EVALUATION OF ON-ROAD RESULTS FROM A TEST FLEET OF HEAVY-DUTY TRUCKS

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Abstract

New and upcoming regulations for heavy-duty diesel (HDD) on-road vehicles are expected to provide significant reductions in the emissions from newly purchased HDD vehicles. California also has a Heavy Duty Vehicle Inspection and Periodic Smoke Inspection Program (HDVIP and PSIP) in place for in-use HDD vehicles, but this only monitors smoke opacity. CARB has conducted several pilot studies to understand the incidence of malmaintenance and tampering in heavy-duty diesel vehicles (HDDVs) and to develop a program to control emissions from in-use trucks. In the earlier Measure 17 or M-17 program, 109 vehicles were tested at the CARB Heavy-Duty Inspection and Maintenance Laboratory (HDIML) facility in Stockton CA over a power lug curve and a steady-state cycle. The objective of the current program was to collect in-use, on-road emissions measurements on a subfleet of 5 vehicles in the Stockton, CA area. Emissions measurements were made with the University of California at Riverside's (UCR's) Mobile Emissions Laboratory (MEL), which is mobile measurement platform with a full dilution tunnel. The results of this study provide information about emissions from in-use HDDVs under typical driving conditions and can be used to better understand emissions inventories and in the development of regulations for in-use vehicles.

Executive Summary

Heavy-duty diesel (HDD) on-road vehicles are a major source of nitrogen oxides (NO_x) and particulate matter (PM) emissions in California and throughout the country. Starting in 2007, new State and Federal regulations will require a more stringent NO_x (0.20 grams per brake horsepower-hour [g/bhp-hr], phasing in 2007) and PM (0.01 g/bhp-hr) standard and will necessitate the use of diesel particulate filters to reduce PM emissions. Additional control measures targeted at the current in-use HDD population are needed, due to low fleet turnover rates. California currently has in place a Heavy Duty Vehicle Inspection and Periodic Smoke Inspection Program (HDVIP and PSIP), but these are not considered to be comprehensive enough because they focus solely on smoke opacity. The California Air Resources Board (CARB) is working on an expanded in-use compliance program and additional market-based incentives for cleaner engines to provide greater reductions.

CARB has conducted several pilot studies to understand the incidence of malmaintenance and tampering in heavy-duty diesel vehicles (HDDVs) and to develop a program to control emissions from in-use trucks. CARB surveyed warranty records and found that incidences were comparable to those currently being used in CARB's emissions inventory models, although records for repairs outside of warranty could not be obtained. Under a second program, the Measure 17 or M-17 program, 109 vehicles were tested at the CARB Heavy-Duty Inspection and Maintenance Laboratory (HDIML) facility in Stockton CA over a power lug curve and a steady-state cycle. The objective of this program was to develop a simple roadside inspection test that would identify or repair trucks with excess emissions due to tampering and malmaintenance.

The focus of this study was to collect in-use, on-road emissions measurements on a subfleet of 5 vehicles in the Stockton, CA area. The vehicles included trucks with the following engines: a 1996 Cummins M-11, 2000 Caterpillar C-15, 2002 Detroit Diesel Series 60, 2003 Mack AC 427, and a 2004 Cummins ISM. The vehicles were tested over a road course that included driving under both highway conditions on State Route 99 (SR-99) and Interstate 5 (I-5), steady state driving on a surface street, stop and go driving on a surface street (Hammer road), and power lugs where the vehicle was held at a maximum rpm and the brake slowly applied to apply a load to the system. The power lugs were designed as a bridging test that could be conducted on the road and at the Stockton Laboratory chassis dynamometer and are not intended to represent real-world driving conditions. Emissions measurements were made with the University of California at Riverside's (UCRs) Mobile Emissions Laboratory (MEL), which has a full dilution tunnel system housed in a trailer that is used as a mobile measurement platform. The results of this study provide additional information about emissions from in-use HDDVs under actual driving conditions.

A summary of the results is as follows:

The on-road testing results in grams per mile (g/mi) for NO_x, PM, THC, and CO are provided in Figures ES-1 and ES-3-5, respectively. Fuel-based emissions for NO_x are also shown in Figure ES-2. EMFAC Emission factors for several speeds from CARB's EMission FACtors (EMFAC) model are also included in the g/mi plots for several speeds, with the base EMFAC emissions representing approximately 20 mph. Overall, the results show that emissions depend on: the

specific emissions component, the type of vehicle, and driving condition. Real-time gaseous data showed that emissions were transient and depend heavily on the specific mode of engine operation, as expected.

For NO_x emissions, the oldest vehicle, 1996 Cummins, had the highest emissions for nearly all types of driving. The on-road emissions measurements were generally comparable to those from EMFAC, with the highway measurements higher than the EMFAC values for the 1996 Cummins, while the steady state (40-65 mph) emission rates for the 2004 Cummins, the 2002 DDC, and 2000 Caterpillar were generally lower than those for EMFAC. Some vehicles showed a tendency toward higher NO_x emissions for the higher speed events ($\geq$55 mph) compared to the 40 mph cruise and the other surface street driving (1996 Cummins and the 2002 DDC), while others did not show as large a difference between different types of driving (2000 Caterpillar, 2003 Mack, and 2004 Cummins). The highest NO_x emissions in g/mile for all vehicles were found for the power lug segments, although on a fuel specific basis, the power lug emissions were comparable to those of the other driving conditions.

Figure ES-1. On-Road NO_x Emissions

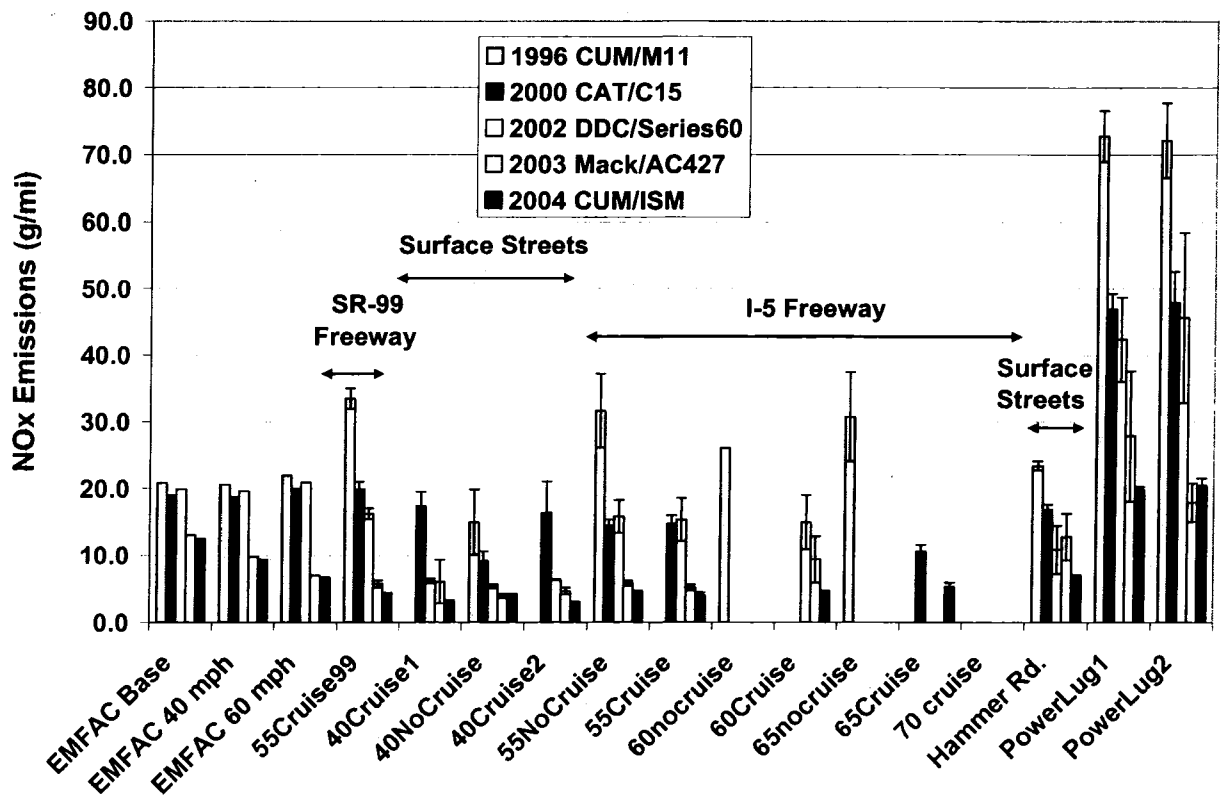
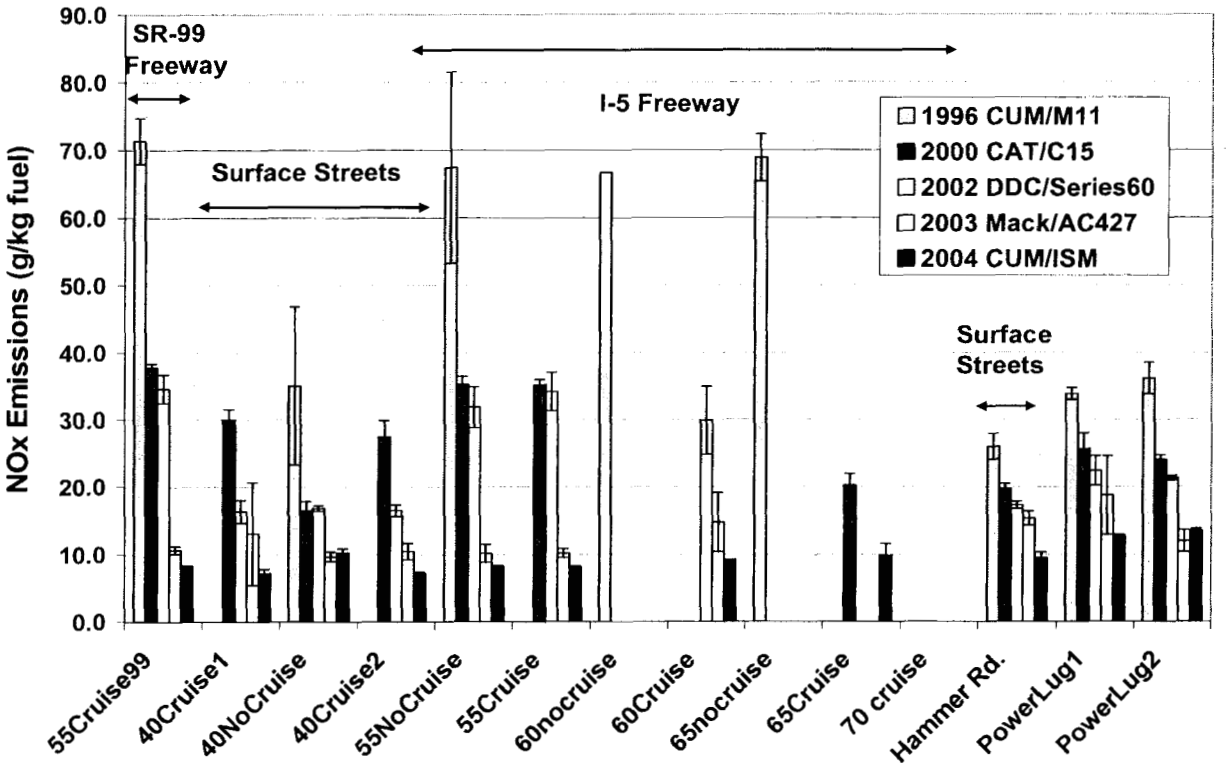
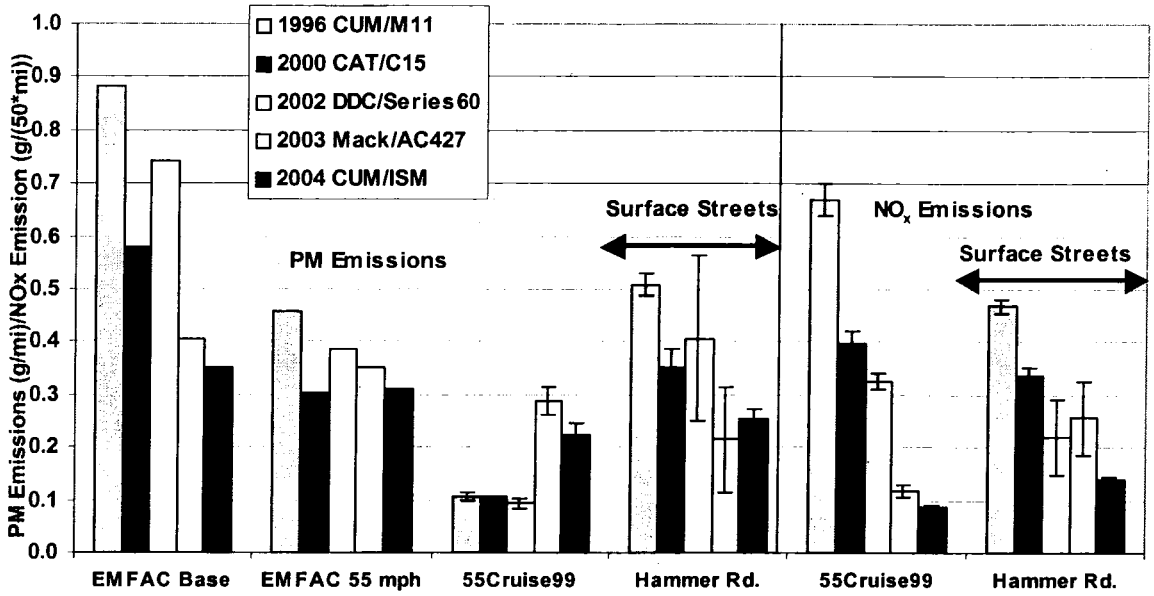


