in evaluating whether these systems are delivering the expected emissions reductions under real-world conditions and where areas for improvement may lie.

To accomplish these goals, an in-situ gaseous emissions measurement study was conducted using portable emissions measurement devices. The first stage of this study, and subject of this paper, focused on engines typically used in line-haul trucking applications (12-15L displacement). Vehicles with the engine families of interest were rented from commercial fleets and driven under conditions that were typical of daily driving while sampling emissions. The data was then evaluated, using a number of metrics, to determine overall emission control effectiveness as well as compliance with not-to-exceed emission standards.

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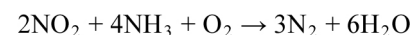
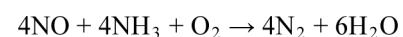
INTRODUCTION

Background

The US Environmental Protection Agency (EPA) is tasked with promulgating and enforcing emission regulations for motor vehicles and engines under Title II of the Clean Air Act. For the heavy-duty on-highway sector, which encompasses all vehicles with a gross vehicle weight rating above 14,000 lbs, these emissions regulations are applicable to engines, independent of the vehicle in which they are used. Engines in this sector produce an estimated 33% of total mobile-source NO_x emissions and 36% of total mobile-source particulate matter (PM) emissions [1], which underscores the importance of ensuring adequate emission controls from these products.

For the 2004 model year (MY), EPA began the implementation of a set of emission standards that ultimately resulted in the current, 2010-level standards (sometimes referred to as "EPA2010") [2]. For MY 2010, the NO_x standard was lowered to 0.20 g/bhp-hr, while retaining the MY 2007-level PM standard of 0.01 g/bhp-hr. The

technology package required to meet the PM standard has universally been the adoption of diesel particulate filters (DPFs) along with electronic control of combustion-related parameters. For adequate NO_x reduction, however, both in-cylinder (high-exhaust gas recirculation or EGR) and aftertreatment-based solutions have been pursued. For the latter, the most widespread solution has been the use of urea-based selective catalytic reduction (SCR) devices. These systems require the use of a liquid reductant, known as "diesel exhaust fluid" (DEF), which is sprayed into the exhaust stream upstream of the SCR catalyst. DEF decomposes into ammonia and reacts with exhaust constituents, ultimately reducing NO_x to N₂ and H₂O, according to:



For these reactions to occur, the SCR catalyst generally needs to be above 150° to 200°C. Engine manufacturers take

active measures, generally referred to as SCR thermal management, to both achieve and maintain these “light-off” temperatures. The effectiveness of these strategies have profound impacts on overall emissions performance, which will be shown later in this paper. In addition to temperature constraints, several other factors, such as ammonia-to-NO_x ratio, catalyst formulation and catalyst size, influence NO_x conversion efficiency and therefore need to be robustly addressed in the system design and calibration.

To ensure emissions are controlled in a manner consistent with the regulations, EPA relies on a broad certification and compliance system. The certification process generally takes place well in advance of production and involves several interactions between manufacturers and EPA so that all aspects of the emission control system are well understood. Testing on low-hour and aged engines is also part of the certification process, which is how compliance with the emission standards is evaluated.

Ensuring compliance beyond certification can be more difficult and requires tailored approaches, which depend on the segment under regulation. Production line testing, defect reporting and in-use testing are a few regulatory requirements that may be applicable to engine manufacturers after the time of certification. In addition, EPA conducts its own “confirmatory” testing of new engines, selective enforcement audits of manufacturer facilities and engines, as well as testing of in-service engines and/or vehicles to evaluate whether products are performing as expected.

With SCR being a relatively new technology to this sector, EPA set out to determine whether the expected emissions reductions were occurring under real-world conditions. In addition, EPA needed to determine if certain operating conditions led to less favorable NO_x control than others. For example, certain light-load conditions may challenge the ability of the thermal management strategy to sustain SCR light-off and therefore cause large increases in NO_x emissions that would not be reflected under conventional emission testing. Understanding how each manufacturer deals with such situations is critical to ensuring real-world emissions reductions. To address these needs, EPA embarked on an in-situ study of gaseous emissions from class-8 (>33,000 lb gross vehicle weight) trucks equipped with 2010-level heavy-duty diesel engines. The details and results of this study are the subject of this report.

