

On-Road NOx Emission Rates from 1994-2003 Heavy-Duty Diesel Trucks

Thomas L. Darlington and Dennis Kahlbaum

Air Improvement Resource, Inc.

Gregory Thompson

West Virginia University

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ABSTRACT

In-service 1994-2003 heavy-duty trucks were acquired by West Virginia University (WVU), equipped with the WVU Mobile Emissions Measurement System (MEMS) to measure on-road NO_x, and driven on road routes near Sabraton, West Virginia, and extending up to Washington, PA to obtain real-world oxides of nitrogen (NO_x) emissions data on highways and local roads. The MEMS measured 5Hz NO_x, and load was obtained from the electronic control unit. Trucks were loaded to about 95% of their gross vehicle weights. Emissions in g/mi and g/bhp-hr were computed over the various road routes. In addition, some of the trucks were tested 1 to 2 years later to determine emission changes that may have occurred for these trucks. Emission results varied significantly over the different road routes due to different speeds, driving patterns, and road grades. Careful analysis of the available data indicates that both the brake-specific and distance-specific NO_x emissions on later model year trucks were lower than the earlier model year trucks, and these average NO_x reductions were approximately proportional to the reductions in the brake-specific emission standards. Furthermore, analysis of the vehicles that were re-tested after 1-2 years (with mileage above their emissions useful life) indicated a small reduction in NO_x emissions with mileage or age, on average. Lastly, the data presented in this report suggests that both the California EMFAC2007 model and the EPA MOBILE6.2 model emission rates could benefit by incorporating in-use emissions data of large population studies.

INTRODUCTION

The EPA regulations have historically required that heavy-duty engines meet their emission standards on an engine dynamometer, operated over a transient cycle, called the Federal Test Procedure, or FTP. In 1998, six of the heavy-duty diesel engine manufacturers signed Consent Decrees with the EPA that introduced new

emissions requirements. Namely the 13-mode steady state cycle, as well as "not to exceed" (NTE) standards. The emissions standards for five of the six Consent Decree engine manufacturers are summarized in Tables 1 and 2.

Table 1. NOx Emission Standards for Heavy-Heavy-Duty Engines From 1994 to 2006 (g/bhp-hr)

	BSNOx (g/hp-hr)		
	FTP	ESC	NTE
1994-97	5	na	na
1998	4	na	na
1999	4	6	7
2000-01	4	6	7
2002 ³	4 / 2.5	6 / 2.5	7 / 3.13
2003-06	2.5	2.5	3.13

Table 2. NOx Emission Standards for Medium-Heavy-Duty Engines From 1994 to 2006 (g/bhp-hr)

	BSNOx (g/hp-hr)		
	FTP	ESC	NTE
1994-97	5	na	na
1998 ¹	4	na / 6	na / 7
1999 ²	4	6 / 4	7 / 5
2000-01	4	4	5
2002 ³	4 / 2.5	4 / 2.5	5 / 3.13
2003-06	2.5	2.5	3.13

note: standards applicable to five Consent Decree engine manufacturers

note: Consent Decrees in effect from 10/01/98 - 10/01/2002

note: 2003 and later years: BSNOx + NMHC (not BSNOx alone)

¹: emissions change starting in 10/01/1998

²: emissions change starting in 07/31/1999

³: emissions change starting in 10/01/2002

na=not applicable

Prior to the Consent Decrees, between 1994-1997, the FTP NO_x standard was 5.0 g/bhp-hr. In January of 1998, the FTP standard was reduced to 4.0 g/bhp-hr. With the signing of the Consent Decrees in October 1998, 13-mode steady-state and NTE standards were introduced. As Tables 1 and 2 indicate, these standards were different for heavy-heavy and medium-heavy duty diesel engines. In October 2002, the emissions standards were reduced once again, and this time they were the same for heavy-heavy and medium-heavy duty diesel engines. There are also much lower 2007-9 and 2010+ NMHC+NO_x standards that have been implemented by the EPA, but these are not shown, since the engines reported in this work did not fall under those standards.

Heavy-heavy duty diesel engine (HHDDE) manufacturers were not required to meet NTE standards until January 1999, and the initial NTE standards were related to the FTP standards with a 1.75X factor between 1999 and October 2002 (these regulations include an additional 0.5 g/bhp-hr measurement allowance). Starting in October 2002, the NTE multiplier was reduced to 1.25X. This difference between NTE and FTP standards is important in the subsequent analysis of in-use emissions for the different model year subgroups.