Figure ES-2. On-Road Fuel Specific NO_x Emissions



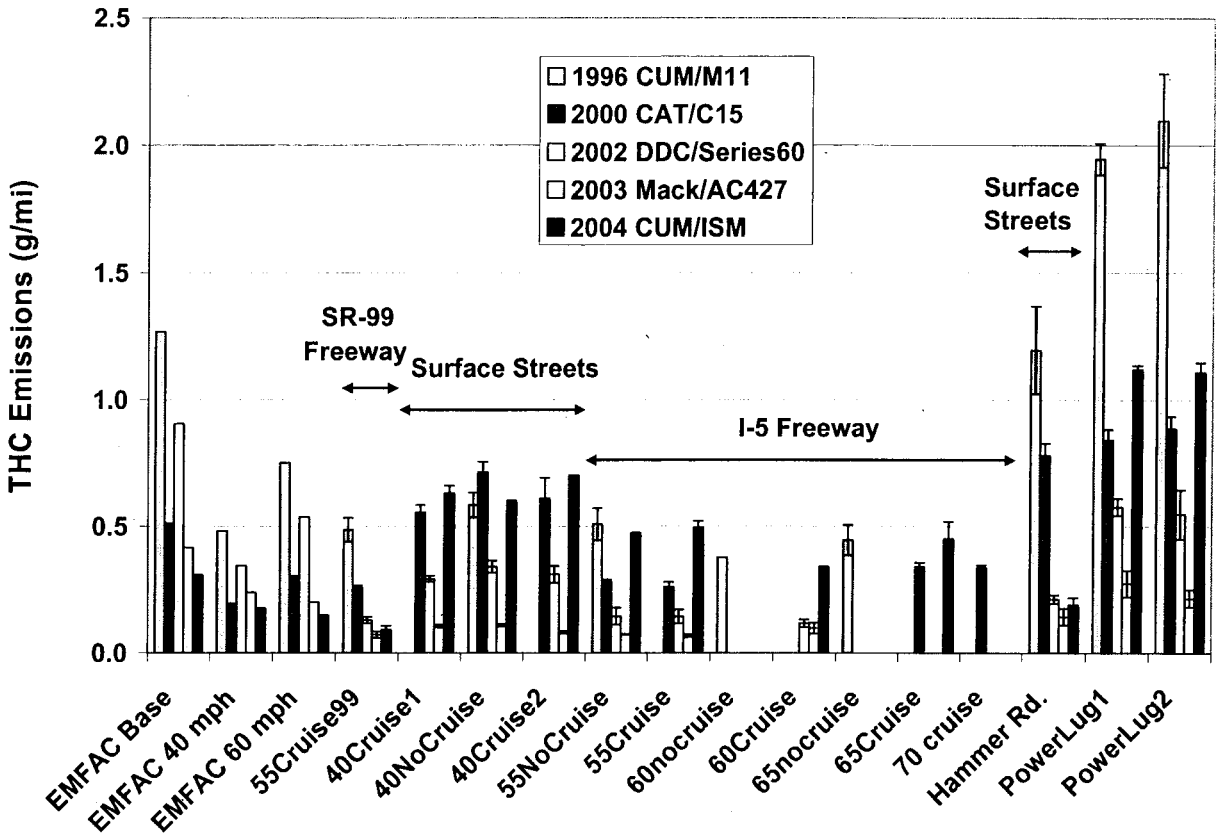
The PM emissions results showed some interesting trends. For surface street driving (Hammer Rd.), the highest average PM emissions were found for the oldest vehicle, while for highway driving on the SR-99, the two newest vehicles had the highest PM emissions. Corresponding NO_x emissions were lower for the newer vehicles for SR-99 indicating that there appears to be a NO_x/PM tradeoff under these operating conditions. Some of the test vehicles showed a trend of higher PM emissions on the surface streets as opposed to the highway driving (the 1996 Cummins, 2000 Caterpillar, and the 2002 DDC). For both operating conditions, the PM emission rates were lower than the PM emission factors from EMFAC.

Figure ES-3. On-Road PM Emissions



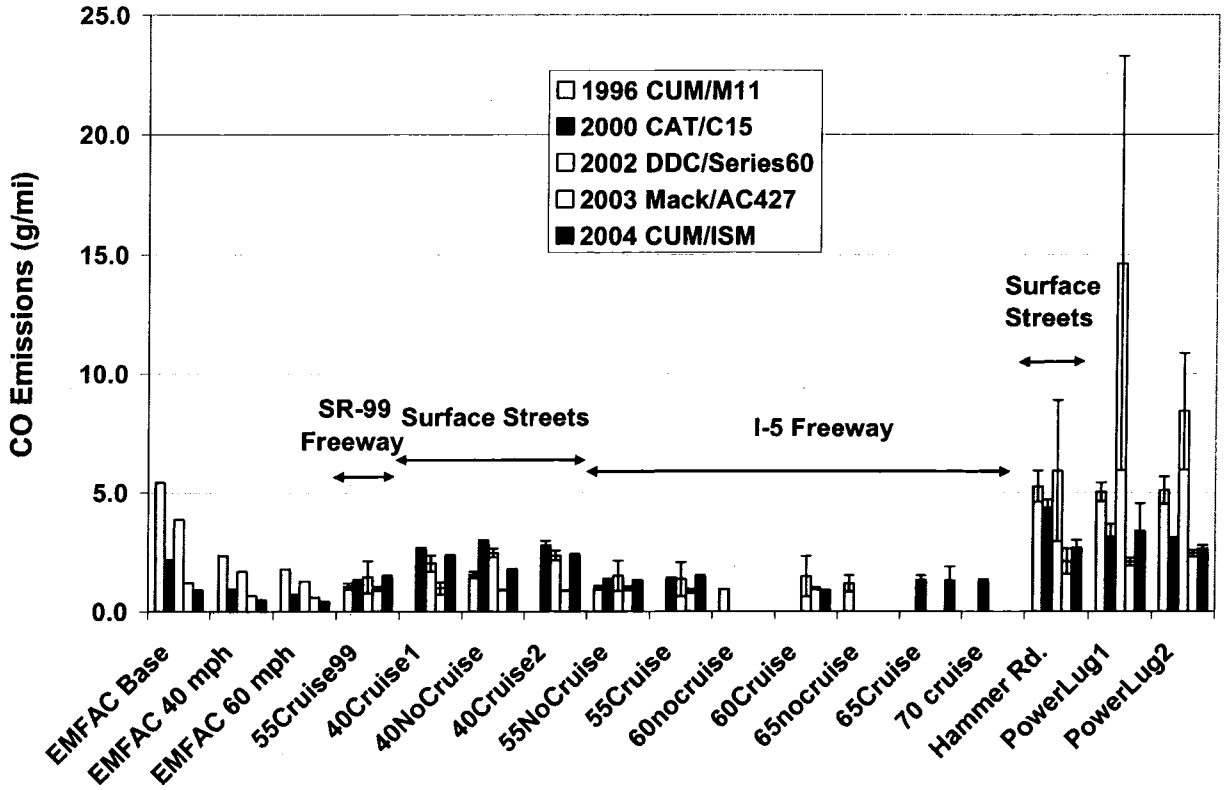
The on-road THC emission rates were comparable to those of EMFAC. Compared with EMFAC, some vehicles showed higher emissions than EMFAC under certain conditions (2000 Caterpillar and 2004 Cummins), while other showed lower emissions (1996 Cummins, 2002 DDC, and 2003 Mack). The 2003 Mack had the lowest THC emissions, with the emission for the 2002 DDC also generally lower than the remaining vehicles. Some vehicles showed a tendency for higher emissions for the surface street segments compared to the steady state segments (the 1996 Cummins). Other vehicles showed a tendency for higher emissions for the 40 mph cruise segments compared to the highway cruise segments (the 2000 Caterpillar and 2002 DDC). THC emissions were found to be highest for the power lug segments, although the fuel-based power lug emissions were comparable to those of other driving conditions.

Figure ES-4. On-Road THC Emissions



CO emissions under steady state driving conditions were relatively low, ranging from slightly less than 1 g/mi to approximately 3 g/mi. Of the real world driving conditions, CO emissions were highest for the surface street driving on Hammer road with lower CO emissions for the higher speeds. There was a reasonable comparison between the on-road measurements and the EMFAC emission rates, and the trends in the on-road data were consistent with the trends in the EMFAC emission factors with speed. The newer (2000 model year and newer) vehicles all tended to have slightly higher emissions than the corresponding EMFAC emissions factors. The older 1996 truck had slightly lower emissions than EMFAC, expect for the tests on Hammer road, which were comparable. CO emissions are highest for the power lug segments, although the fuel base emission rates for the power lug segment were comparable to those for the typical on-road driving. Real-time CO emissions show peaks on the accelerations during the surface street driving.

Figure ES-5. On-Road CO Emissions



1.0 Introduction

Heavy-duty diesel (HDD) on-road vehicles are a major source of nitrogen oxides (NO_x) and particulate matter (PM) emissions in California and throughout the country. State and Federal regulatory actions have been proposed to reduce emissions from future heavy-duty vehicles. However, additional control measures targeted at the in-use HDD population are needed due to low fleet turnover rates.

In response to this problem, increasing interest has been placed on developing in-use compliance programs. Unlike light-duty trucks and passenger cars, the current HDD inspection and maintenance program in California is limited to the Heavy Duty Vehicle Inspection and Periodic Smoke Inspection Programs (HDVIP and PSIP). These programs are not as comprehensive as the current light duty program (Smog Check) in California, which requires vehicles to be tested on an inspection grade chassis dynamometer every 2 years. The California Air Resources Board (CARB) is working on an expanded in-use compliance program and additional market-based incentives for cleaner engines with a goal to achieve reductions of 10 tons per day in NO_x emissions and 1 ton per day of reactive organic gases (ROG) in the South Coast Air Basin by 2010.

To better understand the incidence of malmaintenance and tampering in heavy-duty diesel vehicles, a pilot study was initially conducted to evaluate malfunction rates in heavy-duty diesel trucks. This research was aimed at validating the incidence factors for 19 categories in the EMFAC model for heavy-duty diesel vehicles (HDDVs), using surveys and currently existing data. A significant amount of information covering the warranty period of the vehicles was analyzed with the results being consistent with the incidence rates used in the current EMFAC model. The incidence rates of failing components beyond the warranty period were expected to be higher, but the information needed to make estimates for this period could not be obtained from the original equipment manufacturers (OEMs).

A second research program was the Measure 17 or M-17 program. This project originated as part of a court settlement dealing with California's State Implementation Plan (SIP). M-17 called for CARB to investigate the feasibility of a simple roadside inspection program that would identify and repair trucks with excess NO_x emissions due to tampering and malmaintenance. CARB developed a Heavy-Duty Vehicle Inspection and Maintenance Development Laboratory (HDIML) in Stockton, CA. In the period between 4/19/2001 to 3/6/03, 109 vehicles were tested at the CARB HDIML facility in Stockton CA. Vehicles were tested using two cycles, including a lug curve at the governed maximum RPM and a steady-state 60 miles per hour (mph) cycle at 3 load points. Vehicles with high NO_x emissions were then repaired and retested.

The objective of the current program is to continue efforts to enhance the M-17 program and to evaluate in-use emission rates of HDDVs under on-road conditions. As part of this program, University of California at Riverside's (UCRs) Mobile Emissions Laboratory (MEL) has taken several trips to the Stockton area. Measurements of in-use emissions were made for 5 trucks over roadways near the Stockton, CA area. The results of these measurements are provided in the following report.

2.0 Experimental Procedures

CE-CERT Mobile Emissions Laboratory

UCR has built a unique heavy-duty diesel laboratory that utilizes a full flow dilution tunnel and laboratory grade instruments, but is fully mobile. The transportable nature of the Mobile Emissions Laboratory (MEL) makes it ideal for traveling to Stockton where is can be used in conjunction with the ongoing efforts there. The primary dilution system is configured as a full-flow constant volume sampling (CVS) system with a smooth approach orifice (SAO) venturi and dynamic flow controller. Tunnel flow rate is adjustable from 1000 to 4000 scfm with accuracy of 0.5% of full scale. It is capable of total exhaust capture for engines up to 600 kW.

The MEL contains a suite of gas-phase analyzers on shock-mounted benches. The gas-phase analytical instruments measure NO_x, methane (CH_4), total hydrocarbons (THC), carbon monoxide (CO), and carbon dioxide (CO_2) at a frequency of 10 Hz and were selected based on optimum response time and on road stability. Data can be collected modally or in 200-L Tedlar bags over a complete test cycle. Sample collection is automated with Lab View 7.0 software (National Instruments, Austin, TX).

PM mass measurements are made by drawing a sample from the primary tunnel into a uniquely designed secondary tunnel. The secondary dilution tunnel incorporates many of the requirements specified in 40CFR§86.1310-2007, including the control of filter face temperature to ±5 °C at a fixed mass flow ratio and a pre-classification of the PM sample. A multiple jet particle trap impactor is used to provide a 50% cutoff for course particles greater than 2.5 μm in diameter. The secondary tunnel has several attached ports to allow simultaneous collection of $PM_{2.5}$ onto three separate filter media and up to four phases before reloading sample media.

A schematic of MEL and its major subsystems is shown in Figure 1.

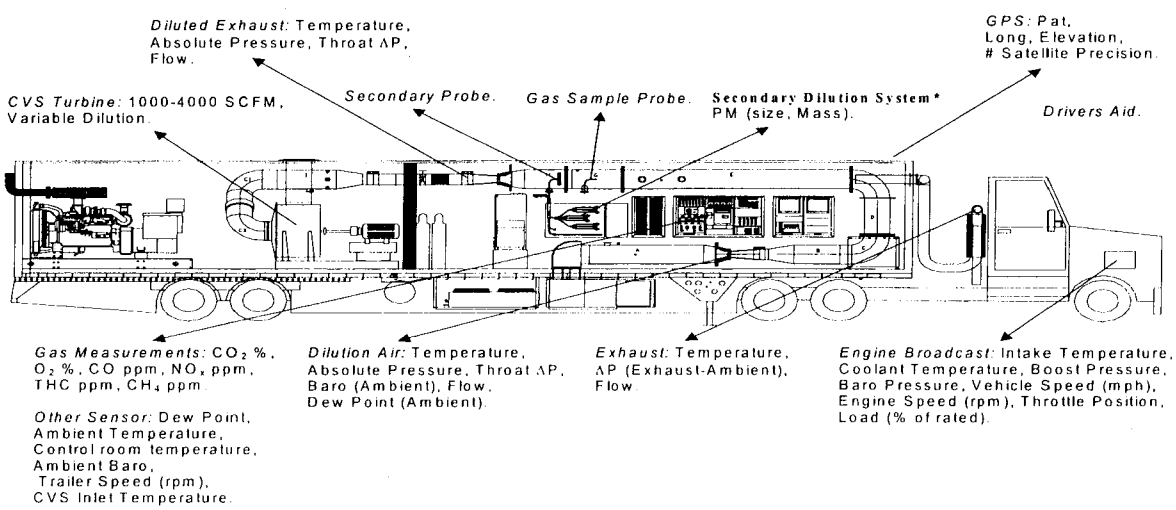


Figure 1. Major Systems within the Mobile Emission Lab

On-Road Test Routes

On-road measurements were made with the UCR MEL for a set of HDDVs. A road course was developed that included driving under both highway conditions and surface street conditions near Stockton, CA. The first segment of the cycle involved steady state driving on State Route 99 (SR-99) at a speed of approximately 55 miles per hour (mph) with the cruise control on. This segment covered approximately 11 miles. For the second segment of the cycle, the trucks were driven over side streets between the SR-99 and Interstate 5 (I-5). Steady state tests at 40 mph with and without cruise control were performed during this segment. During this portion of the cycle, power lug tests were also conducted where the vehicle was held at the maximum rpm and the brake slowly applied to apply load to the system. These power lug curves were not designed to be representative of actual in-use driving, but rather to simulate test conditions similar to those that could be conducted on the Stockton Laboratory chassis dynamometer. The vehicles were then driven on the I-5 where they were tested at various steady state speeds ranging from 55 to 70 mph, generally with the vehicle in cruise control. Finally, the vehicle was driven back using surface streets to the Stockton Laboratory. This segment of road was more heavily populated with businesses and included stop and go driving. The on-road tests were conducted at least twice for each HDDV. All tests for a single vehicle were conducted either the same day or on two back-to-back days. The test route is described in Table 1 and Figure 2 below.