Compliance Metrics/Test Procedures

A key component of demonstrating compliance with emission standards at the time of certification involves testing on an engine dynamometer over two prescribed test cycles. One cycle is meant to replicate mainly transient driving (Heavy-Duty Transient Test, or FTP) and the other is more typical of freeway-type operation (Supplemental Emission Test, or RMC-SET) [3]. Manufacturers are also expected to have a basis for ensuring compliance with “Not to Exceed”

(NTE) requirements at the time of certification, which will be described in further detail later in this paper.

Emissions are measured over these test cycles and the results are normalized by the work done by the engine over the test cycle. The result is a specific emission value, in g/bhp-hr, that can be compared to the emission standard. Adjustment factors are normally applied to these test results to account for aging affects (deterioration factors, or DFs) and influences of infrequently regenerating emission control devices (such as DPFs).

Engine manufacturers generally perform certification testing well in advance of mass production of their products. Along with testing over the prescribed duty cycles, manufacturers are required to demonstrate that their products will comply with the emission standards for the full useful life of the engine, which is 10 years or 435,000 miles for an engine in a typical Class 8 application. This is normally accomplished through durability testing, possibly including accelerated aging methods, to establish DFs. At the time of certification, manufacturers are also required to describe aspects of the emission control system that are not active during the certification test cycles. This typically involves detailed engineering evaluations of strategies that control emissions under varying ambient conditions, engine warm-up, and idling, amongst others.

Independently verifying the performance of emission control systems on production engines or engines from in-service vehicles is a key to achieving the expected emissions reductions prescribed by regulation. Testing engines over the certification test cycles is perhaps the most basic verification testing that can be done by EPA. However, this type of testing requires removal of the engine from the vehicle and adds significant cost and complexity to the test program. The test procedures associated with the NTE requirements briefly mentioned earlier provide a method for conducting in-situ emission measurements and evaluating compliance while the engine remains installed in the vehicle. Under NTE testing procedures, only engine operation within a certain speed and torque range is evaluated and compliance is judged against an “NTE threshold,” which includes measurement and in-use allowances. These allowances add margins to account for variability that may result from testing vehicles in-situ using portable emissions sampling equipment, recognizing that test conditions are not as well-controlled as a test cell environment. It is also worth clarifying that compliance with NTE requirements can also be evaluated in a test cell environment. In this case, measurement and in-use allowances are not applicable.

While the NTE methods provide a valuable tool for evaluating compliance while the engine remains in the vehicle, NTE testing conditions may be quite similar to the certification duty cycles and the NTE threshold can be more than twice the emission standard. Therefore, it is also important to have tests available for broader evaluation of the emission control system. While these tests, which will be described later in this paper, may not provide data ultimately

used for compliance determinations, they offer insight into the effectiveness of emission control technologies and can guide future certification actions. This paper will present results in the context of both compliance with NTE emission standards and overall emission control ability, as determined from in-situ testing.

Previous Studies

California Air Resources Board (CARB) has recently been conducting in-situ evaluations of heavy-duty vehicles and recently published their findings [4]. This study was similar to the study presented in this paper, however CARB chose to conduct a wider range of tests on a more limited number of vehicles when compared to this study. Their findings were generally consistent with ours and where applicable, similarities and differences between the two studies will be highlighted.

West Virginia University has conducted a number of studies [5, 6, 7, 8] investigating emissions from heavy-duty engines and vehicles as well as the test methods themselves. Most recently, they studied the effects of new and aged aftertreatment systems on 1998 model year class-8 vehicles [9]. While this study presents interesting findings on aging affects, the test subjects were not representative of true 2010-level commercially available engines.

