CALIFORNIA HEAVY HEAVY-DUTY DIESEL TRUCK EMISSIONS CHARACTERIZATION FOR PROJECT E-55/59 PHASE 1.5

Short Title: E-55/59-1.5

Final Report

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Final Report

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Executive Summary

Coordinating Research Council Project E-55/59-1.5 had the main objective of quantifying regulated emissions from twelve heavy heavy-duty diesel trucks (HHDDT) operating in southern California. A thirteenth vehicle was added to the study when difficulties were encountered in testing a new 2004 model year truck with intelligent traction control on the chassis dynamometer. The thirteenth vehicle was also a 2004 model year truck in order to meet the model year distribution requirements of the test plan. One 1985 model year truck, one 1992 truck, one 1998 truck, three 1999 trucks, two 2000 trucks, two 2001 trucks and three post-October 2002 trucks were procured from trucking, rental and sales companies. Each vehicle was inspected for safety, and then driven to the test site in Riverside, CA, where the researchers performed a more detailed inspection and queried the truck engine control unit.

Each truck was installed on the West Virginia University Transportable Heavy-Duty Emissions Testing Laboratory (TransLab), which was the same as that used in the E-55/59-1 Program except that an improved chassis dynamometer test bed was used in Phase 1.5. The trucks were tested at 56,000 lbs. simulated weight on the (Heavy-Duty) Urban Dynamometer Driving Schedule (UDDS) and the HHDDT Schedule, consisting of the four modes used in Phase 1 of the program, plus a high speed cruise mode created for Phase 1.5. The high speed cruise mode caused high dilution tunnel and tire temperatures during testing and was shortened in duration at the beginning of the program, after which it was termed the "HHDDT Short" (HHDDT_S). The five modes of the HHDDT schedule were also used to characterize emissions at 30,000 lbs. and 66,000 lbs. test weights, after preliminary work suggested that the original 75,000 lbs. maximum target weight placed too much stress on both truck brakes and the dynamometer. In most cases each run was executed only once.

A substantial data set arose from this study, with emissions factors in units of g/mile, g/cycle, g/minute, g/ahp-hr, and g/gallon for each schedule or mode at each test weight. Particulate matter (PM) and oxides of nitrogen (NO_x) g/mile results for Transient Mode of the HHDDT and the HHDDT_S operation of all trucks at 56,000 lbs. test weight were chosen for detailed examination. The emissions of NO_x prior to model year 1999 on the Transient Mode were variable, but after model year 1999 the levels were all about 15 g/mile. The 2003 engine year truck did not show lower NO_x on the Transient Mode than the 2000 and 2001 trucks. On the HHDDT_S, the 2003 engine year truck showed lowest emissions of NO_x. Except for the oldest truck and two trucks identified as high emitters of PM, the PM emissions on the Transient Mode all fell in the 0.76 to 1.29 g/mile range. On the HHDDT_S, highest PM emissions were noted, unexpectedly, on two of the newest trucks.

To meet a second objective of the study, three "pre-consent decree" vehicles, with engines from three different major manufacturers, were selected for engine control unit "re-flash" and they were re-tested for emissions after re-flash. One of these trucks was found to have a failed manifold air pressure (MAP) sensor (which led to high PM as received) and was tested with and without repair and with and without re-flash. The

repair to the MAP sensor was effective at reducing PM. For example, on the Transient Mode, PM was 6.10 g/mile before repair, and 1.80 g/mile with a new MAP sensor. On the Cruise Mode, NO_x dropped from 24.19 to 16.77 g/mile on this truck as a result of re-flash, on another truck from 26.63 to 18.95 g/mile, and on the third truck from 28.11 to 24.36 g/mile.

Further conclusions from the data were that the two NO_x analyzers used by the TransLab agreed closely, except in the case of one run, and that a strong correlation existed between filter PM and Tapered Element Oscillating Microbalance (TEOM) values. These conclusions were of value because repeat runs were not customary in the study.

To meet a third objective of the study, the West Virginia University researchers provided a dilute exhaust slipstream for use by Air Resources Board (ARB) contractors in examining unregulated aspects of diesel exhaust emissions. This cooperative research was conducted on the two oldest vehicles and three newer vehicles in the study. Tunnel flow rates, dilution factors, and vehicle information have been made available to these ARB contractors.

