

Case Study on the Impact of EPA Emissions Standards for Nonroad Diesel Construction Equipment

Boshra Karimi, Ph.D.
Northern Kentucky University
Highland Heights, Kentucky

Phil Lewis, Ph.D.
Texas A&M University
College Station, Texas

Using the Volkswagen emissions scandal as motivation, the purpose of this case study was to investigate whether or not heavy duty diesel construction equipment exceeds EPA emissions standards for nonroad diesel engines. The equipment analyzed included four separate motor graders with EPA emissions standards Tier 0, Tier 1, Tier 2, and Tier 3 engines. The analysis was based on a dataset of real-world emissions rates collected from in-use equipment on actual jobsites. The results showed that mass per time emissions rates for hydrocarbons, carbon monoxide, nitrogen oxides, and particulate matter decreased as the EPA emissions standards became more stringent. Furthermore, there was only one observation in which the real-world average emissions rate exceeded the EPA emissions standard. Recommendations for improving the analysis include testing more equipment to improve the diversity of the study, focusing on mass per fuel consumed analyses that have less variability in emissions rates, and conducting more refined and controlled experiments in real-world conditions.

Key Words: Construction Equipment, Diesel Engines, Emissions, Engine Emissions Standards

Introduction

The Volkswagen emissions scandal, also known as “Dieselgate”, began in September 2015 when the United States Environmental Protection Agency (EPA) issued a notice of violation of the Clean Air Act to the German automaker Volkswagen Group. EPA found that Volkswagen had intentionally programmed the diesel engines in their onroad vehicles to activate their emissions controls only during laboratory emissions testing, which permitted the vehicles' nitrogen oxides (NO_x) emissions to meet EPA standards during regulatory testing; however, the emissions controls deactivated during real-world driving which increased NO_x emissions by up to 40 times. Volkswagen embedded this program in about 11 million cars worldwide, including 500,000 in the United States, for model years 2009 – 2015 (Parloff, 2018).

Could off-road vehicles, such as heavy duty diesel construction equipment, be guilty of violating EPA emissions standards? The authors addressed this question by conducting a case study that compared real-world construction equipment emissions rates to EPA emissions standards. The purpose of the case study was to investigate whether or not the EPA emissions standards for off-road (or nonroad) diesel vehicles were being exceeded by in-use construction equipment on real-world jobsites. The case study focused on motor graders, which are used extensively in highway construction and maintenance, as well as other horizontal construction activities. Also, motor graders were the only equipment type in the available dataset which had data for four different EPA engine tiers. A typical motor grader is shown in Figure 1.

Figure 1: Typical motor grader.

EPA regulates emissions from on-road and nonroad vehicles by establishing standards for the specific pollutants being emitted. Emissions standards limit the amount of pollution a vehicle or engine can emit. EPA set increasingly stringent emissions standards, known as engine tiers, for carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), and particulate matter (PM). These standards began in the early 1990s for nonroad engines and equipment. Once EPA set emissions standards for a particular engine tier, manufacturers were required to produce engines that met those standards according to the corresponding implementation schedule (EPA, 2018a).

Table 1 summarizes the EPA emissions standards that applies to the motor graders observed in the case study (EPA, 2018b). EPA engine tiers range from 1 to 4, with 1 being the least stringent standard and 4 being the most stringent. For this case study, four motor graders were observed. One motor grader had a model year prior to 1996, which means that its emissions were not required to meet an EPA standard. For the purposes of the case study, this particular motor grader is referred to as Tier 0. Furthermore, the case study fleet did not have a motor grader that was required to meet Tier 4 standards; thus, the case study only compared real-world emissions from motor graders that were required to meet Tier 1, 2, and 3 standards.

The case study had two primary objectives: 1) Compare the real-world, average emission rates of each motor grader to its appropriate EPA emissions standards; and 2) Determine whether or not the EPA emissions standards actually reduced real-world emissions as the standards became more stringent. The purpose of the case study was not to determine whether or not construction equipment and diesel engine manufacturers were falsifying emissions data, as was the case in Dieselgate, but to gain insight into the efficacy and impact of EPA emissions standards for nonroad diesel engines in use on real-world jobsites.

