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Summary of the In-Use Diesel Engine Emissions Forum and Technical Roundtable

Convened by the South Coast Air Quality Management District, September 20, 2006

Prepared for

South Coast Air Quality Management District
21865 E Copley Dr
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Contract Number: 05123
Task Order No. 8 & 10

June 22, 2007

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TIAX Case D0374

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Executive Summary

The South Coast Air Quality Management District (SCAQMD) convened a technical forum and roundtable discussion on the issues of in-use diesel engine emissions. Experts from Federal, state and local agencies, interested stakeholders, and industries representing diesel engine manufacturers were invited to a one day meeting on September 20, 2006 at the SCAQMD in Diamond Bar, California. Presentations by experts were given, followed by a roundtable discussion.

Presentations focused on heavy-duty vehicle chassis dynamometer data that are the basis for emissions factors in the ARB vehicle inventory code, EMFAC2007.[1] ARB changed from emission factors based on engine certification data to chassis data in EMFAC2000. Although somewhat data limited in the development of EMFAC2000, it was believed by most experts that chassis data would represent in-use estimates more than engine certification data. As more heavy-duty[2] truck and bus emission data were collected in programs sponsored by industry and ARB, ARB revised the heavy-duty emission factors with updates in EMFAC2002 and more recently in EMFAC2007. Table 1 summarizes the issues and findings of the forum and roundtable.

SCAQMD staff expressed significant concern about the validity of EMFAC as a means to accurately estimate emissions inventories from on-road heavy duty vehicles. In EMFAC2007, as in previous updates, emissions inventories were revised to indicate increases in pollutant emissions (primarily NO_x). This trend is counter to emissions regulations and calls into question the effectiveness of emissions regulations in this sector. ARB and EPA disputed this position and attribute these discrepancies to the limited chassis emission data.

In-use emissions data from West Virginia University (WVU) and CRC E55/59 were presented. Discussion focused on two key points: validity of current Not-to-exceed (NTE) standards and test cycles; and methods available to collect more accurate in-use emissions data. Portable emissions monitoring systems are generally seen as immature but developing and useful in measuring actual in-use emissions. WVU reports emissions estimates based on the NTE region of engine operation do not accurately capture the majority of actual engine operation. It was agreed that future inventory testing should consider multiple aspects of emission tests including ambient conditions and fuel composition.

EMA suggested that analysis of all emissions data indicates that the emissions standards and requirements are reducing on-road NOx emissions, that ARB's estimates of Tampering, Malfunction, and Malmaintenance rates in EMFAC2007 were too conservative, and that ARB's assumed effectiveness of OBD (30%) is too low. EMA stated that the assumed failure rates were excessive and could not be supported by the

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[1] EMFAC2007 reference.

[2] As used throughout this report heavy-duty refers to vehicles with gross vehicle weights of greater than 33,000 lbs. This is referred to as heavy, heavy duty vehicles in EMFAC.

industry. ARB acknowledged their estimates are conservative and that the automotive industry has demonstrated rapid improvements in reliability and durability in the past.

Table 1. Issues and Findings for Heavy-duty Diesel Engines

Issue	Finding
Estimates of HHDV[a] Emission Factors affect mobile emission inventory and incentive programs	√ Underestimating inventory of NO_x and PM emissions from HHDV affects District's ability to adequately plan to meet attainment standards √ Incentive programs like Carl Moyer and Fleet Modernization could be over incentivizing technology (paying for larger benefits than actually achieved)
Engine Certification does not agree with in-use emission factors	√ Current emission factors in EMFAC 2007 are more in line with engine certification data √ Less emphasis has been place on consent decree engines (MY 1994-1998)
HHDV Emission Factors have increased with each EMFAC revision, will this continue?	√ ARB has been more conservative in predicting future emission factors for 2007 and 2010 technologies √ ARB is estimating only 60% of 2010 technologies will achieve ultra-low emissions; 40% will have aftertreatment failures that will result in higher emissions √ Both EPA and EMA believe ARB's failure rates with newer aftertreatment technologies are too high
EPA's MOBILE Emissions Inventory Program does not agree with EMFAC	√ MOBILE and EMFAC agree for NO_x emissions even though MOBILE based on fuel use and engine certification data
Chassis Dynamometer Drive Cycles not representative of in-use truck operation	√ ARB is now using four (4) different drive cycles to get speed correction factors which are representative of in-use truck operation
Portable Emissions Monitors (PEMs) instrumentation not accurate for NTE emission standards	√ EMA is funding $1.5 million to improve emission sampling procedures √ Measurement accuracy and QA/QC will get better as instrumentation is used
Can PEMs data that is being collected be used to estimate emission inventory?	√ PEMs data will add to understanding of in-use emission performance of trucks but it is too early to determine how to use vast quantities of data that will be collected
How useful are NTEs if they are essentially steady state points (load, speed)?	√ NTEs will show whether an engine has high emissions at operating speed-load points

[a]Heavy, Heavy Diesel Vehicles (HHDV) emission category in EFMAC for vehicles weighing greater than 33,000 lbs.

Overall, based on the presentations and discussion, EMFAC2007 appears to be more robust in assessing future emission technologies. ARB placed more thought on the types of emission system failures that might occur, and developed deterioration factors to account for these failures. They also accounted for improvements in deterioration due to on-board diagnostics (OBD).

1. Introduction

On September 20, 2006 the South Coast Air Quality Management District (SCAQMD) convened a technical and policy forum on in-use diesel engine emissions. The objective of the meeting was to identify key expert perspectives on the in-use emissions of diesel engines and how estimates of these emissions will affect emission inventory projections in future years. The SCAQMD needs to rely on inventory modeling codes like EMFAC to determine the future emissions of criteria pollutants from heavy-duty vehicles. Estimates from EMFAC form the basis for control measures designed to reduce emissions from on road sources and, in particular, from heavy-duty, on road trucks and buses. State and local control measures are incorporated in the upcoming revisions to the Air Quality Management Plan (AQMP) for the South Coast Air Basin.