Introduction

Coordinating Research Council (CRC) Project E-55/59-1.5 had the objective of acquiring regulated emissions measurements from twelve in-use trucks in southern California, and supporting a third-party characterization of non-regulated species from five vehicles in the Phase 1.5 test fleet. In addition, three vehicles were re-flashed with a post consent decree engine map, and re-tested. One of the "re-flash" vehicles was also repaired and re-tested. A thirteenth vehicle was added to the study when difficulties were encountered in testing a new 2004 model year truck with intelligent traction control on the chassis dynamometer. The thirteenth vehicle was also a 2004 model year truck selected to satisfy the requirements for model year distribution of the test plan.

Vehicle Procurement

Thirteen vehicles were procured. Table 1 shows the vehicles identified in the original test plan, which also grouped the vehicles to be tested. In Table 1 Groups A, B, C and D denoted vehicle model year selection. Group A vehicles were scheduled for reflash, as discussed separately below. Group B in Table 1 was to include no more than three engines from the same manufacturer. In Table 1 the term model year was intended to refer to the model year of manufacture of the truck chassis. Some vehicles that were recruited had an engine year that was one year earlier than the chassis model year, but the chassis model year prevailed in these circumstances in satisfying Table 1 requirements. Group C and D represented two older model year trucks.

The actual vehicles procured differed from the vehicle distribution in Table 1 because it was realized that many vehicles did not have engines with the same chassis and engine model years, and because late model ("post-October 2002 engine") trucks were identified as being of greater interest to the sponsors during execution of the test plan. Table 2 provides information on the actual vehicles recruited. All of these vehicles were "full size" over-the-road tractors, which would be regarded normally as having a gross combination weight rating of 80,000 lbs. The trucks were recruited by West Virginia University staff and included rental trucks, in-use trucks, and trucks that were traded in at dealerships for re-sale.

Table 1. Vehicles in planned for recruiting the E-55/59-1.5 program.

Quantity	Chassis Model Year & Engine Manufacturer	Group
1	1998 Cummins	A
1	Caterpillar (1998 engine, 1999 chassis, see text)	A
1	1998 DDC	A
2	1999 See NOTE below	B
2	2001 See NOTE below	B
2	2001 See NOTE below	B
2	2002/2003 chassis (2.5 g/bhp-hr., 2002 year, post-Oct. 2002 NO_x engine) See NOTE below	B
1	1987-1992 Any manufacturer	C
1	Pre-1987 Any manufacturer	D
NOTE: In group B, the engines must be manufactured by Cummins, Caterpillar or DDC. No more than three engines in group B should have the same manufacturers. Model year refers to chassis model year. The 2.5g/bhp-hr engine will be a DDC or Cummins engine, conforming to the post-Oct. 2002 low NO_x level: the engine data plate should be inspected to confirm the NO_x emissions rating.		

Table 2. Basic Information on the 13 trucks actually recruited in Phase 1.5.

E55CRC-(truck)	Vehicle model year	Vehicle Manufacturer	Engine Model Year	Engine Model	Engine Power (hp)	Engine Manufacturer
E55CRC-26	1999	Freightliner	1998	C-10	270	Caterpillar
E55CRC-27	2000	Freightliner	1999	Series 60	500	Detroit
E55CRC-28	1999	Freightliner	1998	Series 60	500	Detroit
E55CRC-29	2000	Volvo	1999	1SX475ST2	450	Cummins
E55CRC-30	1999	Freightliner	1998	Series 60	500	Detroit
E55CRC-31	1998	Kenworth	1997	N14-460E+	460	Cummins
E55CRC-32	1992	Volvo	1991	3406B	280	Caterpillar
E55CRC-33	1985	Freightliner	1984	3406	310	Caterpillar
E55CRC-34	2004	Freightliner	2003	Series 60	500	Detroit
E55CRC-35	2001	Sterling	2000	Series 60	470	Detroit
E55CRC-36	2001	Peterbilt	2001	C-15	475	Caterpillar
E55CRC-37	2004	Volvo	2004	ISX	500	Cummins
E55CRC-38	2003	Volvo	2004	ISX	530	Cummins

Owners of the group A vehicles (see Table 1) agreed to allow a vehicle ECU re-flash, as described below in this report.