Table 1

EPA emissions standards for the case study nonroad diesel engines

Engine Horsepower	Model Year	Engine Tier	HC (g/hp-hr)	HC + NO_x (g/hp-hr)	CO (g/hp-hr)	NOx (g/hp-hr)	PM (g/hp-hr)
175 - 300	1996-2002	Tier 1	1.0		8.5	6.9	0.40
	2003-2005	Tier 2		4.9	2.6		0.15
	2006-2010	Tier 3		3.0	2.6		0.15
	2011-2013	Tier 4 Transitional		3.0	2.6		0.01
	2014-Present	Tier 4 Final	0.14		2.6	0.30	0.01

Literature Review

There is a rich body of knowledge related to the collection and analysis of real-world emissions data for nonroad diesel construction equipment. Much of this related work applies to this particular case study. For example, Lewis et al (2009a) examined the requirements and incentives for reducing emissions from construction equipment and compared emissions data sources for these types of vehicles. Lewis et al (2009b) also proposed a methodology for developing emissions inventories for construction equipment and presented an emissions inventory for a publicly-owned case study fleet of backhoes, motor graders, and wheel loaders. Ahn et al (2013) developed an integrated framework for estimating, benchmarking, and monitoring pollutant emissions from construction activity.

Rasdorf et al (2010) outlined field procedures for collecting real-world measurements of emissions data from construction equipment. Marshall et al (2012) presented a methodology for estimating emissions from construction equipment used for commercial building projects. Rasdorf et al (2012) evaluated pollutants emitted from construction equipment over the duration of a case study commercial building project. With regard to the specific equipment in this case study, motor graders, Frey et al (2008a) characterized real-world activity, fuel use, and emissions for selected motor graders fueled with petroleum diesel and B20 biodiesel. Frey et al (2008b) expanded this study to include backhoes and wheel loaders, in addition to motor graders.

Much of the work on the relationships between construction equipment and pollutant emissions is summarized in three in-depth papers on the topic. Frey et al (2010) presented the results of a comprehensive field study on fuel use and emissions of nonroad diesel construction equipment. Lewis et al (2015) conducted an engine variable impact analysis of fuel use and emissions for heavy duty diesel maintenance equipment. Lewis and Rasdorf (2016) summarized emissions rates based on equipment types and EPA engine tiers in a taxonomy of fuel use and emissions for heavy duty diesel construction equipment.

Case Study Results and Discussion

The data used in the case study came from a real-world emissions dataset for 39 items of nonroad heavy duty diesel construction equipment. This dataset was developed by researchers at North Carolina State University from 2005-2009 (Frey et al, 2010). It includes over 168 hours of quality assured, second-by-second fuel use, emissions, and engine activity data. In-use average emissions rates were determined for HC, NO_x, CO, and PM. These data were collected by a portable emissions measurement system (PEMS) that was deployed on the equipment as it performed typical construction duty cycles on actual jobsites. For the purposes of this case study, four motor graders were selected from the dataset, including a Tier 0, Tier 1, Tier 2, and Tier 3; Tier 4 emissions standards had not yet been implemented at the time the data were collected. The basic equipment attributes for each motor grader are summarized in Table 2.

Table 2

Summary of motor grader engine attributes

Motor Grader	Engine Tier	Horsepower	Model Year
Motor Grader A	0	167	1990
Motor Grader B	1	195	2001
Motor Grader C	2	195	2004
Motor Grader D	3	198	2007

Motor Grader A was the oldest item of equipment in the case study fleet, being over 10 years older than the next oldest. As a result, Motor Grader A was not required to conform to any of the EPA emissions standards and is therefore referred to as Tier 0. Motor Grader A also had the smallest rated horsepower of the four motor graders. Motor Graders B, C, and D all had similar horsepower ratings. Even though these three motor graders were similar in age and power, Motor Graders B, C, and D represented EPA emissions standards Tier 1, 2, and 3, respectively.