With the signing of the 1998 Consent Decrees, engine manufacturers were also required to conduct on-road testing of 1994 and later model year in-use trucks. The manufacturers contracted with West Virginia University (WVU) to conduct this testing with their Mobile Emissions Measurements System, or MEMS. This system measures NO_x emissions produced by the truck engines while the truck is being operated over the road. WVU recruited in-use trucks and buses from service throughout the United States, but most were from the East coast, around the Morgantown, WV area. Testing started in 1999 and continued until late 2006. This testing is typically referred to as the "Consent Decree" testing.

On-road emission models such as the EPA model MOBILE (current version MOBILE6.2) and the California model EMFAC typically estimate emissions from vehicles in g/mi, and multiply the emissions by vehicle miles traveled (VMT) to produce emission inventories in tons per day. These models have historically used two different methods to estimate in-use emissions from heavy-duty vehicles in g/mi. In the first method, emissions in g/bhp-hr are estimated from engine tests on engines with the same emission standards. Conversion factors, which are a measure of the work done per mile (bhp-hr/mi) are also estimated, and emissions in g/mi are then estimated from multiplying the g/bhp-hr emissions by the conversion factors in bhp-hr/mi. This is the process used in the MOBILE model. This process was also used in earlier version of the EMFAC model, but more recently, the ARB has based the emission

estimates in EMFAC on chassis tests of heavy-duty vehicles, which are already in units of g/mi (similar to light duty vehicles) (1). A variety of testing cycles have been used, but the most common cycle is the UDDS chassis test cycle.

The Coordinating Research Council recently concluded a testing program on heavy-duty diesel vehicles, called E55 and E59 that conducted chassis testing of 75 heavy-duty vehicles (2). This testing was also performed by WVU using their heavy-duty transportable chassis dynamometer, and much of these data were utilized by the ARB in estimating emissions for recent versions of EMFAC (3).

The EPA is also re-evaluating its heavy-duty emission estimates for its upcoming MOVES model that will eventually replace MOBILE6. EPA also plans to use chassis testing that is available.

The Consent Decree testing by WVU represents an important validation step of NO_x emission rates from trucks. This study examines NO_x emission trends with lower engine-specific NO_x standards, NO_x emissions versus speed, NO_x versus temperature, and NO_x emissions versus odometer for vehicles that experienced "repeat" tests at least a year apart.

EQUIPMENT

The MEMS consisted of four primary systems and included the gaseous emissions sampling and conditioning component, the exhaust flow meter and transducers, engine control unit (ECU) interface, and a Windows-based data acquisition system to integrate all of the signals. The gaseous emissions of NO_x and CO₂ were measured and reported with a Horiba MEXA 120 zirconium oxide and Horiba BE140 non-dispersive infrared detectors, respectively. A complete description of the test equipment is given in the companion paper SAE2008-01-1298 (4). Real-time NO_x and CO₂ were measured at a 5 Hz rate. Vehicle and engine parameters such as engine speed, engine power, and vehicle speed were broadcast by the vehicle's electronic control unit (ECU). Torque was also obtained either from inference from various signals in the ECU for pre-1999 engine, or directly from the ECU for 1999 and later engines (these engines are required to broadcast torque). All NO_x results were corrected by WVU to standard conditions as specified in the Consent Decrees.

VEHICLES AND FUELS

Test vehicles were obtained by WVU from numerous sources in the Morgantown, WV area. The Consent Decrees specified that the manufacturers had to select engine families to be tested that were based on sales volume. For a given engine family, multiple engines, normally four, were tested over the various road routes.

The engines could be in any type of vehicle and included Class 4 (utility truck) to Class 8 (over-the-road tractor-trailer) vehicles. There was a wide range of engine displacements and hence power ratings with the rated power ranging from 150 to 600 hp. Vehicles included utility trucks, cargo vans, school buses, transit buses, cement mixers, tri-axle dump trucks, and fifth-wheel truck-trailers.