Once recruited, each vehicle was driven to the WVU test site, by a WVU commercial driver. The driver inspected the vehicle before moving the vehicle: no vehicles were rejected on the basis of this preliminary inspection.

Each vehicle was photographed at the laboratory site. These photographs are gathered in Appendix A to this report.

Test Site and Laboratory

The characterization of the emissions took place using a WVU Transportable Heavy Duty Vehicle Emissions Testing Laboratory (TransLab) located at Ralphs Grocery, 1500 Eastridge Ave., Riverside, CA. The TransLab had the same arrangement as the TransLab used in the Phase 1 E-55/59 CRC Study, except that the chassis dynamometer bed was swapped with a unit that had been retrofitted in Morgantown, WV while the E-55/59 Phase 1 program was in progress. Synchronous motors were added to the TransLab chassis dynamometer to permit testing at lower weights, and software was upgraded to allow testing at up to 75,000 lbs. test weights. Otherwise the laboratory equipment, including the analyzer bench, PM system and dilution system used, was the same as described in the final report for Phase 1 of this E-55/59 study. Procedures with respect to PM filter processing, analyzer calibration and background correction were the same as described in the Phase 1 report and are well established by the WVU laboratory. For completeness of this report, a description of the WVU TransLab has been included in Appendix B.

The laboratory used a TEOM analyzer to quantify continuous PM. The TEOM sampled at a setpoint flow rate of 2.0 liters/minute from the primary (full scale) dilution tunnel. TEOM temperature was set at 40°C.

In the Phase 1.5 research, exhaust temperature was measured in the first section of test exhaust after the tailpipe using a J-type thermocouple. Exhaust temperature was not measured in prior Phase 1 research.

Test Cycles

Each vehicle was tested using a suite of test schedules, which are shown graphically in Appendix C of this report. The Heavy-Duty Urban Dynamometer Driving Schedule (UDDS) was used. The Heavy Heavy-Duty Diesel Truck (HHDDT) Schedule [1], consisting of four modes (Idle, Creep, Transient and Cruise), was also used.

A fifth mode, representing higher speed freeway operation, was added to the HHDDT schedule in the test plan for Phase 1.5. This mode was created in the same way as the original Cruise Mode of the HHDDT, but had a higher average speed and a higher maximum speed than the Cruise Mode. This new mode was initially termed ambiguously the “50mph Cruise” (because of its average speed), the “65mph Cruise” (because of its section of high speed), or the HHDDT65 and is shown in Figure 1. This mode was not verified for operation prior to the commencement of Phase 1.5, and it was found during the early part of the study that the sustained high speed caused truck tire overheating on the dynamometer. Also, the sustained high power operation led to unacceptably high dilution tunnel temperatures. It was accordingly replaced with a shorter version of high speed freeway operation. This shorter version, which has now been termed HHDDT_S, proved satisfactory and was used in all subsequent Phase 1.5 testing. HHDDT_S has a maximum speed of 67 mph and an average speed of 50 mph, and it is shown in Figure 2.