SCAQMD Board and staff are concerned with possible emissions increases associated with the heavy-duty fleet. Both oxides of nitrogen (NO_x) and particulate matter less than 2.5 microns in diameter ($PM_{2.5}$) are of particular concern. NO_x is a precursor to ozone formation as well as a source for secondary particulate. PM from diesel engines is a toxic air emission and is mostly composed of $PM_{2.5}$. The South Coast Air Basin is classified by the U.S. Environmental Protection Agency (EPA) as an extreme non-attainment area for ozone and is also in non-attainment for $PM_{2.5}$. As such, SCAQMD will need to substantially reduce hydrocarbon (HC), NO_x, and direct and secondary emissions of fine particulate manner ($PM_{2.5}$) in order to achieve ambient air quality standards.

Estimates of emissions from heavy-duty diesel trucks are also used to determine incentives in the Moyer program and in the Gateway Fleet Modernization program. The purpose of these programs is to reduce NO_x and PM emissions from heavy-duty on road applications. Not accurately determining the emissions for different technologies can result in over paying for reductions and more importantly not achieving the reductions needed for attainment.

Technology for heavy-duty diesel trucks will be changing very rapidly as engine manufacturers introduce new products to meet the 2007 and 2010 heavy-duty emission standards adopted by ARB and EPA. Currently, California requires fuel providers to sell ultra low sulfur diesel fuel (<15 ppm sulfur) with an aromatic content of 10 percent by weight.[3] 2007 model year engines are equipped with diesel particulate filters (DPFs) and 2010 model year engines will need both DPFs and NO_x aftertreatment. These changes are similar to the change in light-duty vehicles with the introduction of the three way catalyst and unleaded gasoline.

There are several uncertainties that arise with heavy-duty vehicles as itemized below.

- For heavy-duty applications engines are certified over a transient engine dynamometer cycle. This cycle was designed to represent the work performed by a

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[3] Or fuel formulation meeting the same NOx performance as 10 percent aromatics.

heavy-duty truck operating in a variety of conditions from stop and go to freeway driving. The vehicle emissions are not certified as in light-duty vehicles, so estimates have to be made of the vehicle emissions or chassis, or in-use testing has to be performed to estimate vehicle emissions.

- Chassis testing of limited numbers of trucks has been ongoing for several decades, but expanded testing programs did not start until the mid 1990s. Data from these testing programs showed that engine certification levels did not always correspond to chassis testing levels.

- Using certification results in order to project in-use emissions did not agree with limited chassis testing of newer technologies. The chassis testing of the newer technology gave higher than anticipated emissions than that expected from the engine certification results.

- Based on the chassis testing data, EPA and ARB modified the engine test procedure (often referred to as the Federal Test Procedure or FTP) to include a series of not-to-exceed (NTE) test points that the engine manufacturers have to certify to in addition to the transient engine dynamometer test cycle.

- The NTE's and the development of portable emissions monitoring (PEM) equipment have also resulted in manufacturers agreeing to providing data to EPA and ARB on selective in-use testing of their technologies. PEMs are relatively new and there is uncertainty of how data collected from PEMs will compare with chassis emissions data and with engine dynamometer data.

- Advanced aftertreatment equipment on heavy-duty diesel vehicles is required by the emissions regulations to be covered by warranty by the engine manufactures for 490,000 miles. Useful life of the aftertreatment equipment is expected to last as long as the vehicle. often greater than 1 million miles. There is uncertainty in equipment reliability and durability as these vehicles age.

- The use of on-board diagnostics (OBD) will help to determine when emissions equipment is not meeting specifications, although these standards will not be fully implemented until 2016.

SCAQMD pulled together a number of experts to address these issues. Table 2 shows the agenda for the September 20th meeting and the invited roundtable members. The agenda was divided into three segments: context and framing of issues, formal forum presentations, and roundtable discussion. The SCAQMD provided a presentation on the context and framing of issues. A spectrum of presenters then provided views on in-use diesel engine emissions. Views representing Coordinating Research Council (CRC), academia, engine manufacturer's association (EMA), ARB and EPA were provided.

Table 2. In-Use Diesel Engine Emissions Forum and Technical Roundtable Agenda

South Coast Air Quality Management District Headquarters — Auditorium

9:00 AM	**I.**	**Welcome**	Dr. Chung Liu, Deputy Executive Officer, Science & Technology Advancement, AQMD
9:05 AM	**II.**	**Self-Introductions**	Attendees
	III.	**Context and Framing of Issues**	
9:15 AM		Background and Objectives	Dean Saito, Manager, Mobile Source Strategies Unit, AQMD
	IV. Forum Presentations		
9:30 AM	1)	Auto/Oil Research Efforts	Dr. Chris Tennant, Deputy Director, CRC
9:45 AM	2)	E55/59 Program and Academia Perspective on Engine Testing Discrepancy	Dr. Mridul Gautam, Director. Particulate Studies, WVU
10:15 AM	3)	Worldwide In-Use Diesel Emissions Testing and Research Efforts	Mark Carlock Consultant, Saint Malo Solutions
10:35 AM	***Break (15 minutes)***		
10:50 AM	4)	In-Use Diesel Emissions Modeling California Perspective	Dr. Michael Benjamin, Branch Chief, Mobile Source Analysis Branch, CARB
11:10 AM	5)	CARB's Proposed In-Use Compliance Program to Ensure Low Emissions	Michael W. Carter, Branch Chief, Emission Research & Regulatory & Development Branch, CARB
11:30 AM	6)	Diesel Engine Emission Standards Federal Policy Perspective	Byron Bunker Center Director-Heavy Duty Onroad Center, Assessment & Standards, U.S. EPA
11:50 PM	***Lunch (60 minutes)***		
1:30 PM	**Roundtable Discussion**		Moderator: Mike Jackson, Senior Director, TIAX
Additional Panelists —			
	Tom Cackette, Deputy Chief, California Air Resources Board		
	Timothy French, Counsel, Engine Manufacturers Association		
	Dr. Elaine Chang, Deputy, Executive Officer, Planning & Rules, AQMD		
3:30 PM	**Public Comment**		
	Summary and Next Steps		Mike Jackson, Senior Director, TIAX

TIAX LLC was responsible for documenting written and oral content from the roundtable, moderating the roundtable discussion, and writing a report summarizing the findings of the meeting.

The roundtable discussion was meant to provide any of the invited participants or the audience the opportunity to ask questions of any of the presenters. Three additional panel members were added for the roundtable discussion: Tom Cackette, ARB, Timothy French, EMA and Dr. Elaine Chang, SCAQMD. The roundtable discussion touched on the issues presented above as discussed later in this report.