Table 1. Test Route Description

Segment	Description	Cycles Performed
1	Steady State Driving on State Route 99	55 mph cruise
2	Surface streets between the SR-99 and I-5	Power Lug, 40 mph (w and w/o cruise)
3	Steady state driving on the I-5 at different speeds	Cruise 55, 60, 65 and 70 mph
4	Surface streets returning to the Stockton Laboratory	Follow normal traffic pattern through business district

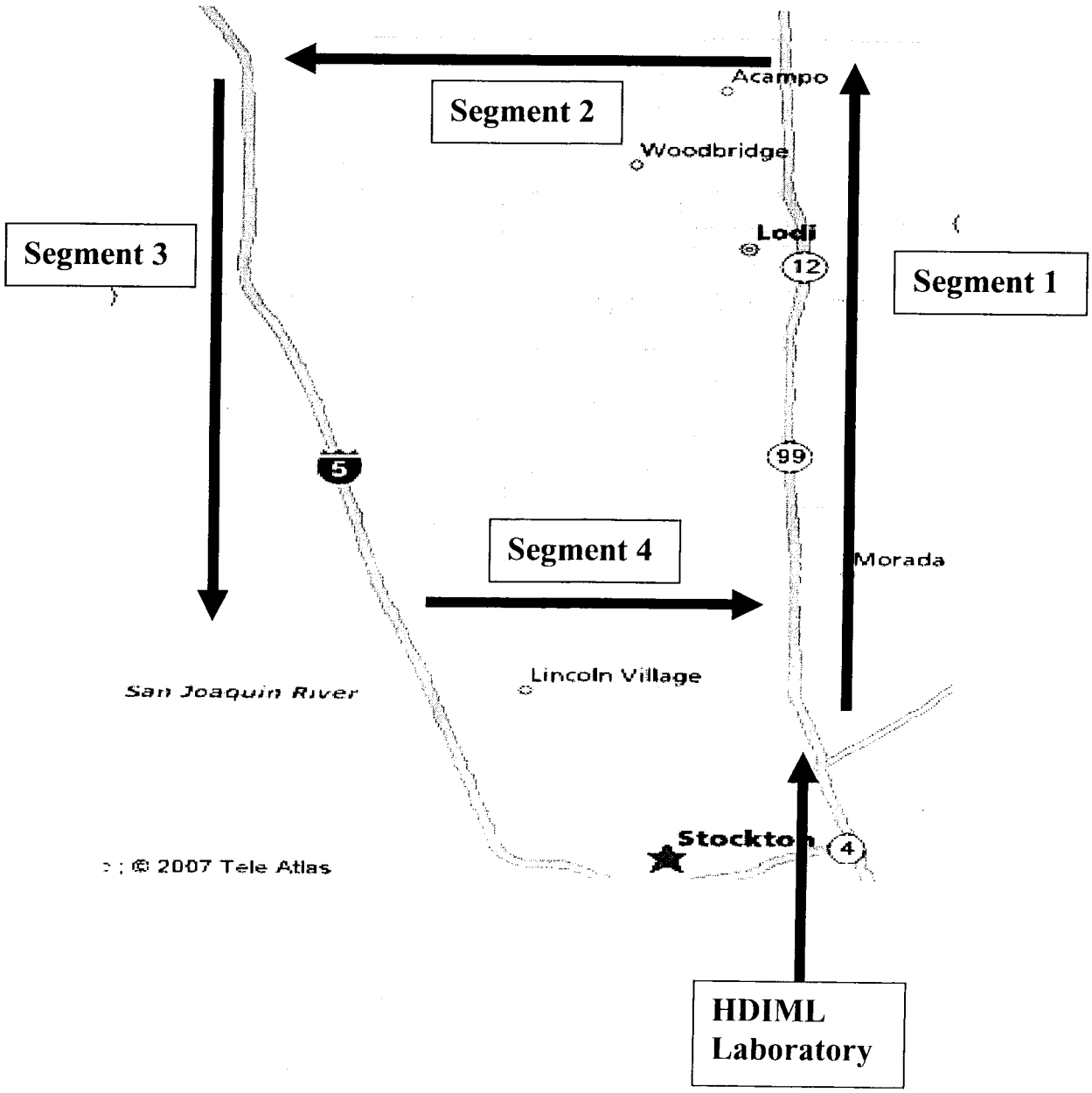
Test vehicles

A total of 5 HDDVs were tested over the on-road course in Stockton, CA. The vehicles included the UCR in-house, class 8 heavy-duty truck and four other trucks recruited through rental facilities and other outside sources. A description of the trucks is provided in Table 2. Overall, the engines represent 2000 and newer engines, with one older 1996 engine. Two of the five vehicles had relatively low mileages. The 1996 Cummins and 2000 Caterpillar were tested in April/May of 2004 while the other three vehicles were tested in June of 2005.

Table 2. Vehicle/Equipment Descriptions for Test Fleet

Year	Engine	Chassis	Odometer (miles)
1996	Cummins M-11	Freightliner	337,024
2000	Caterpillar C-15	Freightliner	17,826
2002	Detroit Diesel Series 60	Freightliner	181,328
2003	Mack AC427	Mack	107,567
2004	Cummins ISM	International	7,664

Figure 2. Map of In-use Test Route



3.0 Results

The on-road testing results for NO_x, PM, THC, and CO, respectively, are provided in Figures 3, 5, 7, and 9 on a g/mi basis. NO_x, PM, THC, and CO emissions, respectively, per mass of fuel are also provided in Figures 4, 6, 8, and 10. The values represent averages over all tests conducted on each vehicle for a particular travel segment or mode of operation. The individual power lugs and 40 mph cruise segments are listed separately since they were conducted at specific parts of the test route. For the driving on the I-5, a range of different speeds was used throughout the testing from 55-70 mph, hence data for a particular speed may be available for some vehicles but not others. Error bars represent one standard deviation of all measurements conducted under a particular test condition.

Emission factors from EMFAC are also provided in the figures with g/mi results. These emission factors are based on the running exhaust emissions factors being used in the current EMFAC2007 and the associated deterioration factors (Zhou, 2006). The base EMFAC emission factors for each of the test vehicles were determined using the zero-mile rates for the corresponding model year of the vehicle and multiplying the vehicles mileage by the deterioration rate. The base emission factors are representative of emissions expected for a speed around 20 mph. This is in the range of speeds found for the testing on Hammer road, although these test runs ranged from approximately 16 to 34 mph. The EMFAC emission factors using the speed correction factors for 40 mph and 60 mph are also included since these provide a comparison for the higher speed steady state driving segments that were performed. It is important to note that the EMFAC emission factors are meant to be representative of fleet average emissions for a particular model year, mileage, and speed. These may not necessarily be representative of the individual vehicles tested for this program.

The real-time results for the different vehicles are presented in Appendix B.

NO_x Emissions

The results show that emissions vary depending on the specific emissions component, the type of vehicle, as well as driving condition. For NO_x emissions, the oldest vehicle, 1996 Cummins, had the highest emissions for nearly all types of driving. The 2003 Mack and 2004 Cummins had the lowest NO_x emissions over the different driving conditions, with the emissions for the 2004 Cummins generally being below those of the 2003 Mack.

The NO_x emission rates in g/mi are relatively comparable to the base emission factors for EMFAC. The emission factors for the highway cruise for the 1996 Cummins were generally higher than those for EMFAC, while the emission factors for the steady state (40-65 mph) driving conditions for the 2004 Cummins, 2002 DDC, and 2000 Caterpillar were generally lower than those for EMFAC. The emission measurements for the 2003 Mack showed good comparability with the EMFAC emission factors.

The 1996 Cummins and the 2002 DDC showed some tendency toward higher NO_x emissions for the higher speed events ($\geq$55 mph) compared to the 40 mph cruise and the other surface street driving. This trend was seen in both the g/mi and fuel-based emission rates. The other three vehicles had comparable emissions for the surface street and highway driving.

Figure 3. On-Road NO_x Emissions

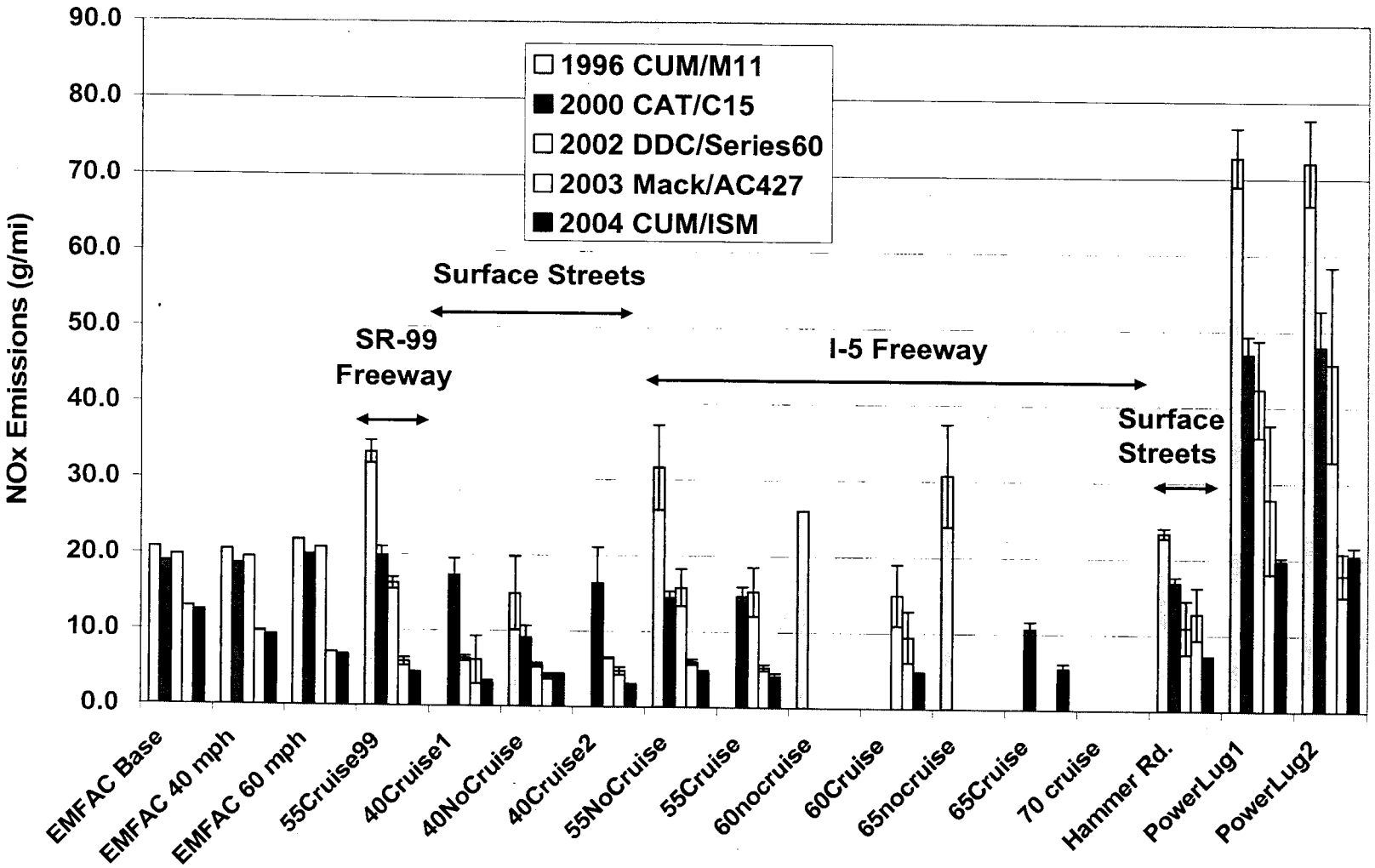
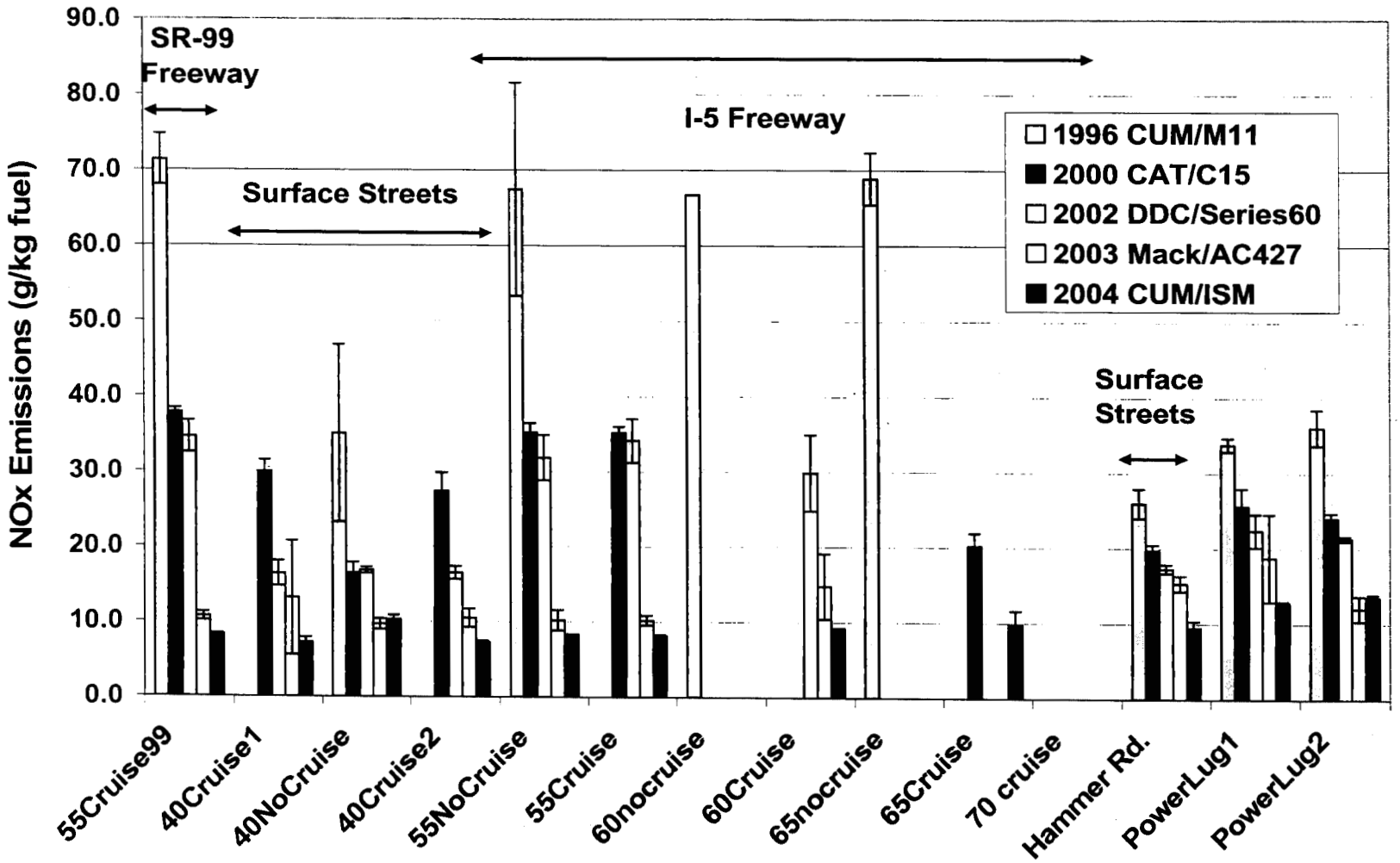


Figure 4. Fuel Specific NO_x Emissions



The power lug segments provided the highest NO_x emissions on a g/mi basis, since they represent an aggressive driving condition that is not typical of in-use driving. On a fuel specific basis, however, the emissions during the power lug were only slightly higher than the typical surface street driving on Hammer road.