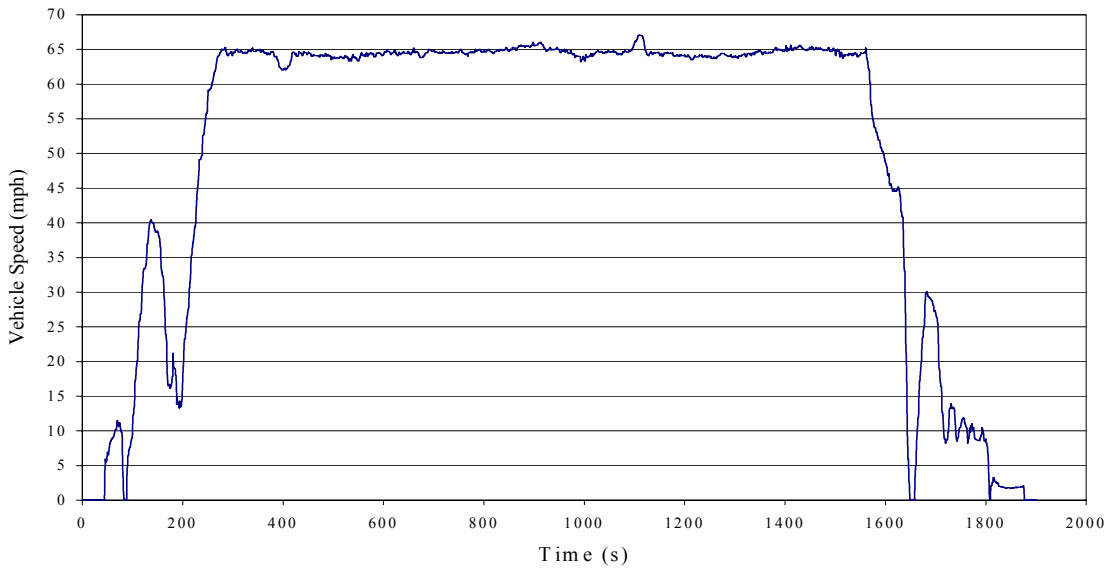


Figure 1. HHDDT65 original speed versus time schedule represents high speed freeway cruise operation.

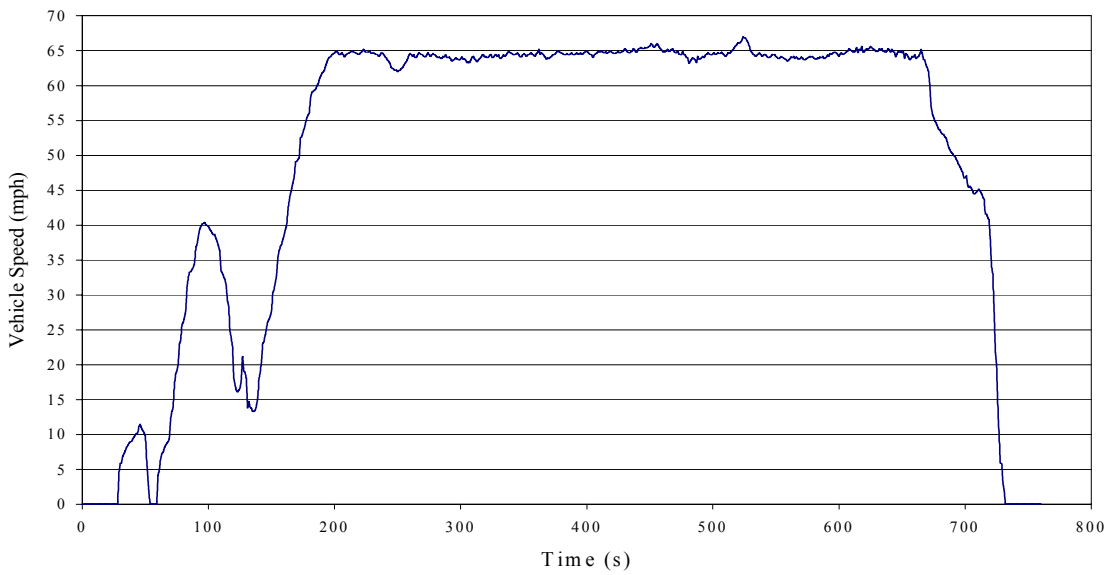


Figure 2. HHDDT_S speed versus time schedule. The major acceleration and deceleration portions of the cycle are the same as for the HHDDT65 shown in Figure 1.

Comparative data between the HHDDT65 cruise and the HHDDT_S are shown in Figure 3 and Figure 4. These figures show data repeated on two days (6/2/03 and 6/7/03) for the high speed and cruise modes. They compare distance specific (g/mile) data from the HHDDT65 (on 6/2/03) with data from the HHDDT_S (on 6/7/03). These data suggest that the HHDDT65 and HHDDT_S yield similar distance specific data for PM and NO_x and that there was no disadvantage with respect to PM and NO_x emissions due to shortening the High Speed Cruise Mode.