WVU contacted local truck fleet owners and rental agencies to obtain trucks. The vehicles were kept for approximately 1 week, and vehicle owners were compensated for the use of their trucks at their normal daily rate. Trucks were visually inspected by WVU to ensure that they were in a good state of operation. Trucks were run on the fuel in their tanks, but if it was necessary to add fuel, then diesel fuel was purchased locally. Vehicles were tested at 95% of the Gross Vehicle Weight Rating (GVWR), and vehicles with an 80,000 lb GVWR were also tested at 60,000 lbs. Only the 95% GVWR results were used in this analysis. The trucks were mostly driven over various road routes by WVU technicians and engineers, but in a few cases, the companies renting the trucks to WVU provided their own drivers.

A number of the trucks (but not all) were re-recruited a year or so later to determine changes in emissions over the period. These trucks were analyzed in this study to determine NOx emission changes.

ROAD ROUTES

There were ten different road routes utilized in the testing and the data reported here. The routes differed mainly in average speed, but also in road grades. In this analysis, routes were divided into “urban” and “rural” by average speed. Routes with average speeds exceeding 40 mph were considered rural, and routes with average speeds less than 40 mph were considered urban. These are simply convenient definitions for this analysis, they are not meant to imply that all of the driving on the urban routes was in urban areas, or that all of the driving on rural routes was in rural areas. But the urban routes consisted mostly of driving on major arterials and local streets, while the rural driving was predominantly on divided highways. The average speeds of the routes and their urban and rural classification for the purpose of this paper are shown in Table 3. It is noted that the Sab2bm and Bm2sab were divided highway routes with 70 mph speed limits but had significant hill climbs that reduced the average vehicle speed.

It is important to note that the routes and vehicle loading were specifically selected to cause frequent operation of the engine in the “not to exceed” zone, or at high power levels. As such, the routes and loading may not represent “typical” terrain in the United States, but are certainly representative of hilly or mountainous areas of

the country. The vehicles were loaded to 95% of their gross vehicles weight. Not all trucks operate at this weight all the time – many trucks are “cubed out” (i.e., fully loaded in volume) before they “gross out” (i.e., fully loaded in weight). The routes were not necessarily representative of all driving in the U.S., nor are they representative of the FTP transient test. Therefore, one should not expect the emission results for these routes to be the same as FTP transient test or vice-versa. In fact, the FTP cycle is a single, well-controlled engine (not vehicle) cycle. Real world in-use emissions cycles can have an infinite number of speed/torque cycles. That is the very reason for the introduction of the NTE standards. The on-road emission results should, however, show the relative impact of the changes in NTE and other standards on NOx emissions.

Table 3. Road Route Average Speeds and Classification For This Paper

Cycle (WVU names)	Average Speed (mph, all vehicles)	Classification
Washpa2	27.1	Urban
Washpa1	27.3	Urban
Mrgntwn	32.3	Urban
Bm2sab	34.9	Urban
Sab2bm	35.4	Urban
Sab2sw	46.4	Rural
Sw2sab	48.0	Rural
Washpa3	51.6	Rural
Sab2wash	52.9	Rural
Washpa32sab	54.6	Rural

Operation of the vehicles on the routes occurred at all times of the year, and at widely varying temperatures and humidity. This allows an evaluation of NOx emissions as a function of ambient temperature.

Table 4 in the Appendix shows the sample size of vehicles and tests for the different model year groups and routes.

ANALYSIS METHODS

MODEL YEAR TRENDS IN EMISSIONS – Vehicles were classified into model year groups by similar emission standards. The model groups used are 1994-1997, 1998, 1999-2002, and 2003. The 1999 model year is a “split” model year from the standpoint of emissions standards, because engines manufactured after July 1 met lower 13-mode and NTE standards than the first six months of the year (see Table 1), however, all of the 1999 model year engines have been included with the 1999-2002 group. The 2002 model year group is also a “split” model year group, because Consent Decree engines started meeting the lower 2.5 NMHC+NOx standards and other requirements October of that year, so engines made after October 1st should be



classified as meeting the 2003+ standards. Since this is only 3 months of the 2002 model year, all 2002 engines were grouped with the 1999-2001 model year group instead of 2003+. For 2003, the 90th percentile emissions appears to exceed the NTE limit, but these emissions do not exceed the NTE limit plus 0.5 g/bhp-hr measurement allowance.

WVU aggregated emissions for three different periods – for a 30 second NTE window, for a continuous NTE window, and over the entire route. This analysis focused on the route-average NOx emissions only .