The real-time data show that NO_x emissions are transient with responses during accelerations. The real-time data show that the 1996 Cummins had higher baseline emissions during the steady state runs, contributing to the overall higher emission rate. The differences in the steady state emissions for the 1996 Cummins and the 2002 DDC at the 40 mph and the higher speeds is also visible in the different baselines in the real-time data. The 55 mph cruise on the SR-99 also shows that the vehicles accelerated and decelerated during this segment to maintain the 55 mph cruise speed. This was due in part to small elevation changes that occur in the roadway.

PM Emissions

The PM emissions results showed some interesting trends. PM filters were collected for only 2 driving segments, the SR-99 and the Hammer Rd. surface streets. The corresponding NO_x emissions are also shown in the Figures. For both operating conditions, the PM emission rates were lower than the PM emission factors from EMFAC for all vehicles. Interestingly, for the highway driving on the SR-99, PM emissions were highest for the two newest vehicles, i.e., the 2003 Mack and the 2004 Cummins. Corresponding NO_x emissions were lower for the newer vehicles for SR-99 indicating that there appears to be a NO_x/PM tradeoff under these operating conditions. This PM trends are somewhat reversed on the surface street driving, however, where the highest average PM emissions were found for the 1996 Cummins. The 1996 Cummins, 2000 Caterpillar, and the 2002 DDC all showed considerably higher PM on the surface street driving compared to the highway driving. The PM emissions for the two newest vehicles, on the other hand, had similar PM emissions for the highway and surface street driving. The trends for the fuel-based emission factors were comparable to those found for the results in g/mi.

Figure 5. On-Road PM Emissions

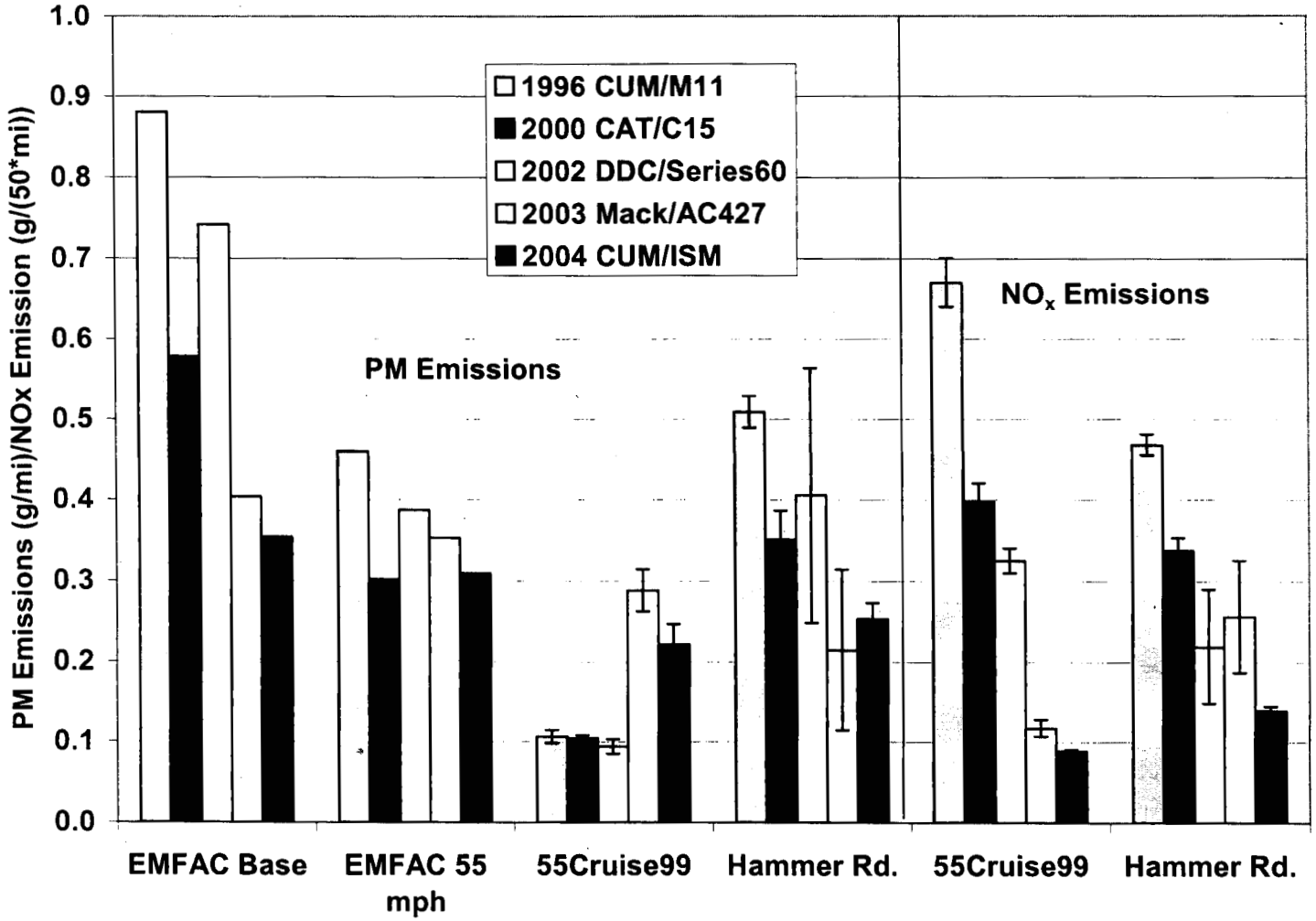
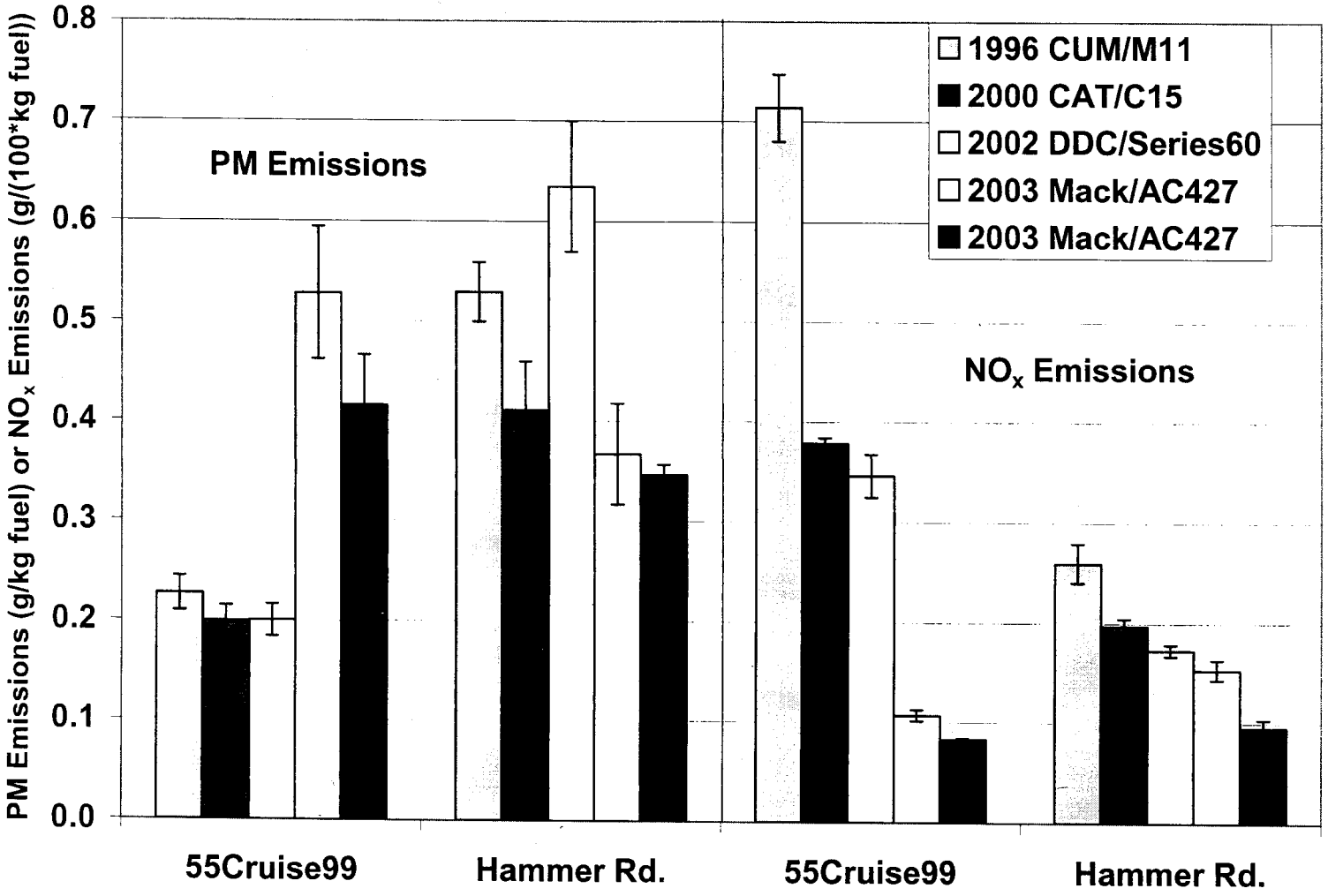


Figure 6. Fuel-Based PM Emissions



THC Emissions

The 2003 Mack had the lowest THC emissions, with the emissions for the 2002 DDC also generally lower than the remaining vehicles. The emission rates for the 2003 Mack were generally lower than those for EMFAC for the different driving conditions. The emission rates for the 2002 DDC were lower than those for EMFAC for the Hammer road and highway driving, but were comparable to those of EMFAC for the 40 mph steady states. The 2002 DDC showed higher emissions on the lower speed steady state cruises at 40 mph than the highway steady state driving. This trend was seen for the emissions on a g/mi basis and for the fuel-based emission rates.

Other vehicles showed a tendency for higher emissions for the surface street and 40 mph cruise segments compared to the highway cruise segments. For the steady state driving, the 2000 Caterpillar showed the highest emissions at 40 mph followed by the 65 to 70 driving and then by the 55 mph. The fuel specific THC emissions were also higher for the 2000 Caterpillar at 40 mph compared to the higher speeds. The emission rates for the 2000 Caterpillar were comparable to those from EMFAC for the higher speed driving, but were higher than the EMFAC factors for Hammer road and the 40 mph steady states.

The 1996 Cummins had higher THC emissions for the surface street driving on Hammer road than any of the steady state cruise cycles between 40 and 65 mph on a g/mi basis. A similar trend was not found for the fuel-based emission rates. The real-time data show that the actual emission peaks as a function of time for the 1996 Cummins on Hammer road are similar in magnitude to those of the steady state driving. The emissions are higher on a g/mi basis due to the lower number of miles driven. The emission rates for the 1996 Cummins were comparable to those of EMFAC for Hammer road and the 40 mph steady state, but were lower than the EMFAC values at the higher speeds.

The emission rates for the 2004 Cummins were higher than the EMFAC rates for the 40 mph and higher steady states, but were lower than the EMFAC factors for Hammer road.

THC emissions on a g/mi basis were found to be highest for the power lug segments for most conditions, although this is not representative of typical in-use driving. The fuel-based THC emissions during the power lug were comparable to those found under the other operating conditions.