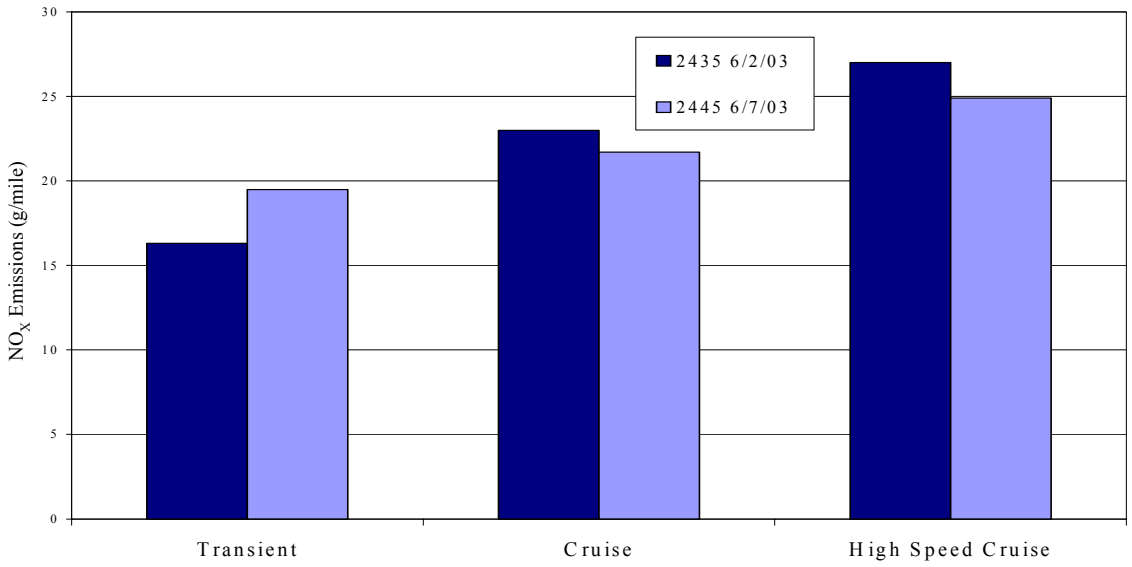


Figure 3. NO_x data from 6/2/03 and 6/7/03 for E55CRC-26 at 56,000 lbs. On 6/2/03 the high speed cruise test was the HHDDT65 while on 6/7/03 it was the HHDDT_S.

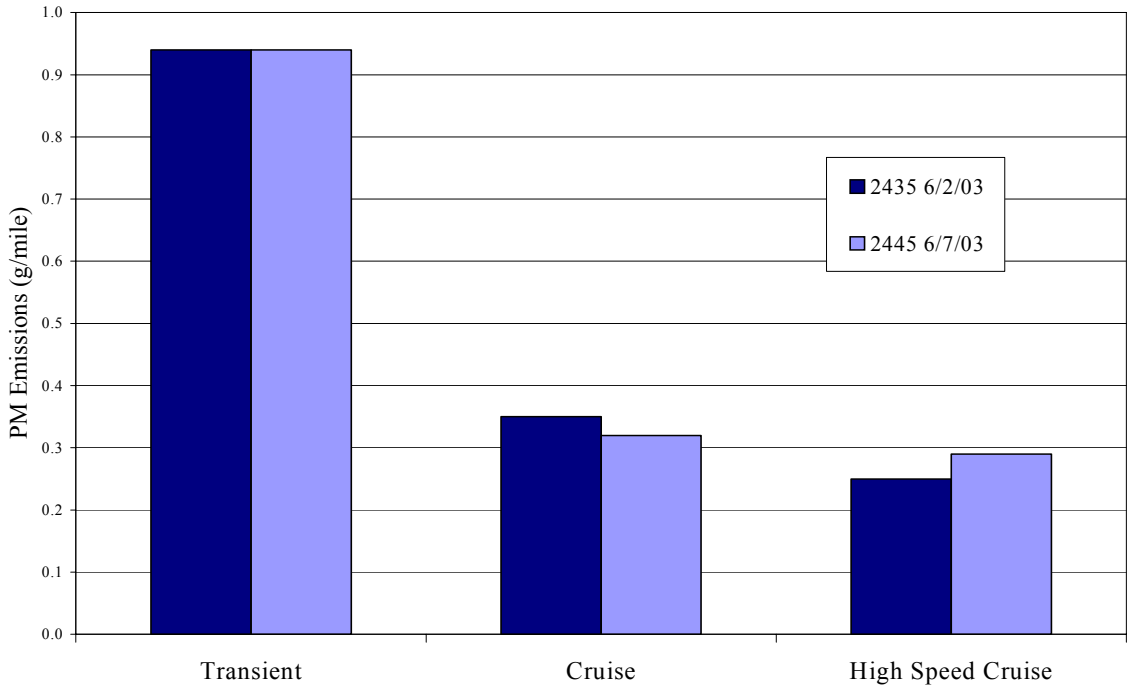


Figure 4. PM data from 6/2/03 and 6/7/03 for E55CRC-26 at 56,000 lbs. On 6/2/03 the high speed cruise test was the HHDDT65 while on 6/7/03 it was the HHDDT_S.