Table 3 summarizes the average engine loads for the case study motor graders. Engine load represents the fraction (or percentage) of available horsepower from the engine. Diesel engines in construction equipment seldom operate for long periods at maximum engine load (100%), but typically operate intermittently at various engine loads during their duty cycles over the course of a workday. Furthermore, it is common for heavy duty diesel construction equipment to idle for long periods; thus, the overall average engine load for the equipment engine is lowered by long idling episodes. A load factor of 59% is often used as a benchmark value for motor graders (EPA, 2010). For the case study motor graders, the average engine load ranged from a minimum of 10% to a maximum of 53%; thus all of the motor graders operated at an average engine load lower than the stated benchmark.

Table 3 also summarizes the mass per time (grams per hour) emissions rates for HC, CO, NO_x, and PM. Mass per time emissions rates are highly correlated with engine load. For example, equipment that operates under a high average engine load will have a higher rate of emissions for a given unit of time than it would operating at a lower engine load. For NO_x and PM emissions versus engine load, the mass per time emissions rates had Pearson correlation coefficients of $r = 0.52$ and $r = 0.87$, respectively; thus, these emissions rates were moderately to highly correlated with engine load. For HC and CO emissions, however, there was little to no correlation with engine load.

This confounding evidence may be attributed to the fact that each motor grader had different EPA emissions standards, which were developed with the intention of reducing emissions; therefore, engine load alone is not the only variable to impact pollutant emissions.

Table 3

Summary of average engine loads and emissions rates

Motor Grader	Load (%)	HC (g/hr)	CO (g/hr)	NO_x (g/hr)	PM (g/hr)
MG A (T0)	27	95	141	596	2.3
MG B (T1)	53	53	67	643	4.9
MG C (T2)	10	50	48	192	1.0
MG D (T3)	38	21	17	163	1.8

Figure 2 assesses the impact of EPA engine tier standards. Note that the values in Table 3 were normalized to the maximum emission rate for each pollutant by dividing each value by the pollutant's maximum emission rate. This was done for the convenience of showing all pollutants on one graph. For HC and CO, emissions rates were reduced with each successive engine tier. For NO_x and PM, however, there was an increase from Tier 0 to Tier 1, although the values for each tier were quantitatively similar. There was a significant reduction for Tier 2 and Tier 3, compared to Tier 0 and Tier 1, for both NO_x and PM. Of course, the reported emissions rates for all pollutants are affected by their respective engine load. The purpose of EPA engine tiers was to reduce the overall quantity of pollutants being emitted. Based on the information in Table 3 and Figure 2, it is apparent that EPA emissions standards have been successful in reducing emissions.

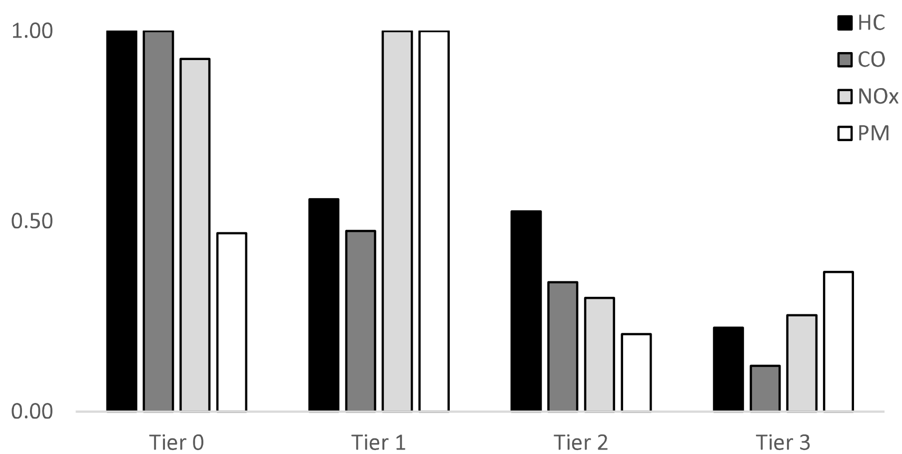

Figure 2. Summary of normalized emission rates.