Figure 7. On-Road THC Emissions

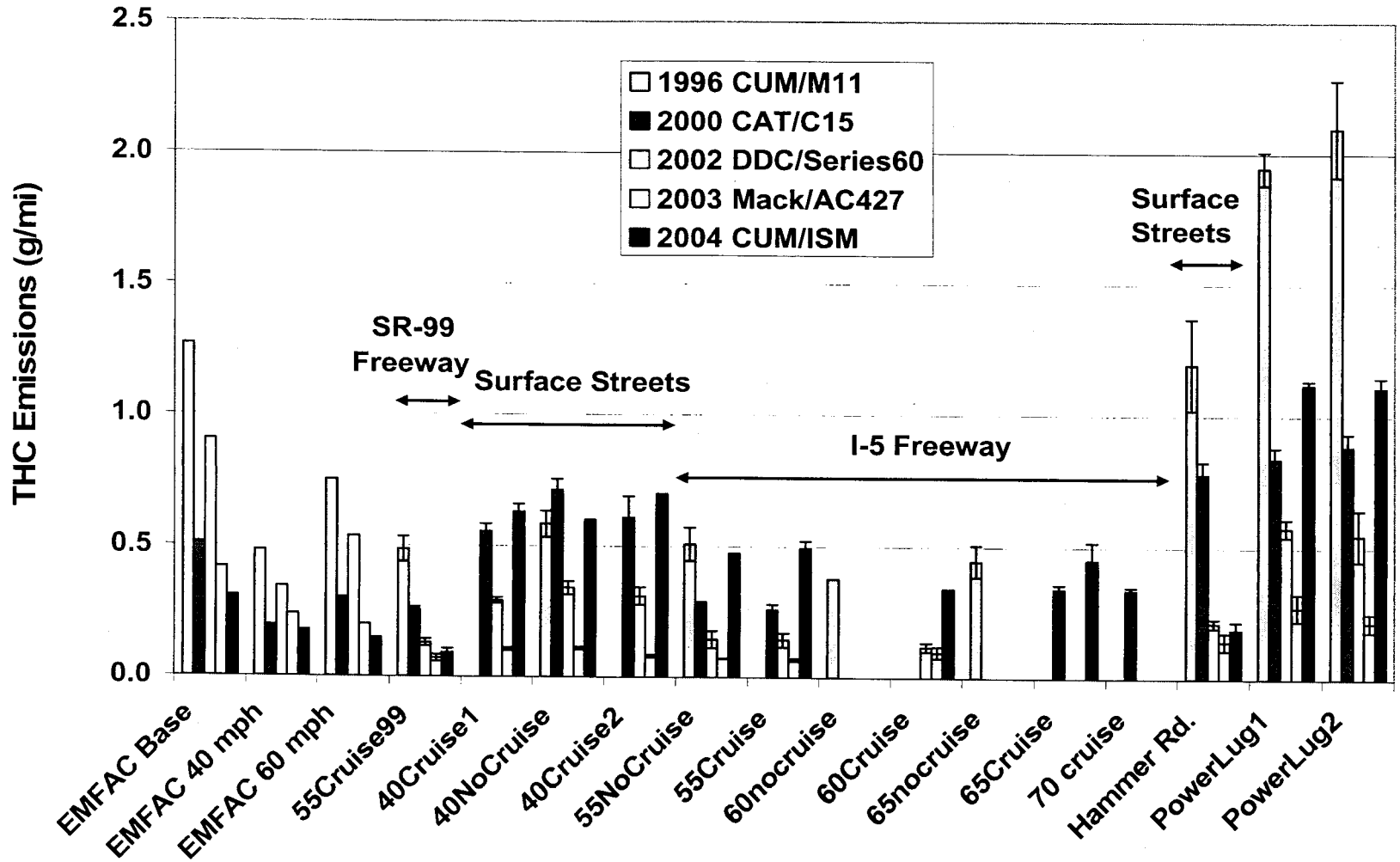
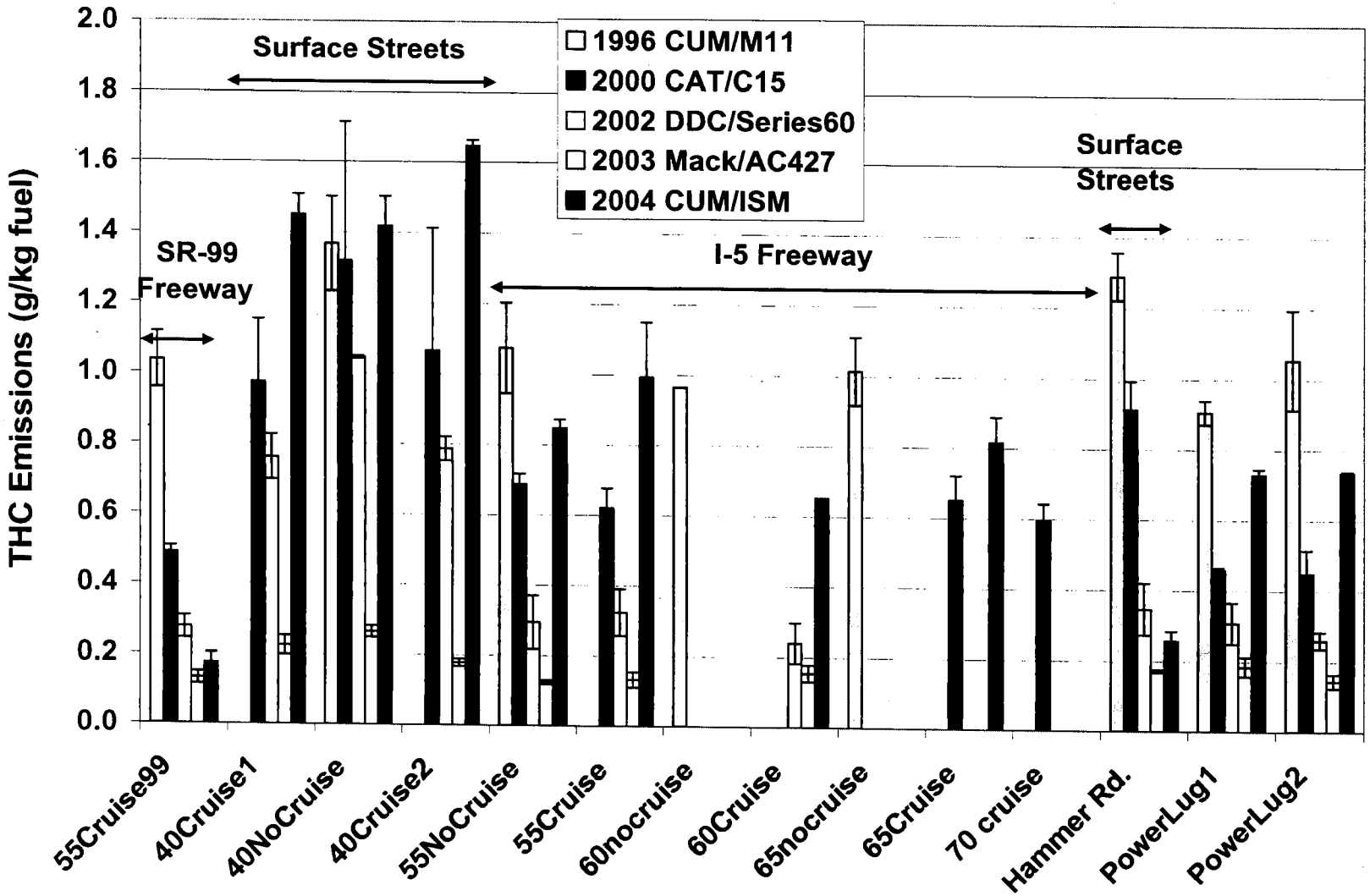


Figure 8. Fuel-based THC Emissions



CO Emissions

CO emissions under steady state driving conditions were relatively low, ranging from slightly less than 1 g/mi to approximately 3 g/mi. Of the real world driving conditions, CO emissions were highest for the surface street driving on Hammer road with lower CO emissions for the higher speeds. There was a reasonable comparison between the on-road measurements and the EMFAC emission rates, and the trends in the on-road data were consistent with the trends in the EMFAC emission factors with speed. The newer (2000 model year and newer) vehicles all tended to have slightly higher emissions than the corresponding EMFAC emissions factors. The older 1996 truck had slightly lower emissions than EMFAC, expect for the tests on Hammer road, which were comparable. CO emissions are highest for the power lug segments, although the fuel base emission rates for the power lug segment were comparable to those for the typical on-road driving. Real-time CO emissions show peaks on the accelerations during the surface street driving.

Figure 9. On-Road CO Emissions

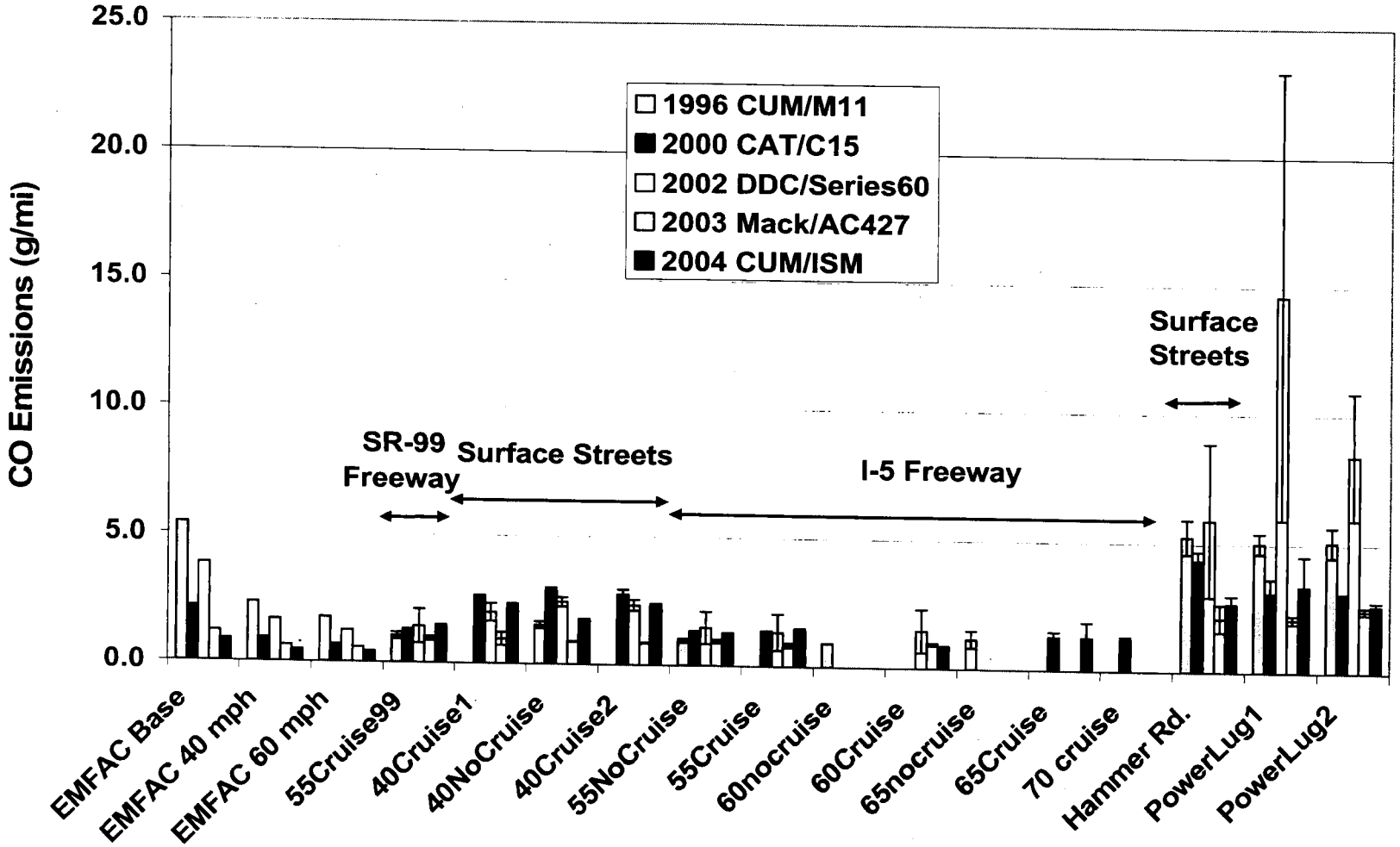
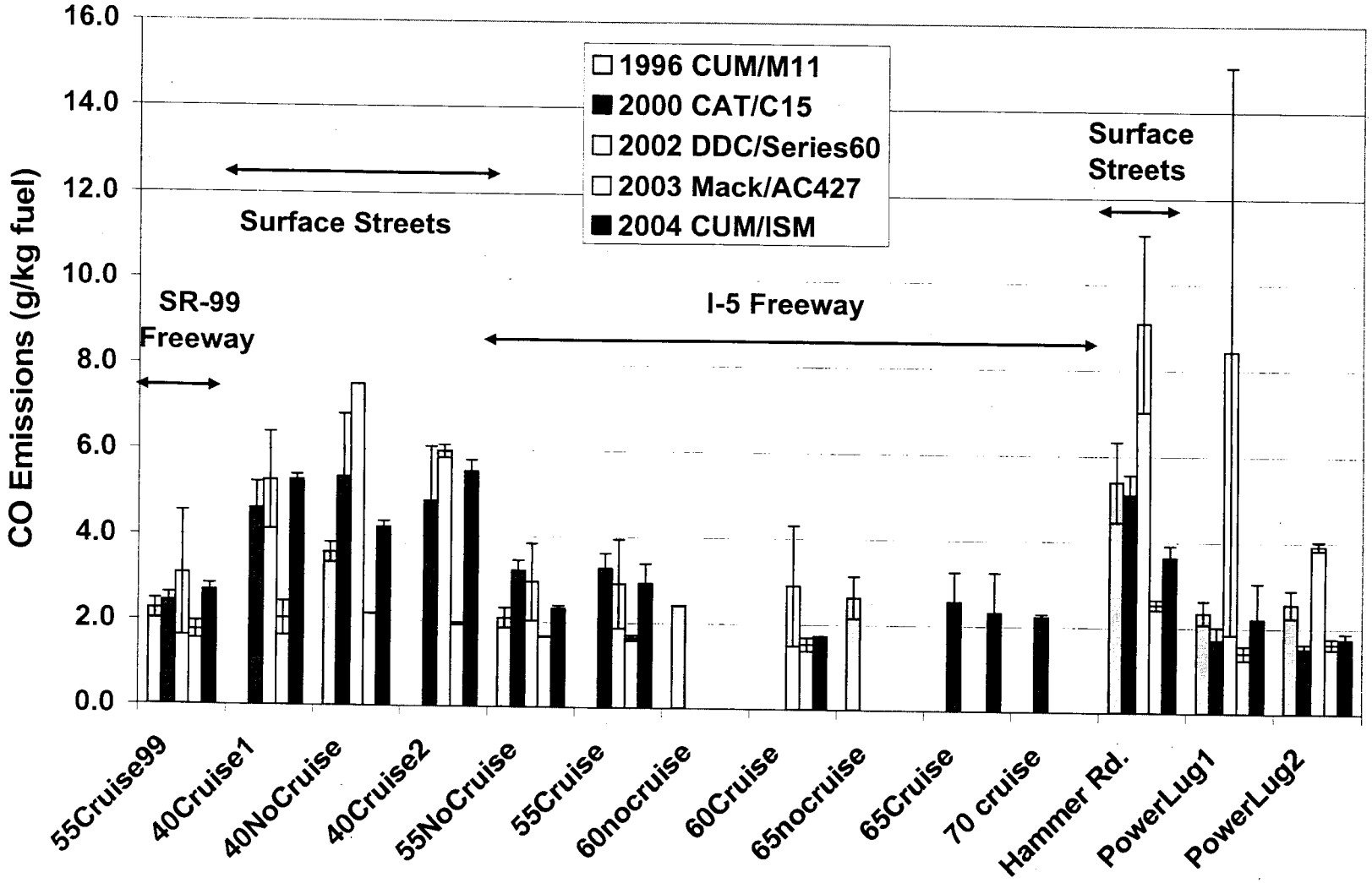


Figure 10. Fuel-based CO Emissions



4.0 Summary and Conclusions

This program was conducted as part of CARB's Measure 17 or M-17 program to understand in-use diesel emissions and develop new compliance programs to reduce emissions from the in-use diesel fleet. The focus of this program was to collect in-use, on-road emissions measurements on a subfleet of 5 vehicles with engines ranging in model year from 1996 to 2004 in the Stockton, CA area. The vehicles were tested over a road course that included driving under both highway conditions on State Route 99 and Interstate 5 and surface street conditions. Emissions measurements were made with UCRs Mobile Emissions Laboratory. The results of this study provide additional information about emissions from in-use HDD Trucks under actual driving conditions.

A summary of the results is as follows:

- Overall, the results show that emissions vary depending on the specific emissions component, the type of vehicle, as well as driving condition. Real-time data were also collected that showed that emissions were transient and depend heavily on the specific mode of engine operation.

- The highest NO_x emissions for all vehicles were found for the power lug segments. Some vehicles showed a tendency toward higher NO_x emissions for the higher speed events ($\geq$55 mph) compared to the 40 mph cruise and the other surface street driving (1996 Cummins and the 2002 DDC), while others did not show as large a difference between different types of driving (2000 Caterpillar, 2003 Mack, and 2004 Cummins). For NO_x emissions, the oldest vehicle, 1996 Cummins, had the highest emissions for nearly all types of driving.

- For surface street driving, the highest average PM emissions were found for the oldest vehicle, while for highway driving on the SR-99, the two newest vehicles had the highest PM emissions. Some of the test vehicles showed a trend of higher PM emissions on the surface streets as opposed to the highway driving (the 1996 Cummins, 2000 Caterpillar, and the 2002 DDC).

- THC emissions were found to be highest for the power lug segments. Some vehicles showed a tendency for higher emissions for the surface street segments compared to the steady state segments (the 1996 Cummins), while others showed a tendency for higher emissions for the 40 mph cruise segments compared to the highway cruise segments (the 2000 Caterpillar and 2002 DDC). Corresponding NO_x emissions were lower for the newer vehicles for SR-99 indicating that there appears to be a NO_x/PM tradeoff under these operating conditions.