This report is meant to capture the views of the various experts in attendance at this meeting. We have attempted to summarize the meeting through meeting notes that outline each presentation, questions and answers, selective use of graphics presented at the meeting, and subsequently by synthesizing the major points and conclusions that we thought were reached during the meeting.

This report is organized as follows. Section 2 summarizes the issues and discussions surrounding the testing/certification of heavy-duty engines and vehicles. Section 3 outlines the issues and discussions around inventory models to predict the current and future emissions of heavy-duty, on road diesel vehicles. Section 4 deals with advanced systems for ensuring the emission performance of heavy-duty diesel vehicles over their useful life. Section 5 provides a summary of the roundtable discussion and also provides some concluding remarks on the emissions from heavy-duty vehicles.

Presentations are posted on the SCAQMD web site: http://www.aqmd.gov. To navigate the SCAQMD web site use the search feature and search for "technical forum." Click on the technical forum result. This will provide agenda and presentations from several forums held at the district. Choose the September 20, 2006 In-Use Diesel Engine Emissions Forum and Technical Roundtable forum or use the link below:

http://www.aqmd.gov/tao/ConferencesWorkshops/Diesel_Forum/InUse_Diesel_Forum.htm

2. Emissions from Heavy-Duty Diesel Vehicles

Unlike light-duty vehicles which are certified on a chassis dynamometer to g/mi standards for tailpipe pollutants, heavy-duty diesel engines are certified by engine families on an engine dynamometer to g/bhp-hr standards. This system evolved since a heavy-duty engine is used in a variety of applications from off-road equipment to on-highway trucks. A major issue that arises is determining the in-use performance for on and off road vehicle applications. ARB and local air districts need to estimate the emissions that result from these applications to determine current and future inventory and control programs that could be developed to reduce current and future emissions from these sources.

2.1 Importance of Controlling Emissions from Heavy-duty Diesel Vehicles

Dean Saito (SCAQMD) outlined the impact of heavy-duty vehicles on air quality in the South Coast Air Basin (SCAB). The SCAQMD is in nonattainment for ozone and $PM_{2.5}$. NO_x and hydrocarbons along with sunlight form ozone. $PM_{2.5}$ is a result of direct diesel particulate emissions as well as secondary particulate form in the atmosphere from NO_x and oxides of sulfur (SO_x) emissions. Heavy-duty diesel vehicles are a large contributor to NO_x and $PM_{2.5}$ emissions in the basin.

Although there has been considerable progress in reducing ozone levels in the basin, the number of days exceeding the current 8-hour ozone standard has leveled off at about 100 days per year as shown in Figure 1. In addition, four counties in the basin have some of the highest annual average $PM_{2.5}$ concentrations in the U.S, as indicated in Table 3. High exposures to ozone and $PM_{2.5}$ levels are linked to public health issues of asthma and increased cancer risk.

Table 3. Ranking of Annual AveragePM$_{2.5}$ Counties

Figure 1. Ozone History in the South Coast Air Basin

Heavy-duty diesel vehicles are a large source of NO_x emissions in the SCAB as shown in Figure 2. Most of the vehicles in the categories of port related, diesel vehicles, and off road equipment are diesel powered. Thus, NO_x emissions from the diesel equipment exceeds the emissions from gasoline vehicles even though the population of gasoline vehicles far exceeds that of diesel vehicles. Also NO_x emissions from diesel equipment far exceed that from industrial sources. Sources of $PM_{2.5}$ are direct emissions from diesel vehicles and secondary emissions from NO_x and SO_x emission that are formed by atmospheric interactions with ammonia.

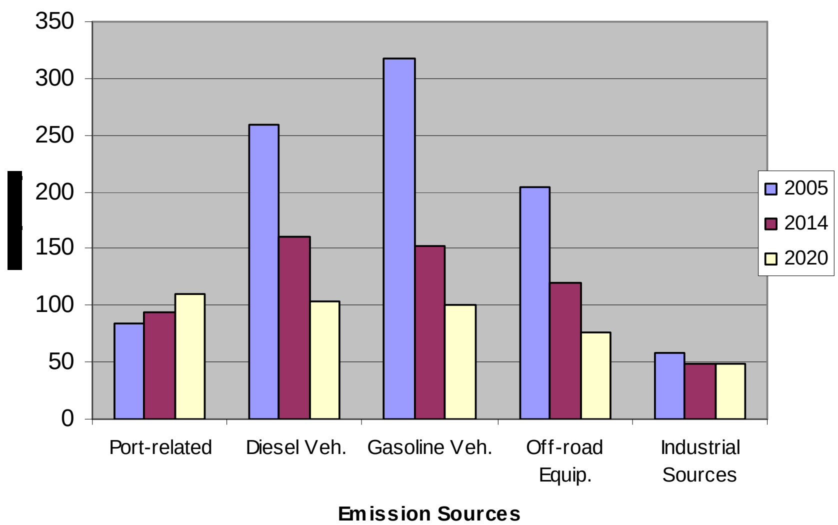


Figure 2. Estimated NOx Emissions from Various Sources

Both ARB and the SCAMQD are faced with developing control programs to reduce the precursors to ozone and $PM_{2.5}$ formation. Since heavy-duty diesel vehicles contribute significantly to NO_x and direct PM emissions, control programs and control measures are needed to reduce these emissions for ozone and $PM_{2.5}$ attainment. A key requirement in developing strategies to reach attainment is estimating the emission inventory for various applications such as those shown in Figure 2. This is done using inventory codes like ARB's EMFAC which is used in California or EPA's MOBILE which is used in the rest of the United States. Both of these codes used engine or chassis emission data to estimate emission factors for various on road applications from heavy-duty trucks to light-duty vehicles. Then, based on data on vehicle use and average speed, the emissions by category for various years are estimated. Other codes like ARB's OFFROAD model similarly determine emissions based on use and emissions factors for off road applications.