In some cases trucks were governed at a sufficiently low road speed that the HHDDT_S Mode could not be executed reasonably. In these cases, as judged by the WVU field engineer, no HHDDT_S Mode was attempted.

Test Weights

All of the vehicles tested in this study were deemed to have gross vehicle weights of 80,000 lbs., in that they were all typical over-the-road tractors. For tractor-trailers, it is the combination weight that is of interest, rather than the tractor weight. The test weights were planned to be 30,000 lbs., 56,000 lbs. and 75,000 lbs. However, it was evident that the 75,000 lbs. operation proved stressful to the truck brakes because only one or two axles were being used to slow an inertia that would be slowed with five axles in normal use. Also, the accelerations and decelerations at 75,000 lbs. showed potential to cause repeated dynamometer damage. Some ad hoc runs, presented in Figure 5 and Figure 6, showed that a difference still existed in emissions between 56,000 lbs. and 66,000 lbs. operating weight, and so the 66,000 lbs. weight was used instead of the 75,000 lbs. weight for the remainder of the program. PM increased monotonically with test weight for the Transient Mode, but did not change appreciably between the 56,000, 66,000, and 75,000 lbs. runs on the HHDDT_S, where wind drag becomes more important. For the case of NO_x (see Figure 6), the Transient Mode NO_x emissions at 66,000 lbs. were substantially higher than at 75,000 lbs.

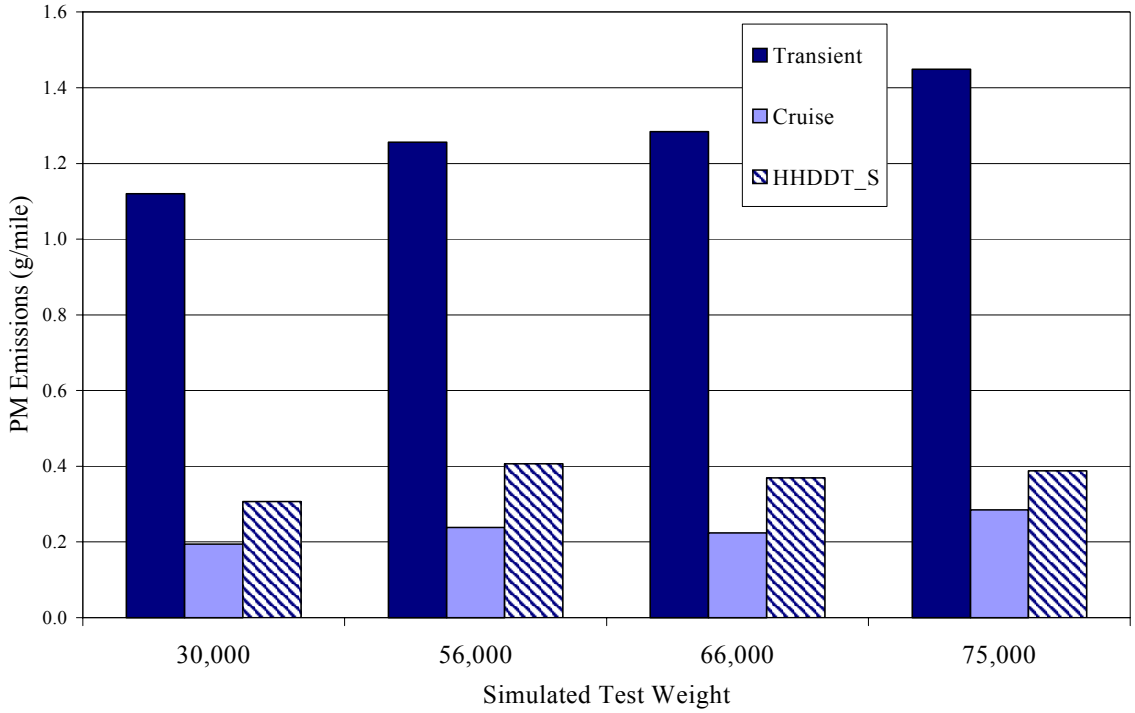


Figure 5: Vehicle E55CRC-27 was tested at four weights, before 66,000 lbs. was adopted as the highest test weight.