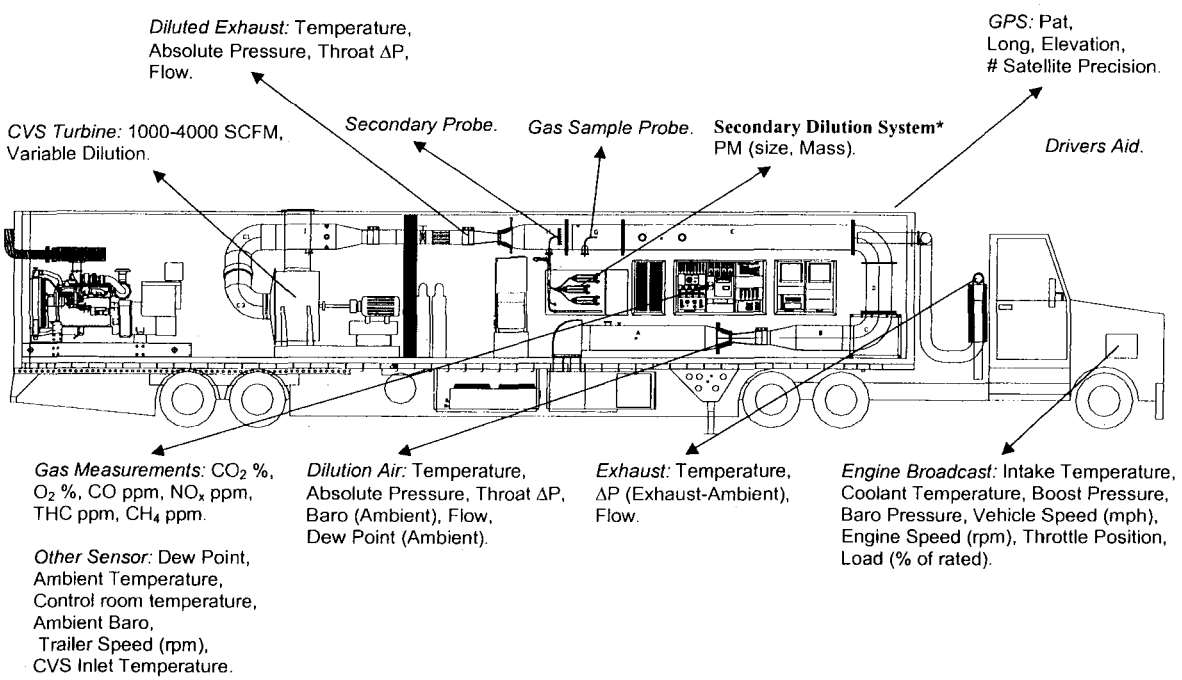
- CO emissions are highest for the power lug segments followed by surface street driving. CO emissions under steady state driving conditions were relatively low, ranging from slightly less than 1 g/mi to approximately 3 g/mi.

5.0 References

Zhou, L., (2007) EMFAC Modeling Change Technical Memo: Revision of Heavy-Duty Diesel Truck Emission Factors and Speed Correction Factors. Technical memo from the California Air Resources Board, October, www.arb.ca.gov.

Appendix A – Background Information on UCR's Mobile Emission Lab

Extensive detail is provided in Reference 1; so this section is provided for those that may not have access to that reference. Basically the mobile emissions lab (MEL) consists of a number of operating systems that are typically found in a stationary lab. However the MEL lab is on wheels instead of concrete. A schematic of MEL and its major subsystems is shown in the figure below. Some description follows.



Major Systems within the Mobile Emission Lab

The primary dilution system is configured as a full-flow constant volume sampling (CVS) system with a smooth approach orifice (SAO) venturi and dynamic flow controller. The SAO venturi has the advantage of no moving parts and repeatable accuracy at high throughput with low-pressure drop. As opposed to traditional dilution tunnels with a positive displacement pump or a critical flow orifice, the SAO system with dynamic flow control eliminates the need for a heat exchanger. Tunnel flow rate is adjustable from 1000 to 4000 scfm with accuracy of 0.5% of full scale. It is capable of total exhaust capture for engines up to 600kW. Colorado Engineering Experiment Station Inc. initially calibrated the flow rate through both SAOs for the primary tunnel.

The mobile laboratory contains a suite of gas-phase analyzers on shock-mounted benches. The gas-phase analytical instruments measure NO_x, methane (CH_4), total hydrocarbons (THC), CO, and CO_2 at a frequency of 10 Hz and were selected based on optimum response time and on road stability. The 200-L Tedlar bags are used to collect tunnel and dilution air samples over a complete test cycle. A total of eight bags are suspended in the MEL allowing four test cycles to

be performed between analyses. Filling of the bags is automated with Lab View 7.0 software (National Instruments, Austin, TX). A summary of the analytical instrumentation used, their ranges, and principles of operation is provided in the table below. Each modal analyzer is time-corrected for tunnel, sample line, and analyzer delay time.

Gas Component	Range	Monitoring Method
NO_x	10/30/100/300/1000 (ppm)	Chemiluminescence
CO	50/200/1000/3000 (ppm)	NDIR
CO_2	0.5/2/8/16 (%)	NDIR
THC	10/30/100/300/1000 & 5000 (ppmC)	Heated FID
CH4	30/100/300/1000 (ppmC)	FID

Summary of gas-phase instrumentation in MEL

Quality Assurance and Quality Control Requirements

Internal calibration and verification procedures are performed regularly in accordance with the CFR. A partial summary of routine calibrations performed by the MEL staff as part of the data quality assurance/quality control program is listed in the table below. The MEL uses precision gas blending to obtain required calibration gas concentrations. Calibration gas cylinders, certified to 1 %, are obtained from Scott-Marrin Inc. (Riverside, CA). By using precision blending, the number of calibration gas cylinders in the lab was reduced to 5 and cylinders need to be replaced less frequently. The gas divider contains a series of mass flow controllers that are calibrated regularly with a Bios Flow Calibrator (Butler, New Jersey) and produces the required calibration gas concentrations within the required ± 1.5 percent accuracy.

In addition to weekly propane recovery checks which yield >98% recovery, CO_2 recovery checks are also performed. A calibrated mass of CO_2 is injected into the primary dilution tunnel and is measured downstream by the CO_2 analyzer. These tests also yield >98% recovery. The results of each recovery check are all stored in an internal QA/QC graph that allows for the immediate identification of problems and/or sampling bias.

An example shown below is for propane mass injected into the exhaust transfer line while sampling from raw and dilute ports (three repeats) to evaluate exhaust flow measurement on steady state basis (duration = 60 sec, Date completed January 2005).

Tests	Raw C3H8 g	Dil C3H8 g	CVS DF	Raw C3H8 est	Diff
1	2522	608	4.11	2499	-0.9%
2	2485	598	4.10	2454	-1.2%
3	2462	601	4.13	2484	0.9%
ave	2490	602	4.12	2479	-0.4%
stdev	30	5	0.01	23	
COV	1.2%	0.8%	0.3%	0.9%	

Recent example of propane quality control check

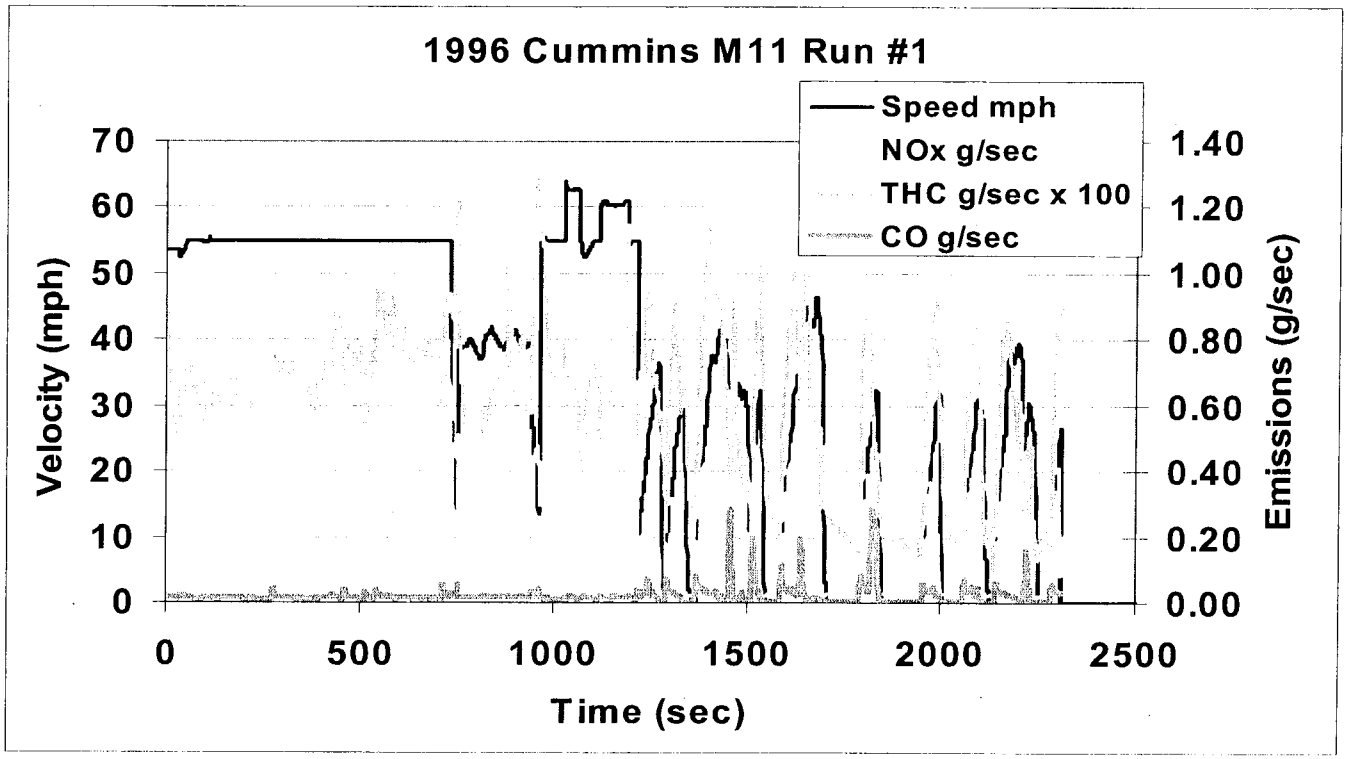
EQUIPMENT	FREQUENCY	**VERIFICATION PERFORMED**	**CALIBRATION PERFORMED**
CVS	Daily	Differential Pressure	Electronic Cal
	Daily	Absolute Pressure	Electronic Cal
	Weekly	Propane Injection	
	Monthly	CO_2 Injection	
	Per Set-up	CVS Leak Check	
	Second by second	Back pressure tolerance ±5 inH_20	
Cal system MFCs	Annual	Primary Standard	MFCs: Drycal Bios Meter
	Monthly	Audit bottle check	
Analyzers	Pre/Post Test		Zero Span
	Daily	Zero span drifts	
	Monthly	Linearity Check	
Secondary System Integrity and MFCs	Semi-Annual	Propane Injection: 6 point primary vs secondary check	
	Semi-Annual		MFCs: Drycal Bios Meter & TSI Mass Meter
Data Validation	Variable	Integrated Modal Mass vs Bag Mass	
	Per test	Visual review	
PM Sample Media	Weekly	Tunnel Banks	
	Monthly	Static and Dynamic Blanks	
Temperature	Daily	Psychrometer	Performed if verification fails
Barometric Pressure	Daily	Aneroid barometer ATIS	Performed if verification fails
Dewpoint Sensors	Daily	Psychrometer Chilled mirror	Performed if verification fails

Sample of Verification and Calibration Quality Control Activities

Appendix B – Real-time Emissions Results

The real-time data are presented for each test on each vehicle, in order of ascending vehicle age. In the real-time data, the first ~700 seconds of steady state driving is on the SR-99. The next 200 seconds of driving in the 40 mph range represent the second segment of driving. The segment from 900 to 1300 seconds at speeds of 55 mph and higher is on the I-5. The final 1000 seconds is the driving on surface streets on Hammer Road.