It is important, therefore, to have a good estimate of the engine/vehicle emission factors. Figure 3 shows truck chassis emissions data in g/mi (these data are adjusted to zero miles (ZM emission factors using ARB deterioration factors). Also shown on this figure are the emission standards in g/bhp-hr. This figure illustrates the problems of trying to

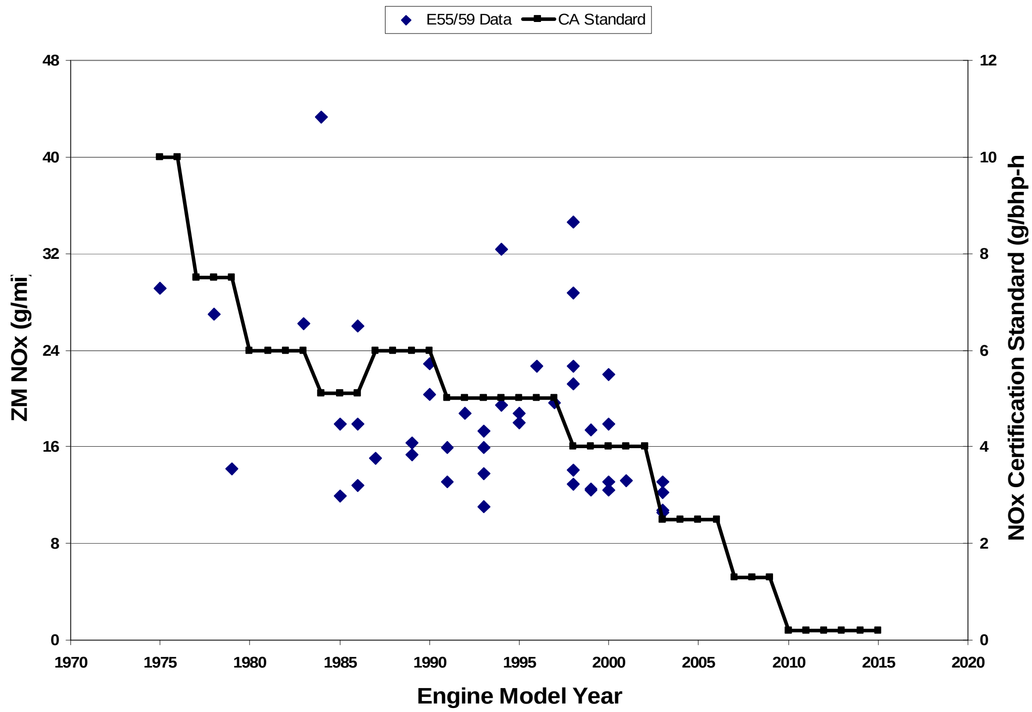


Figure 3. In-Use Heavy-Duty Chassis Emissions Data and Engine Certification Data

compare in-use emission performance to engine certification results. First, as shown, there is a lot of scatter in the data. This scatter is not surprising given that these test results span various engine and vehicle manufacturers and have different levels of maintenance. Second, it is not obvious that in-use performance correlates with ever lowering emissions standards.

This is a major concern to the SCAQMD for several reasons. The District needs to do the best it can to estimate emission inventories as discussed above in order to develop strategies to meet attainment. Just as important, however, are control measures that are designed to reduce emissions from older vehicles. The ARB has developed an incentive program—the Carl Moyer Program—to encourage lower NO_x technologies in existing vehicles. This program provides incentive funding based on emission reductions which are often based on EMFAC emission factors. Similarly, fleet modernization programs like the Gateway Cities Program also rely on EMFAC emission factors to determine the incentive for scrapping older trucks and replacing them with newer used trucks. The intent of both of these programs is to provide real emission reductions at competitive costs.

In summary, experts were invited to this technical forum to explore the relationships and uncertainties in estimating emissions from current heavy-duty vehicles but also estimating the emissions from future heavy-duty vehicles.

2.2 Chassis Dynamometer Emission Testing Programs

There were two presentations regarding chassis testing of existing heavy-duty diesel trucks. Chris Tennant, Coordinating Research Council (CRC), described CRC's role of providing cooperative, precompetitive research between the automobile and petroleum industries. Dr. Mridul Gautam, West Virginia University (WVU), described chassis emissions testing performed for CRC and others.

Tennant described CRC's objectives of providing technical data to ensure vehicle fuel compatibility and customer satisfaction and to achieve clean air and other goals. CRC's real world vehicle emissions and emissions modeling group is responsible for funding research on in-use emissions. This group is responsible for CRC's annual "On-Road Vehicle Emission Workshops" and they were also the contracting agency for the heavy-duty vehicle chassis dynamometer testing for the emission inventory project (CRC project E-55/59). This project was also co-funded by ARB, EPA, EMA, DOE/NREL, and SCAQMD. This project is the main source of heavy-duty, diesel truck in-use emission data.

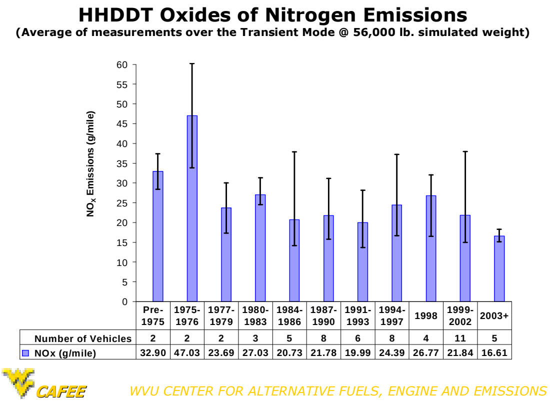
Other projects CRC are sponsoring are:

1. CRC E-75 "Compilation of Diesel Emissions Speciation Data"
2. CRC E-66 "2007-Level Diesel Particulate Measurement Research"
3. ACES "Advance Collaborative Emission Study"
4. CRC ACES-1 "ACES-Cycle Development, CARB Heavy Heavy-duty Diesel Engine Cycle"
5. CRC E-70 "Non-Road Vehicle Emissions"

Potential future CRC research includes collaboration with DOE/NREL on heavy-duty on-road truck remote sensing, additional analysis of E-75 database, and investigating avenues to support the 2005 Energy Policy Act through collaboration with other agencies.

Dr. Gautman's presentation reviewed data collected by WVU on their mobile chassis dynamometer and work WVU has done with portable emissions monitoring (PEMs) equipment. Dr. Gautman's comments on chassis data will be discussed here. His discussion on PEMs is provided in Section 4.