For each model year group, box plots of NOx emissions showing mean, median, 75 and 25 percentile emissions, and 90 and 10 percentile emissions were constructed (in g/mi and g/bhp-hr). Emissions were compared for urban routes, highway routes, and for urban and highway routes combined. The analysis evaluated medium duty vehicles (not buses), and all Class 8 vehicles as a group.

SPEED EFFECTS – Route NOx emissions were plotted against route average speed, and an equation was developed through the data and compared to the EPA and California EMFAC model speed correction factors for these vehicles. This is similar to the approach used by EPA and ARB for their models, where cycles are developed with different average speeds (but a wide range of speed within each cycle), and the speed correction factors are developed from vehicle testing on these cycles in the laboratory.

VEHICLES WITH REPEAT TESTS – Since tests were conducted at different times of the year and at different temperatures, the vehicles with repeat testing were evaluated for temperature effects first (NOx emissions are already corrected for different humidity). Then the NOx emissions were corrected to a common temperature of 77°F and NOx emissions were plotted versus truck mileage, and linear regressions drawn through the data to determine emissions trends with mileage or odometer value.

RESULTS

GROUPED BY SIMILAR EMISSION STANDARDS

Results are shown in Figures 1 (urban routes), 2 (rural routes), and 3 (all routes) in the appendix. Results are shown in side-by-side figures, where the left side are the distance specific NOx results in g/mi, and the right side are work-specific results in g/hp-hr.

For urban routes at lower speeds, the 1998 model year g/mi emissions appear to be similar to the 1994-1997 model year, with average NOx emissions around 30 g/mi for both model year groups. NOx emissions drop significantly (to about 22 g/mi) for the 1999-2002 group with the introduction of the NTE and 13-mode standards

for the first time. NOx emissions drop again very significantly for the 2003 model year group, to about 12 g/mi. The reduction from 1994-1997 from 30 g/mi to 12 g/mi is 60%, which is similar to the 52% reduction in the FTP standard reduction from 1994-1997 (5 g/bhp-hr) to about 2.4 g/bhp-hr (if one assumes about 0.1 g/bhp-hr HC). Thus, over the period from 1994-1997 to 2003, the data suggests that combination of FTP, NTE, and 13-mode tests provided significant reductions in on-road NOx emissions, even on these aggressive routes.

For the same urban routes, the work specific emissions show similar trends. For the 1994-1997 group, the average emissions are higher than the FTP standard, which may be no surprise for the reasons previously mentioned. The 1998 model year group is slightly lower. The 1999-2002 model year group has lower work-specific emissions than 1998, and the 2003 engines are significantly reduced, with the average emissions very close to the standard, and no excursions above the NTE level. One also notices a tightening of the distribution of emissions with advancing standards, as the NTE standards are first implemented, and then the spread between the FTP and NTE standards is subsequently reduced.

The 2003 engines had very low mileage, by heavy-duty vehicle standards, when initially tested. If NOx deteriorates with age, one could say that this study is comparing very young engines with much older engines, not just a difference in emission standards. That is true to some extent, but later analysis of NOx deterioration rates shows very little evidence of NOx deterioration for the 2001 to 2003 engines, therefore the primary comparison here is one of different emission standards.

The rural route results at higher speeds in Figure 2 display similar trends. The distance specific emissions from 1994-1997 engines are lower on the higher speed rural routes than on the urban routes. This is probably due to significantly less idle time on the rural routes. The 1998 model year vehicle average is slightly higher than 1994-1997, but the 1999-2002 and 2003 levels drop from the 1998 level. The work-specific average emission results for 1994-1997, 1998, and 1999-2002 engines are a little higher on the rural routes than the urban routes. However, for 2003 engines, there appears to be no difference in urban and rural work-specific emissions. A likely contributing factor to this behavior is that the 2003 standards had an NTE limit of only 1.25X the FTP and/or the ESC standards. In other words, engine manufacturers were required to implement designs that produced very little variation in emissions over the entire NTE region.

The All Routes results in Figure 3 follow similar patterns to the average of the Urban and Rural routes in Figures 1 and 2.

Figures 4-6 show similar plots for medium heavy-duty vehicles tested. These figures show more dramatic NOx reductions between 1994-1997, 1998, 1999-2002, and 2003.