Figure B-1. Real-time Emissions for 1996 Cummins



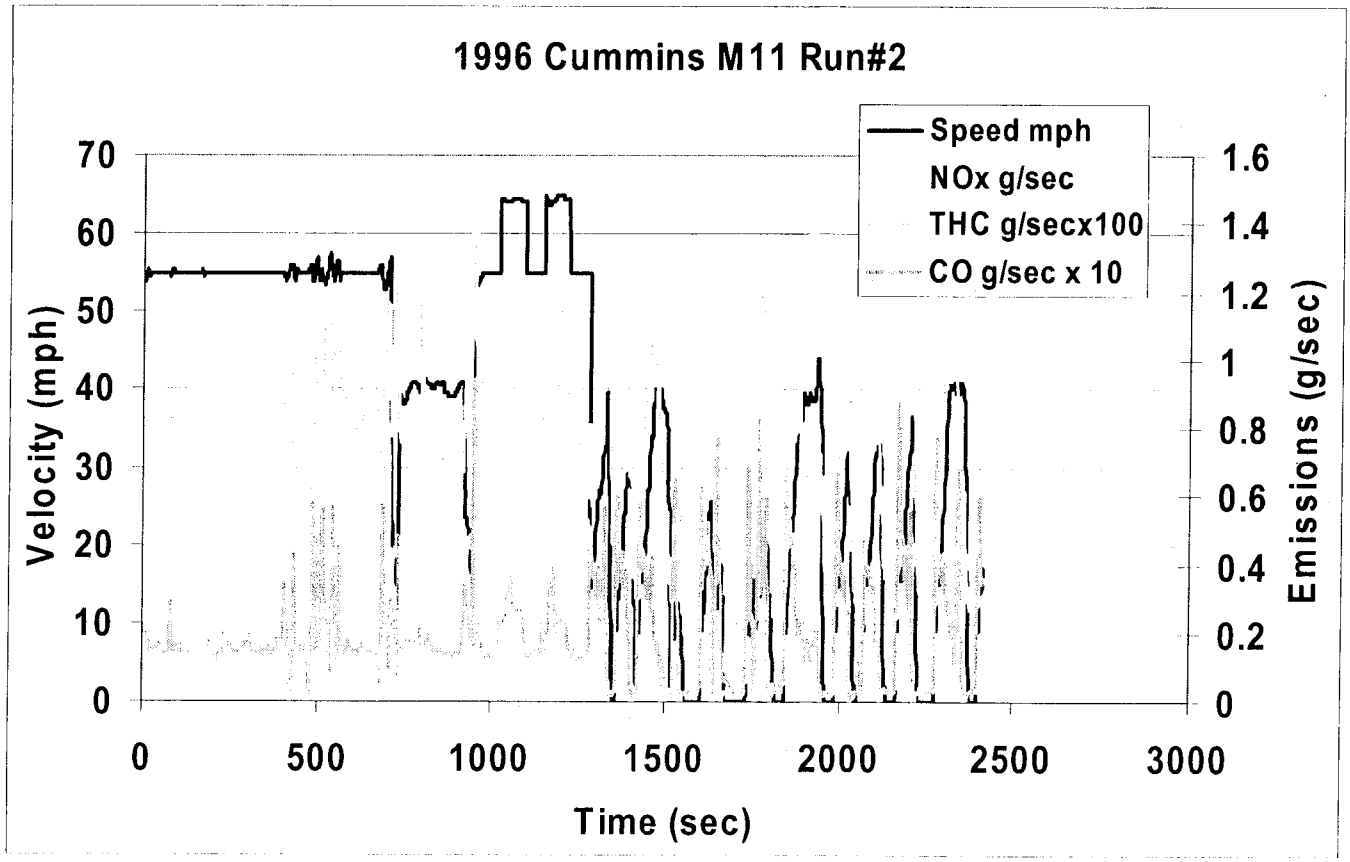
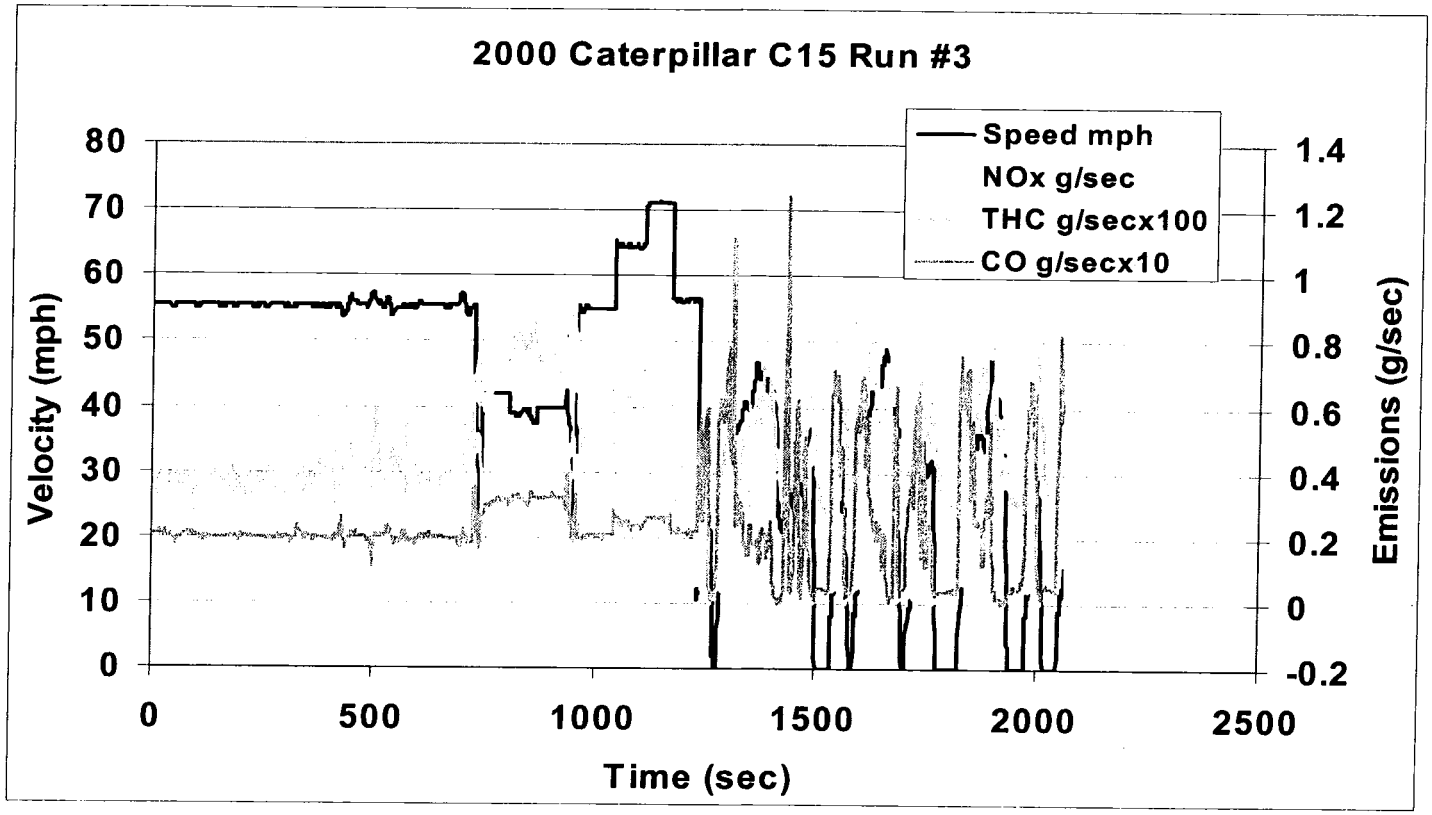


Figure B-2. Real-time Emissions for 2000 Caterpillar



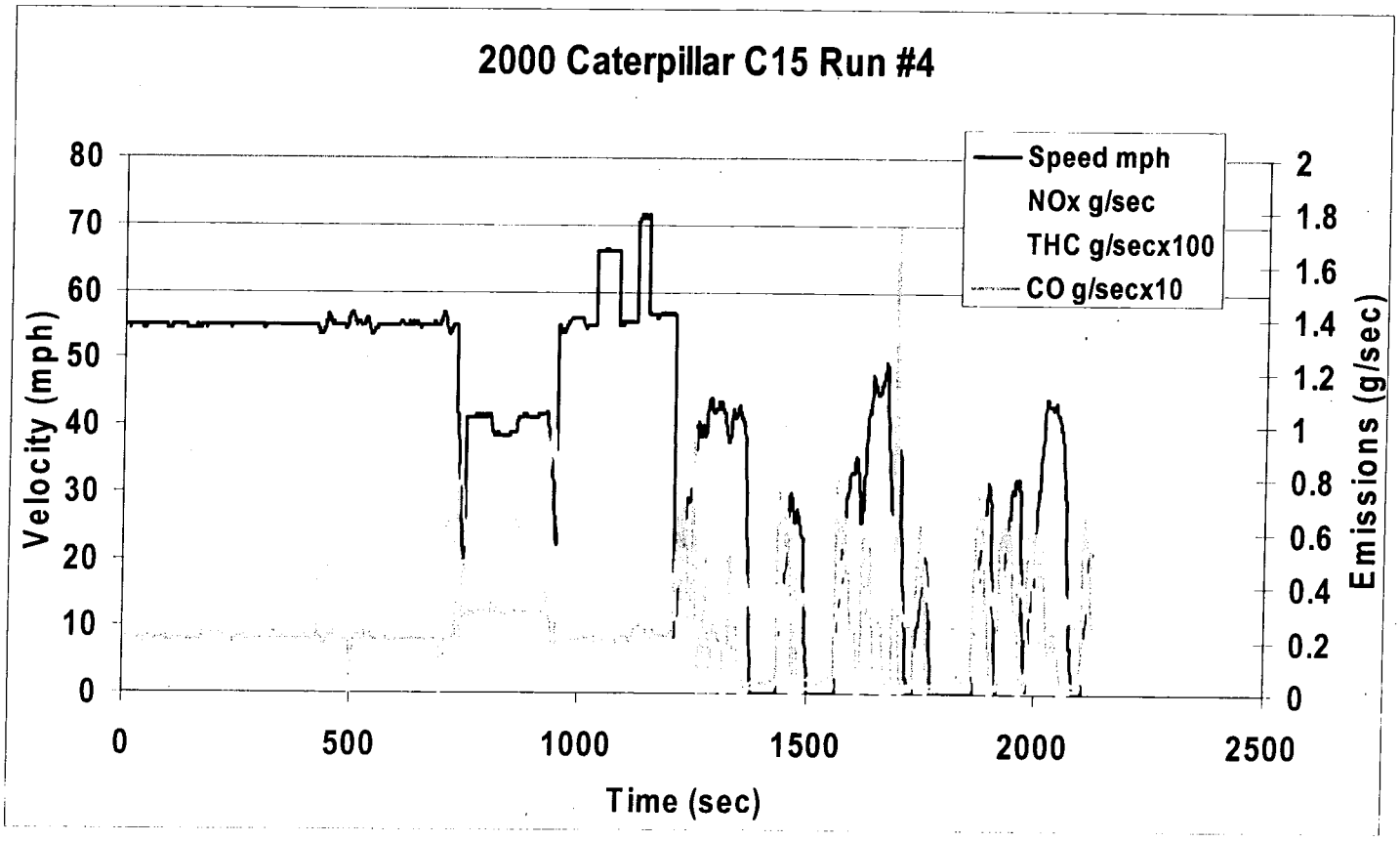
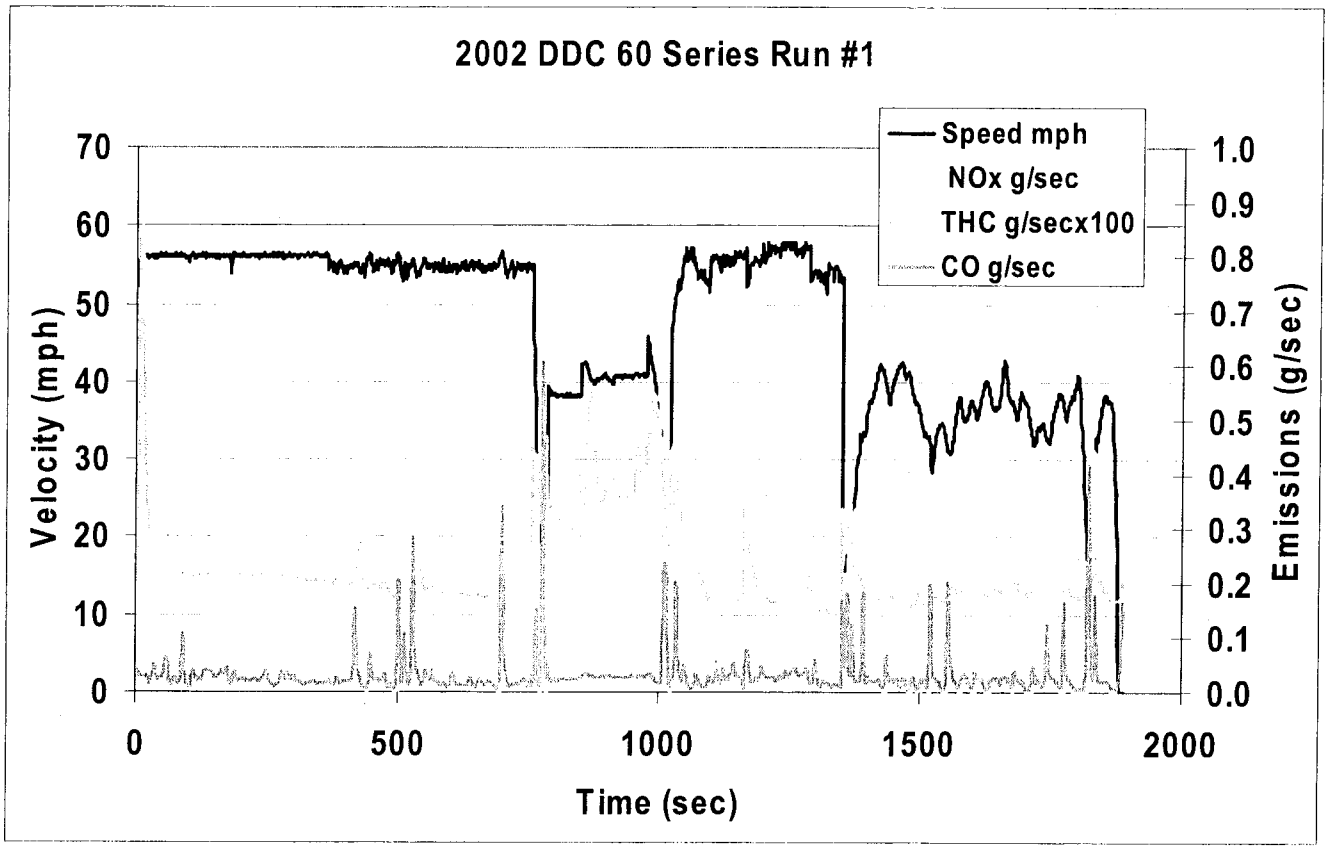