WVU was the contractor to CRC on project E-55/E-59. In these projects, WVU tested 75 vehicles—56 heavy, heavy-duty diesel trucks (HHDT) and 19 medium, heavy-duty diesel trucks (MHDT). Figure 4 shows the NO_x emission results for a transient and cruise test cycles. As shown, there is a general decline in in-use NO_x emissions from engine model years (MY) 1975-1976 to 2003. On the transient results there is a flatting trend in the mid 1990's and a slight increase in MY 1998 trucks. These NO_x increases are more dramatic in the cruise test cycle results. These results at the time were unexpected since the standard dropped from 5 g/bhp-hr to 4 g/bhp-hr. Subsequent investigation by EPA and ARB led to the engine manufacturers agreeing to a consent



	Pre-1975	1975-1976	1977-1979	1980-1983	1984-1986	1987-1990	1991-1993	1994-1997	1998	1999-2002	2003+
Number of Vehicles	2	2	2	3	5	8	6	8	4	11	5
NOx (g/mile)	32.90	47.03	23.69	27.03	20.73	21.78	19.99	24.39	26.77	21.84	16.61

Figure 4. HHDDT NO_x Emissions—Transient and Cruise Test Cycles

decree where they would introduce 2004 technology (2.4 g/bhp-hr NO_x) early and also agreed to test for NTE points in the engine map (this is discuss further in Section 4). The tests of the MY 2003 HHDT vehicles (certified at 2.4 g/bhp-hr on the engine dynamometer) showed much lower in-use NO_x emissions. Further, the amount of scatter was also reduced with this test group.

Dr. Gautam also showed corresponding particulate emissions for the 56 HHDT tested over the transient and cruise chassis test cycles. Figure 5 shows the in-use PM emissions for the transient cycle. The cruise data trend is comparable but slightly lower than the transient results (this is expected since it is hard to control emissions during engine transients than at steady state conditions). Data scatter between vehicles is higher for the PM results compared to the NO_x results. There is a general trend of decreasing PM with the newer MY technologies.

Figure 5. HHDDT NO_x Emissions—Transient and Cruise Test Cycles

Dr. Gautam also indicated that changing the engine calibration—so called “reflash”—reduced NO_x emissions on HHDT. Finally, he showed data on the effects of vehicle weight on NO_x emissions for HHDTs and MHDTs. These test results showed that NO_x emissions increase with vehicle weight as could be expected since the trucks are required to perform more work with the heavier vehicle weights.

2.3 Worldwide Testing Programs

Mark Carlock, Saint Malo Solutions presented an overview of efforts in other countries to quantify emissions from heavy-duty vehicles. In-use diesel testing has occurred in several countries outside the U.S. including Australia, India, Hong Kong, and Thailand. Carlock indicated that progress of emissions testing has included laboratory testing using engine dynamometers, to in-use opacity tests, to in-use dynamometer tests, and finally to in-use testing with “in-flight” analyzers (or as used in this report, PEMs).

Mr. Carlock showed emissions testing data from the Australia National Environmental Protection Council comparing the data for various test cycles. Not surprising the emission results varied by test/test cycle due to the differences in work required by the vehicle during testing. Australia has also developed a technique using laser light-scattering photometry to instantaneously measure PM emissions from diesel vehicles.

Efforts in India include implementing smoke opacity tests on chassis dynamometers for all commercial vehicles. These tests will be part of India’s short test procedures for regular inspection and maintenance (I/M). India is also working to phase in both NO_x and PM measurements to these procedures. India’s goal is to establish a number of chassis dynamometer lanes sufficient to test all heavy-duty commercial vehicles.

Hong Kong has a smoky vehicle emission program that requires vehicles spotted by accredited spotters to undergo a smoke test within a specified period. Failure of the smoke test results in canceling the vehicle’s license. To date more than 19,000 licenses have been cancelled in this program.

Thailand is performing laboratory emissions testing to develop emission factors for Bangkok. Thailand is currently using a free acceleration test for vehicle I/M, but the experience of other countries has shown a load mode test to be more effective.

3. Estimating Emissions Inventories and In-use Compliance for Heavy-Duty Diesel Vehicles

The previous sections provided background on the importance of estimating the in-use performance of heavy-duty diesel vehicles and efforts that have been taken to obtain data for this purpose. This section describes how these emissions data are used to develop inventory codes that estimate the in-use performance. Also this section describes ARB's program to ensure that the emission control systems perform as required over their useful life.

3.1 EMFAC2007

Dr. Michael Benjamin presented ARB's modeling of in-use chassis dynamometer data. Emission factors for EMFAC2007 for various MY technology groupings were estimated by adding the CRC E-55/59 chassis test data. These data increased the data set from 23 to 70 HHDTs. The most recent CRC results also incorporated testing of 1999 to 2003 MY vehicles. ARB then made estimates of 2007 and 2010 engine technologies based on the results of the 2003 data. Figure 6 shows a comparison of the emission factors for EMFAC 2002, EMFAC2007, and the emission standards in g/bhp-hr. As indicated, EMFAC2007 smooth out the emission factors for both NO_x and PM.

Figure 6. EMFAC NO_x and PM In-use Estimate Compared to Dynamometer Standards

One of the concerns with EMFAC modeling is the changing emissions from one model version to the next. As shown in Figure 6, EMFAC2007 emission factors are greater than EMFAC2002 factors. These changes do not provide confidence that the next update, albeit with better data, will be any different. NO_x and PM inventories are estimated with this tool and poor estimates will lead to developing control strategies that do not achieve air quality standards.

Byron Bunker's presentation (EPA) provided comments on ARB's current approach to modeling emissions from heavy-duty vehicles. EPA's current approach to modeling heavy-duty vehicle emissions uses engine certification data obtained on an engine dynamometer. EPA uses a conversion factor to convert engine certification results in g/bhp-hr (or pollution per work) to g/mi. The conversion factor is expressed as follows:

$$CF\ (bhp\text{-}hr/mi) = \frac{\text{Fuel Density (lb/gal)}}{\text{BSFuelCons (lb/bhp-hr)} \times \text{Fuel Economy (mi/gal)}}$$

For the following nominal values for diesel fuel Mr. Bunker determined a CF of 3.25 bhp-hr/mi:

- Fuel density 7.11 lb/gal
- Brake specific fuel consumption (BSFuelCons) 0.372 lb/hp-hr
- Vehicle fuel economy 5.9 mpg

The heavy-duty vehicle NO_x standard in 2004 is 2.2 g/bhp-hr. Using the conversion factor (CF), this corresponds to 7.1 g/mile. EMFAC2007 zero mile emission factor is 12.7 g/mile at the average speed of the E55 UDDS test cycle (18.8 mph). The EPA g/mile estimate is based on an average speed of 48 mph. Figure 7 shows the comparison of these two NO_x emissions factors as a function of average vehicle speed.