Overall, these tests provide evidence that the combination of FTP, 13-mode and NTE standards are producing significant reductions in real-world NOx emissions from Class 4 to 8 trucks.

SPEED EFFECTS

NOx emissions in g/mi versus speed are shown in Figures 7 (1994-1997), 8 (1998-2002), and 9 (2003+). Linear regressions have also been fitted through the data points. Also shown are the regression slope, intercept, R^2 , and statistical tests on whether the slope is zero. If the probability is less than 0.05, the hypothesis that the slope is equal to zero can be rejected (and values above 0.05 mean that the slope is zero).

Figure 7 for 1994-1997 trucks show a slight decline in NOx with higher speeds, but the decline is small and statistically significant. However, the highest results decline at higher speeds – note that at 30 mph the highest result is near 60 g/mi, but above 50 mph, there are no route results above 40 g/mi.

Figure 8 shows results for the 1998-2002 vehicles, and this time, the slope could be considered zero. The 1998 vehicles have been grouped with the 1999-2002 vehicles to avoid making a chart just for 1998 that would have few data points. The regression is flat, but again, the highest route emission rates decline with increasing speed. One can also observe two groups of data – above and below about 40 mph. This is a reflection of the fact that the routes are generally either rural, higher speed routes, or urban, lower speed routes.

Figure 9 shows the results for the 2003 vehicles. There is a statistically significant decline in NOx emissions with increasing speed. The higher points are from one truck that experienced higher emissions than the rest.

Examination of all the data indicates that of 105 total trucks, 77 of the trucks show a decline in NOx emissions with increasing speed.

In Figures 10 (1994-2002 HHDT) and 11 (2003+), the emissions have been normalized to the average of all routes, and the figures also show the California EMFAC2007 model and EPA MOBILE6.2 model speed correction factors for Class 8 trucks. The EMFAC2007 speed correction factors were developed from a variety of tests in the CRC E55/59 data. The EMFAC speed correction factors seem to fall within the Consent Decree data quite well. However, the MOBILE6.2 NOx speed correction factors for heavy-duty diesels appear to

increase at higher speeds, and this behavior is not observed in these Consent Decree data.

DETERIORATION RESULTS (REPEAT TESTS)

A number of trucks were recruited for follow up testing (repeat tests) about a year after the initial tests. The goal of this part of the Consent Decree in-use testing was to re-test engines after they had reached at least 150% of their useful lives. For engines prior to 2004, the EPA defined useful life for HHDEs was 190,000 miles. The definition of useful life increased to 435,000 miles from 2004 onwards. Table 5 in the Appendix lists the trucks that received repeat testing. These tests allow the examination of emissions on the same set of vehicles on a longitudinal basis, which is very useful in determining whether deterioration in emissions occurred in this test program. The EPA is currently basing the exhaust emissions from light duty vehicles on longitudinal inspection and maintenance (I/M) tests which can be tracked on the same vehicles from test-to-test (the I/M program being used is the Arizona I/M program, which tests vehicles on a biennial basis).

Since the vehicles were tested under real ambient conditions, there was a need to eliminate any influence of temperature that could potentially bias the deterioration results from vehicles tested about a year apart (it was determined not necessary to correct the earlier emissions because these tests were not repeat tests and occurred throughout the year). Figure 12 shows route NOx emissions versus temperature (in °F) in g/mi for all vehicles undergoing both initial and repeat testing. The figure shows that NOx emissions decrease with increasing ambient temperature (the decrease is statistically significant). Neither the EMFAC model nor the MOBILER6 model account for these temperature effects, because until now, there has been little or no data on on-road trucks operated at different temperatures.

The average temperature for all the tests is 63 °F. All of the NOx results in this part of the analysis were corrected to 77 °F using the regression in Figure 12 (77 °F is the midpoint of the FTP test temperature).

Figure 13 shows NOx emissions in g/mi for all Class 8 vehicles with tests at two different odometer values. Figure 8 also shows a linear regression of the data. The results show that NOx emissions decline with time, rather than increase. The slope in this case is statistically significant (i.e., not equal to 0).

To show the consistency of this trend, Figure 14 shows the ratio of emissions at the higher odometer reading to the emissions at the lower odometer reading for each truck with repeat tests. Positive numbers indicate higher emissions at the higher mileage, and negative numbers indicate lower emissions at higher mileage. Ratios are