Figure B-3. Real-time Emissions for 2002 DDC



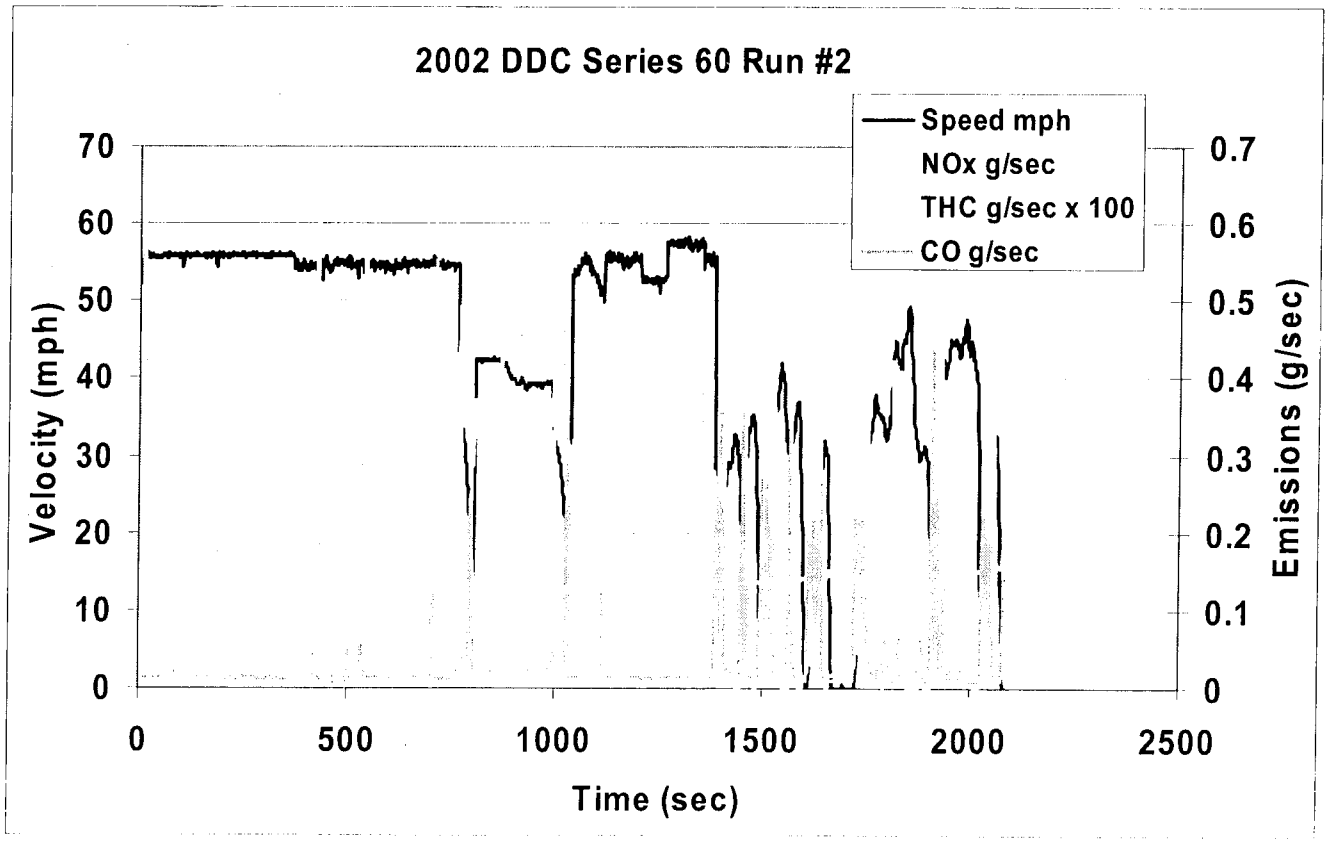
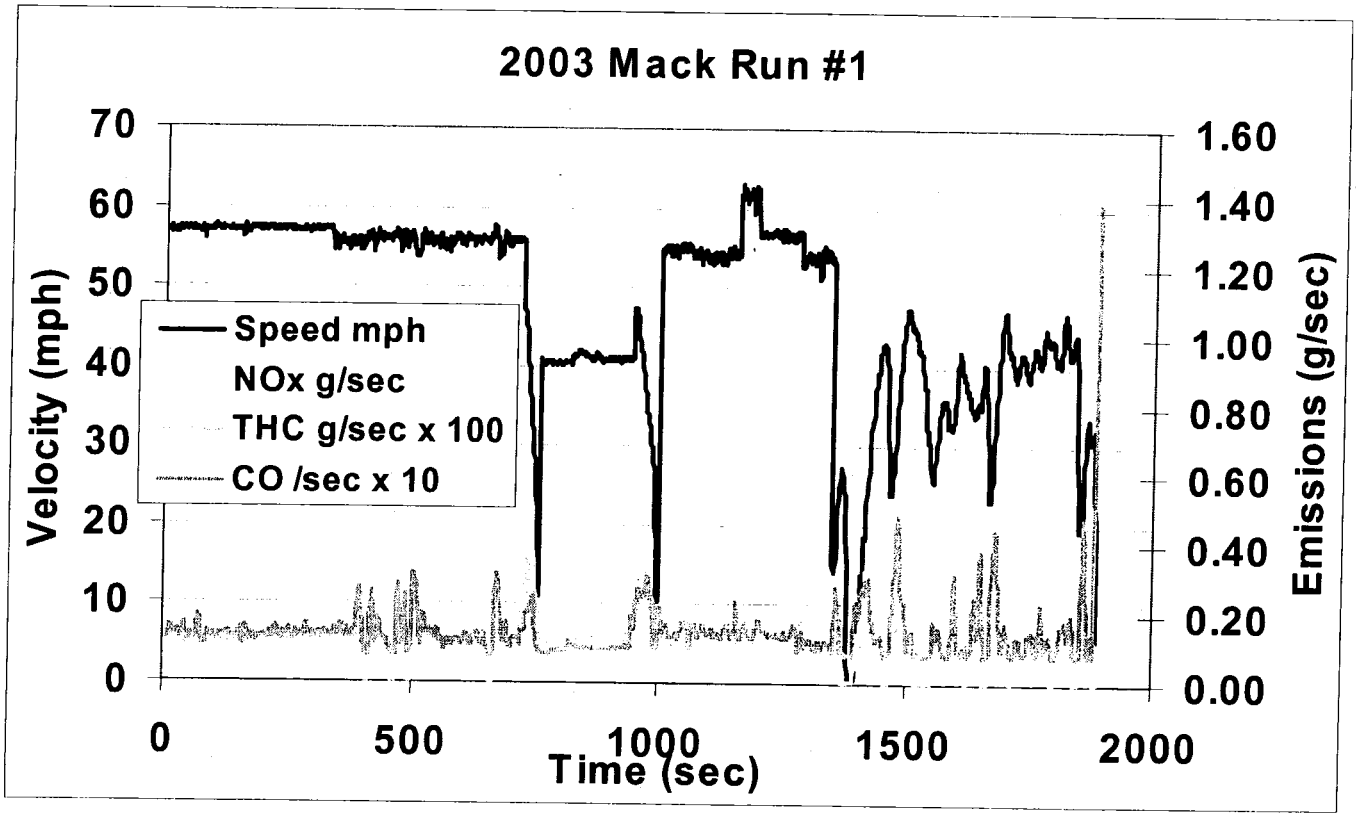


Figure B-4. Real-time Emissions for 2003 Mack



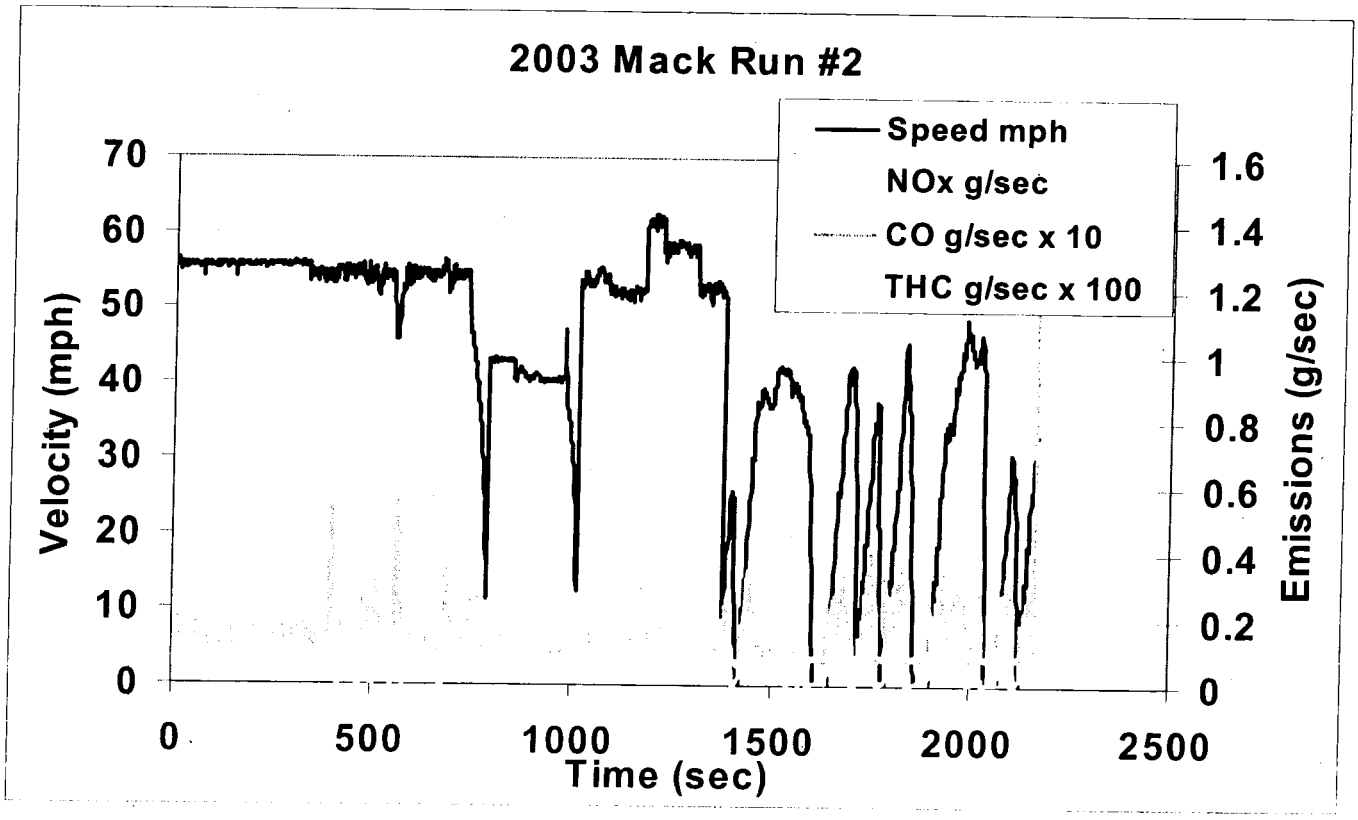
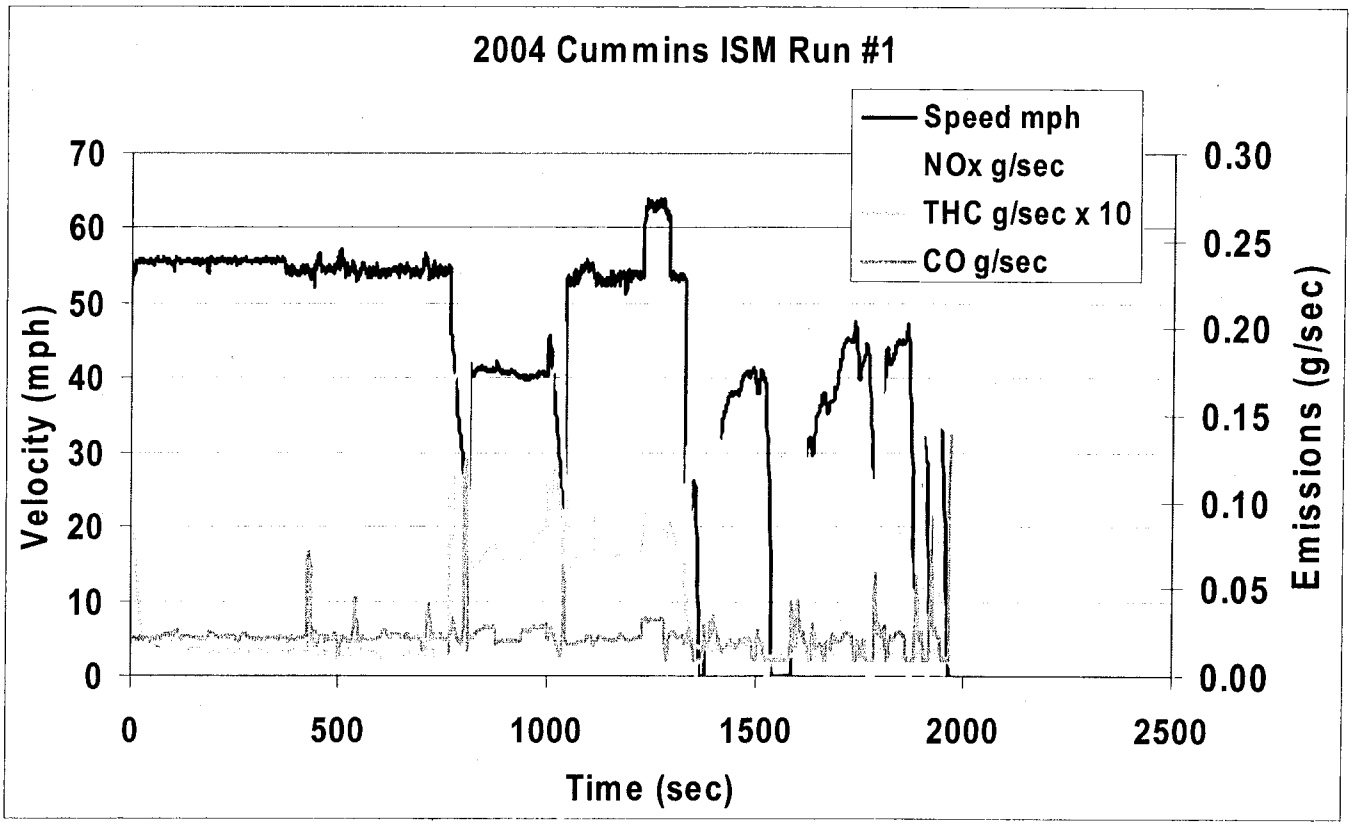
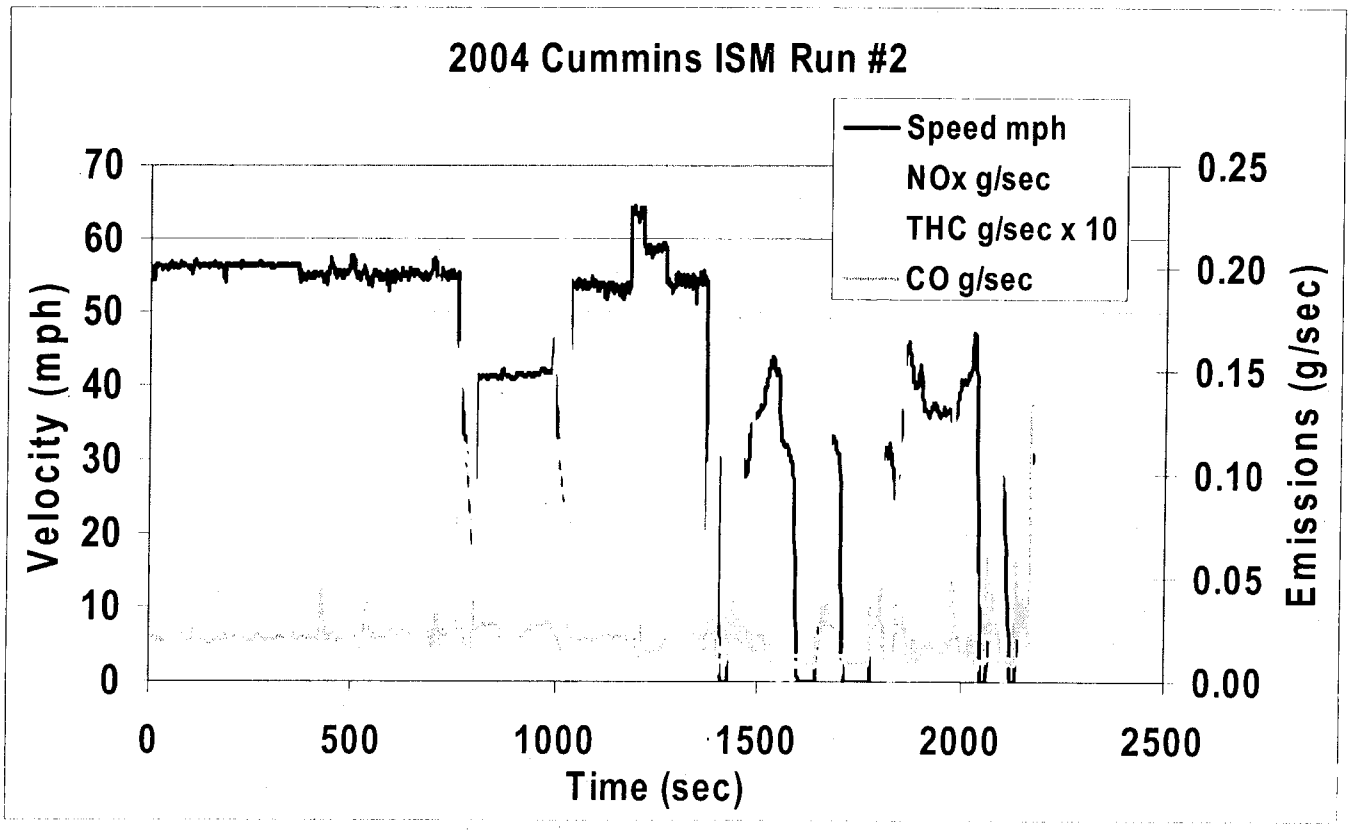



Figure B-5. Real-time Emissions for 2004 Cummins ISM