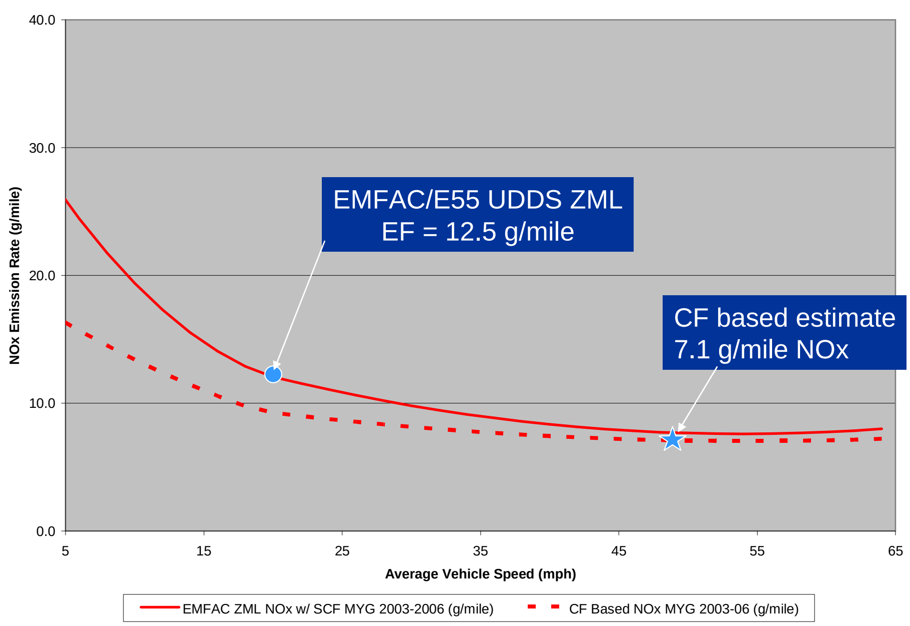


Figure 7. Comparison of EPA's NO_x Conversion Methodology to EMFAC2007 (based on E55 Data)

As shown in this comparison there is good agreement between EPA's conversion of engine dynamometer data and EMF2007 at the higher speeds. At lower speeds EPA's conversion method predicts lower in-use NO_x emissions than EMFAC2007. EMFAC2007 estimates are based on a number of different test cycles—all having different speeds—and, therefore. these estimates are more likely representative of in-use emissions. Using multiple test cycles provides better estimates of the NO_x emissions (as well as other emissions) over various speeds.

Dr. Benjamin explained in developing EMFAC2007 considerable more analyses were completed to estimate the in-use performance of 2007 and 2010 technologies. In 2007, diesel particulate filters will be required to reduce PM emissions. In 2010, NO_x aftertreatment will also be required. No aftertreatment is currently required (pre 2007 MYs) so deterioration may be quite different than for technologies without aftertreatment. Table 4 shows ARB's estimate of tampering, malfunction, and malmaintenance (TM&M) rates for 2010 technology (equipped with DPF and NO_x aftertreatment). These estimates are made considering systems that include OBD and systems that do not. OBD is estimated to reduce the TM&M rates. Compared to EMFAC2002 ARB's estimates of TM&M rates have increased considerably.

Table 4. Tampering and Malmaintenance Rates for 2010 Diesel Emission Controls

TM&M Act	EMFAC2002	EMFAC2007 wd	
	2003+	2010+ No OBD	2010+ w/OBD
NO_x Aftertreatment Sensor	n/a	53%	40%
NO_x Aftertreatment Sensor (R)	n/a	2%	11%
NO_x Aftertreatment Malfunction	n/a	17%	12%
PM Filter Leak	n/a	14%	10%
Electronics Failed	3%	30%	20%
Oxi Cat Malfunction/Removed	0%	5%	3%
EGR Disabled/Low Flow	15%	20%	13%

EMA and their consultant, Thomas Darlington of Air Improvement Resource, Inc argued that these failure rates of the various 2010 emission system components is too high— NO_x deterioration rates have been increased 5 to 7 times. Darlington gave one example of why he felt that ARB was over estimating NO_x emissions. ARB estimated failure for NO_x sensors is much higher than experience with light duty vehicle sensors. Darlington suggests that these high failures will not be accepted by the marketplace and the commercial relationship between engine manufacturers and their customers.

Byron Bunker of EPA also commented that ARB is more pessimistic than EPA on in-use deterioration of 2010 emission control systems. 2010 systems will provide a 96 percent reduction in NO_x emissions at zero miles compared to uncontrolled pre-1983 technologies. 2010 technology at ARB's TM&M rates would reduce emissions by 88 percent at 500,000 miles.

Other improvements to EMFAC2007 include updated idle emission factors for NO_x and PM. NO_x idle emission factors were changed as a function of engine technology (as represented by MYs) with lower rates in 1993 MY and older and higher rates than EMFAC2002 for 1994 MYs and newer. PM rates with deterioration were less than EMFAC2002 except for the MY grouping of 1994-1997. Speed correction factors were also added to EMFAC2007. Three NO_x and PM curves are now included for pre-1991 technologies, 1991-002, and 2003 plus technologies.

3.2 ARB's Proposed In-Use Compliance Program to Ensure Low Emissions

Mr. Stephan Lemieux of ARB provided an overview of how ARB plans to maintain the low emissions of the newer, heavy-duty diesel technology over their useful life. ARB's program has four primary elements:

- Progressively more stringent compliance standards
- Not-to-Exceed (NTE) compliance starting in 2005
- In-use compliance beginning in 2007 for gaseous emissions and 2008 for PM
- On-board Diagnostics (OBD) starting in 2007 and fully implemented by 2016

The in-use emission performance of heavy-duty vehicles has not necessarily followed the ever tightening standards as indicated in the last section. During the 1990's there was a general trend of increasing emissions even as the emission standards where lowering. This resulted in a closer look at the emission control systems employed by the engine manufactures and it was found that the manufacturers were changing controls during highway driving conditions (steady-state conditions). This led to higher NO_x levels in-use as illustrated in Figure 4 shown previously.

This led to an agreement between the engine manufacturers and regulatory agencies—ARB and EPA. As part of that agreement, the engine manufacturers agreed to a NTE test. This NTE test was made part of certification testing and is now required for all engines. Figure 8 shows the NTE region. The intent of this test is to ensure that for most of the on highway engine operating conditions that emission standards are not exceed. The previous certification test procedure included only the transient test cycle. The NTE can also be used in monitoring in-use vehicle emissions and not just used in engine certification testing.