A number of additional studies involving in-situ heavy-duty diesel emissions have been undertaken and published in the literature [10, 11, 12, e.g.]. Since these studies were predominantly conducted on pre-2010 level emission control systems, there remains a need to further investigate emissions from current generation engines.

EXPERIMENTAL DETAILS

Test Equipment

All testing reported in this paper was completed using a Semtech-DS (Sensors, Inc.) portable emissions measurement system (PEMS) and associated exhaust flowmeter (EFM; Sensors, Inc.). This unit is capable of raw emissions measurements of gaseous constituents (CO, CO₂, NO, NO₂, HC) to the precision, accuracy and repeatability requirements of 40 CFR Part 1065, Subpart J. In addition to gaseous emissions, the PEMS unit records weather data (temperature, pressure, rel. humidity), GPS tracking data, and vehicle interface (VI) data available over the engine's diagnostic port. This VI data includes a variety of engine and exhaust temperatures/pressures as well as vehicle speed, engine speed and information to calculate engine torque. The latter is critical for this study, since emissions need to be normalized by work for comparison to the emission standards. All data is recorded at 1 Hz.

A dedicated post-processing software product is supplied with the PEMS equipment that converts the raw data file to a useable format. A limited number of user inputs, such as fuel properties and a peak torque curve, are used by this software to calculate brake-specific emissions as well as all

information to evaluate compliance with NTE standards. The output file consists of second-by-second data (both as-recorded and as-calculated), summary data, and data from recent calibration checks.

Zero, span, and audit checks were performed prior to, and immediately following testing, consistent with the requirements of 40 CFR Part 1065 and the recommendation of Sensors, Inc. When pre and post-test span values were within specification, and zero checks were stable, analyzer drift was found to have a minimal impact on the results. As an added quality check, the total fuel consumption as measured by exhaust carbon was compared to the value based on the VI broadcast. An unexpectedly large difference between these two values is indicative of a leak in the sample path or other analyzer fault. Finally, a quick check is made on all recorded data channels to determine if signals dropped out during testing. While it is not uncommon for any signal to drop out for a few seconds over the course of a day, any significant loss of data usually resulted in the test being repeated.

Test Subjects

As stated earlier, the subject of this study was 2010-level heavy-duty diesel engines. More specifically, the focus was on the engines typically found in class-8 line-haul trucking applications. These engines are normally 6-cylinders and displace between 11 and 16 liters. Cummins, Detroit Diesel, Navistar, PACCAR, and Volvo are the sole producers of engines in this segment in the United States. At the time of this study, Navistar was relying on high-EGR for NO_x reduction while all others were utilizing SCR aftertreatment.

To gain the broadest perspective of emissions from these engines, EPA attempted to locate the most common engines from each manufacturer in this size segment. Vehicles were normally sourced from large daily rental fleets and two vehicles were tested for each engine family selected (see Table 1).

Table 1. Engines included in this study

Manufacturer	Model	Engine Family	NOx Control	NOx Std or FEL (g/bhp-hr)
Cummins	ISX15	B/CCEXH0912XAP	SCR	0.35
Detroit Diesel	DD13	BDDXH12.8FED	SCR	0.20
Detroit Diesel	DD15	CDDXH14.8EED	SCR	0.20
Navistar	MF13	BNVXH0757GA/C	High-EGR	0.50
PACCAR	MX13	A/BPCRH12.9M01	SCR	0.20
Volvo	D13	BVPTH12.8S01	SCR	0.20

For certification, the regulations require engines of similar size, architecture, and emissions controls to be grouped into "engine families." Engine families are identified by a 12-digit alphanumeric name and the first digit of the family name indicates the model year of the engine ("A"=2010, "B"=2011, etc.). Typically, engine families are certified to the same emission standard (e.g., the 0.20 g/bhp-hr NO_x standard). However, the regulations also allow engine manufacturers to certify an engine family to a self-declared