Another way of evaluating the efficacy of EPA emissions standards is to compare the real-world emissions rates measured in the field to the EPA engine tier standards themselves. Table 4 completes this task for the Tier 1, 2, and 3 motor graders. The Tier 0 motor grader was not included because there were no emissions standards for Tier 0. The emissions rates in Table 3 were converted to a grams per horsepower-hour basis by dividing the grams per hour emission rate by the horsepower rating and average engine load of the motor grader. Of all the values in Table 4, only once did the field measured emission rate exceed the EPA emission standard rate – the Tier 2 Motor Grader C field rate for HC + NO_x was higher than the EPA emission standard. Based on these comparisons, it appears that the EPA emissions standards have been effective in reducing emissions rates for nonroad diesel equipment.

Although the field values in Table 4 are adequate for general comparisons, they should not be considered for regulatory use. When agencies such as EPA conduct regulatory testing, they typically require that specific instrumentation and protocols be utilized under certain conditions (EPA, 2018 c). The PEMS unit used to collect the data in Tables 3 and 4 did not adhere to any particular set of testing specifications or protocols aimed at collecting data for a specific purpose; however, the values in Tables 3 and 4 are quite reliable for comparing emissions from one item of equipment to another, or making comparisons of one dataset to another.

Table 4

Comparison of real-world (field) emissions rates to EPA emissions standards

	HC (g/hp-hr)		**$HC+NO_x$ (g/hp-hr)**		**CO (g/hp-hr)**		**NO_x (g/hp-hr)**		**PM (g/hp-hr)**	
	EPA	Field	EPA	Field	EPA	Field	EPA	Field	EPA	Field
MG B (T1)	1.0	0.5			8.5	0.6	6.9	6.2	0.40	0.05
MG C (T2)			4.9	12	2.6	2.5			0.15	0.05
MG D (T3)			3.0	2.4	2.6	0.2			0.15	0.02

Conclusions and Recommendations

Given the negative attention that onroad diesel vehicles received in the mainstream media, especially Dieselgate, an investigation to determine whether or not nonroad vehicles were violating emissions standards seemed worth the effort. The authors addressed this issue by performing a cursory review of an existing emissions dataset for nonroad heavy duty diesel construction equipment. By examining emissions rates for motor graders with three different EPA emissions standards (Tier 1, 2, and 3), the authors concluded that EPA emissions standards have been effective in reducing emissions from nonroad vehicles; however, there are other issues that need to be considered.

Although this case study concluded that EPA engine tier standards have had a positive impact on reducing emissions from diesel-powered construction equipment, the results are based on a limited analysis of limited data. Additional research needs to be performed. For example, not only do more motor graders need to be examined, but other equipment types should be investigated as well. Other candidate equipment includes backhoes, bulldozers, excavators, nonroad trucks, wheel loaders, skid steer loaders, and track loaders. Introducing more equipment types into the analysis will not only improve diversity in the research but it also will increase statistical robustness, ultimately leading to statistically significant results. The existing dataset used for the case study should be updated to include Tier 4 equipment as well.

Comparing mass per time emissions rates among different items of equipment may become convoluted due to variability in engine loads. Mass per time emissions rates are positively correlated with engine load – as engine load increases, emissions per unit of time increase; thus, it is possible that equipment with a more stringent engine tier and high engine load could actually have a higher mass per time emission rate than equipment with a less stringent EPA engine tier and lower average engine load. In order to offset the impact of variability in engine loads, an analysis based on mass per fuel consumed (grams per gallon) should be conducted. Grams per gallon emissions rates are much less susceptible to variability in engine load, therefore, providing a more consistent comparison among EPA engine tiers.

The most definitive way to determine whether or not nonroad diesel equipment is exceeding EPA emissions standards is by direct testing. Although the results in the database used for this case study were collected by direct testing, the methodologies did not match the requirements of testing protocols used for regulatory purposes. In order to obtain the most accurate field emissions rates possible and compare them to EPA emissions standards, equipment must be tested using the specified instrumentation with the specified approach. It is possible to design experiments that capture real-world emission rates, even in controlled environments.

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