Figure 8. NTE Test Region

Engine manufacturers are now also required to perform in-use compliance testing. This testing is generally performed on-road using portable emission monitoring (PEMs) equipment. The tests can also be performed on chassis dynamometers. ARB and EPA select various engine families to be tested and the engine manufacturers screen, procure and test the vehicles. Up to 25 percent of a manufacturer's engine families are tested. The purpose of these tests is to detect bad designs and durability issues in real world conditions—operating on road. Manufacturers are subject to remedial action if problems are found.

The next major tool to maintain low in-use emissions is OBD. OBD's purpose is to detect emission system failures. Starting in 2007 manufacturers will have to introduce the basic OBD system which will use only existing engine sensors, monitors and the engine monitoring system to detect problems with the emission system. This basic system will be expanded to include sensors to judge or determine the performance of the emission controls. This expanded OBD system will be phased in starting in 2010 with final compliance by 2016. Figure 9 lists the characteristics of the OBD systems.

ARB believes that these improvements will provide better control of the emissions from heavy-duty vehicles. New engines will have to meet very stringent emissions standards. In use or real world emissions will be controlled with NTE requirements. Low engine emissions will be sustained through in-use compliance and OBD.

- **Threshold monitoring**
  - **Warning light when emissions increase by a certain percentage**
  - **8-10 checks per engine, e.g., PM filter, EGR, NOx catalyst, fuel system**
- **Non-threshold monitoring**
  - **Functional, rational, electrical**
  - **75-100 checks per engine**
- **OBD testing and validation**

Figure 9. NTE Test Region

4. Advanced Emissions Monitoring Systems for In-Use Measurements

This section explores issues surrounding the use of emissions monitoring systems to collect in-use emissions data. Of significant concern is the technical readiness of in-use emissions monitors and how data from these systems can be utilized to improve emissions models.

4.1 Portable Emissions Monitoring (PEM) Equipment

Dr. Gautam, in the second half of his presentation, discussed West Virginia University's experience with portable emission monitoring equipment. WVU has been using designs of their own as well as PEM from commercial suppliers such as CATI, Horiba, and Sensors. The challenges of on board on road diesel emission monitoring include: accurately measuring torque, exhaust flow rate, and emissions. Factors that contribute to variations characterizing in-use emissions include variable fuel quality, environmental conditions, and engine conditions.

The concept of in-use emissions is to characterize the emissions performance of heavy-duty on road trucks over a variety of driving conditions like highway, city-suburban, city traffic conditions. Additional testing over a range of road/driving conditions and a range of ambient conditions to see how these conditions change in-use emissions is also desirable.

WVU has tested various PEM systems on their portable emission dynamometer and have compared the performance of these systems to laboratory grade instrumentation and measurement results. Figure 10 illustrates level of error in measuring NO_x that has been observed with these systems.

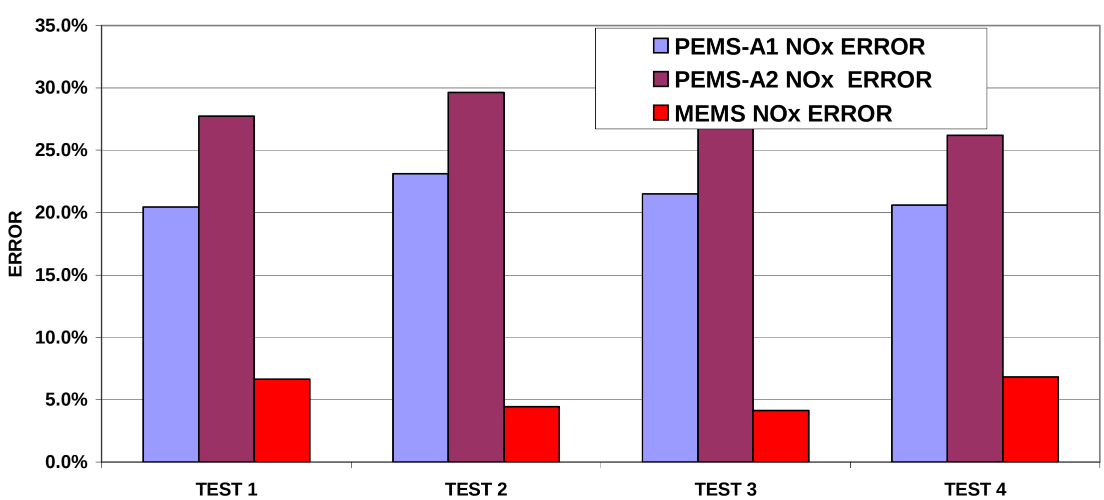


Figure 10. NO_x Measurement of Various PEM Equipment Compared to WVU Chassis Dynamometer Measurement System

WVU has characterized the errors associated with using the engine control unit (ECU) derived torque compared to measured shaft torque. WVU sees high errors at low torque and decreasing error at higher torque levels. Over the NTE region the average error was found to be -3.48 percent. Figure 11 compares the error from three transient test cycles (cycle used in certification testing FTP).

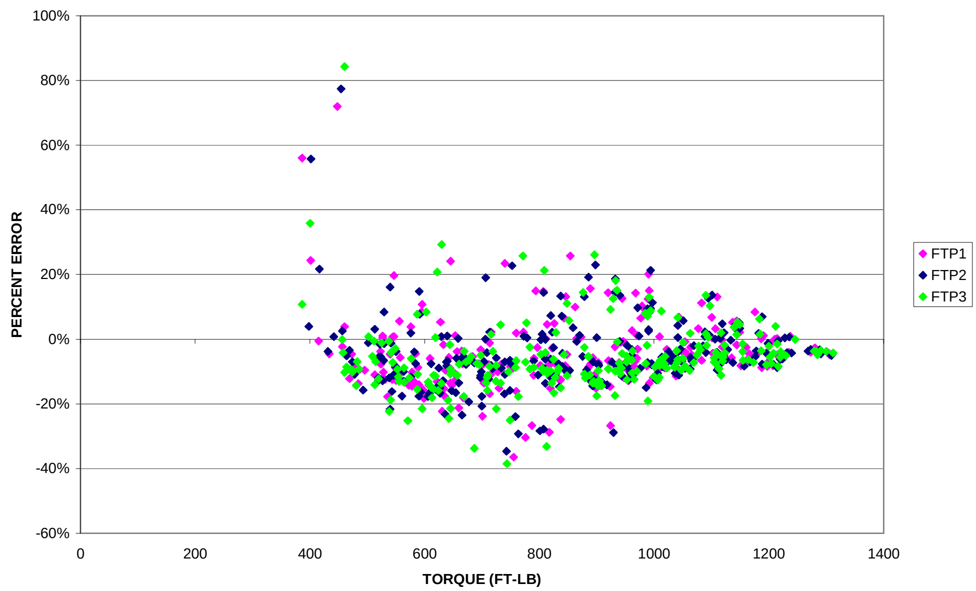


Figure 11. Torque errors within NTE Region as tested over Transient Cycle FTP

4.2 Use of PEMs in over the road testing

Dr. Gautam also showed the effects of fuel variation. NO_x emissions decreased with lower aromatics and higher cetane fuels. The variation in commercial fuels could have a 12 percent effect on NO_x. The variation in PM was higher at 50 percent with a sulfur content range from 40 ppm to 410 ppm (on-highway diesel is now limited to 15 ppm).

Relative to environmental effects on emissions—temperature and pressure—WVU observed 12 percent variation in NO_x, 46 percent variation in PM, 11 percent variation in CO, and 30 percent variation in HC. Conditions varied in this set of experiments included fuel temperature, intercooler temperature, intake air temperature, and airflow restriction.

All of these factors introduce uncertainties in emissions measurements in-use. Dr. Gautam summarized lessons learned with portable emissions measurement equipment:

- Driver impact on emissions not as great as had been expected
- Emissions at low engine speed and power are difficult to quantify (due to low exhaust flows)

- Changes in atmosphere conditions affect emissions more than expected
- Fuel quality can have a major impact on emissions

The main message here is that there are a number of factors that will contribute to in-use measurements and as the instrumentation and procedures are developed more sophisticated systems may be necessary to correct for some of these variables.

4.3 Comments on PEM Use

Several presenters commented on the use of PEMs. This section summarizes their comments.

Bryon Bunker, EPA, discussed EPA's actions to ensure in-use compliance of heavy-duty diesel vehicles. EPA's program uses portable testing equipment that rides on the truck. Two duty cycles have been developed: local driving route (2.5 hrs, 68 miles) and marathon route (3,500 miles). The program started in 2001 and 372 trucks/engines have been tested so far. The trucks were obtained from a variety of owners: private companies, government agencies, truck rental companies, and private individuals. Vehicles were tested using the NTE test procedure.

Figure 12 shows one of the results presented by Mr. Bunker. This figure shows the highest NO_x emissions on various segments of the marathon route (3,500 miles, various altitudes) and on the local driving route (APG; 68 miles, 2.5 hrs, no elevation change). Most measurements are below the NTE level of 3.1 g/bhp-hr. Although not shown here the average NO_x for these same routes and segments ranged from 2 g/bhp-hr to 2.5 g/bhp-hr and the average grams per mile ranged from 8 g/mi to 12 g/mi with the local "APG" route having the highest NO_x.

Thomas Darlington, Air Improvement Resources, Inc., showed data taken by WVU using PEMs equipment. An example of in-use data compare to chassis emissions data is shown in Figure 13. The on-road data, shown on the left hand side of this figure, show similar emission trends for the MY groupings as does the chassis data from the CRC E55/59 project. In addition, Darlington contented that the on-road data in the figure show that the recent emission standards changes from 5.0 to 4.0 g/bhp-hr from 1997-1998, and from 4.0 g/bhp-hr to 2.5 g/bhp-hr (NMHC+NOx) from 2002 to 2003, coupled with NTE requirements, are reducing on-road NOx emissions from heavy-duty trucks. The agreement between the two sets of data indicates the usefulness of on-board data which are being generated during compliance testing and may therefore be added to the chassis testing results. These PEM data will greatly increase the amount of data needed for statistical correlations.

ARB also agreed that as PEM technology improves with experience they might be able to use the in-use compliance data set to determine emission factors. Most presenters agreed that PEM systems were a good tool and will provide valuable data. PEM technology is a good tool for compliance

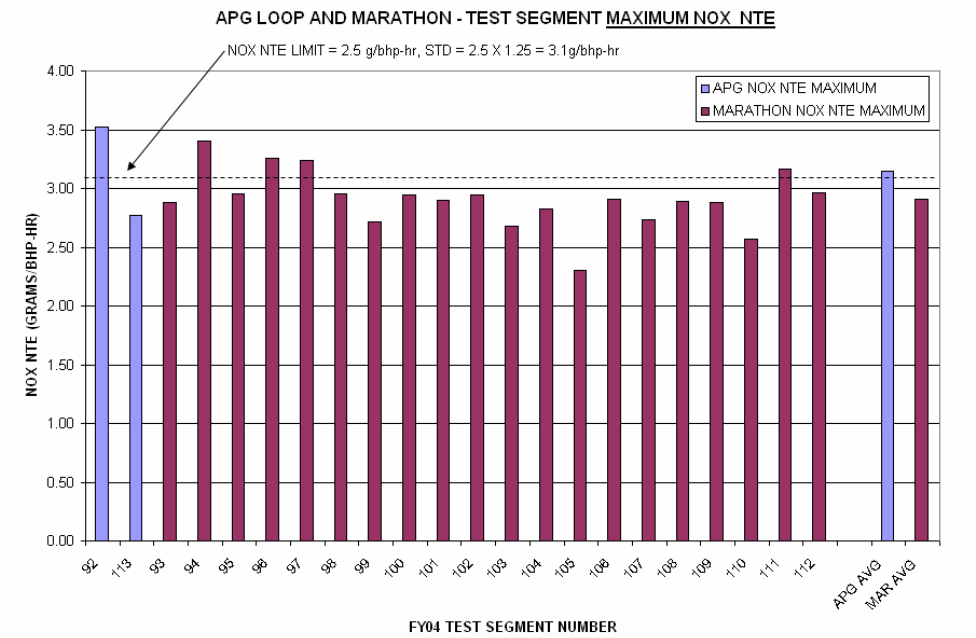


Figure 12. Example of Maximum NO_x NTE Measured Over Local and Marathon Routes