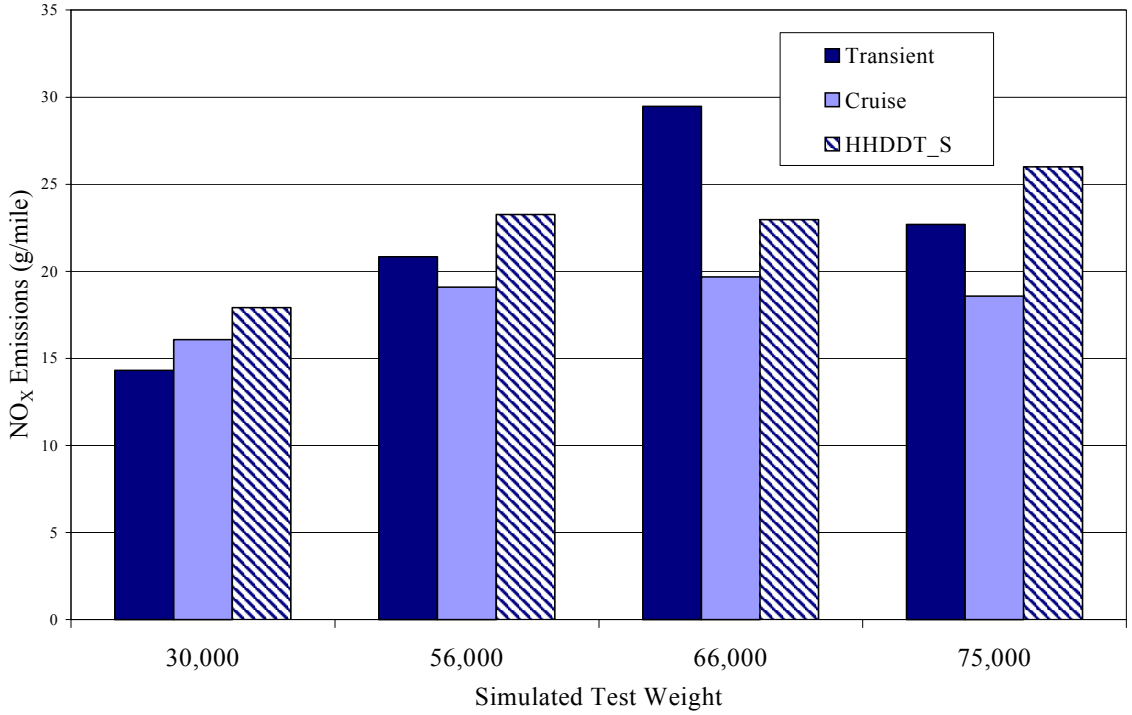


Figure 6: Vehicle E55CRC-27 was tested at four weights, before 66,000 lbs. was adopted as the highest test weight.

Test Runs

In the interest of economy, a single test run was planned and executed for each combination of truck, weight and schedule or mode. Only if a fault was detected was a run repeated.

Each execution of a cycle or mode was assigned a sequence number and a run number. Table 3 presents a listing of sequence and run numbers, with the corresponding name of the cycle, vehicle number and test weight. Some sequence and run numbers are omitted in Table 3 because they are associated with background tests or with rejected runs. In Table 3 the test modes or cycles are designated by the actual file names used. "Test D" corresponds to the UDDS, trans3 and cruise3 refer to the three point smoothed versions of the Transient and Cruise Modes that are customarily used. Some modes are lengthened by being repeated to collect sufficient PM mass during the mode. Idle32 refers to a double length idle (1,800 seconds instead of 900 seconds), and creep34 refers to four repeats of a creep run as a single mode. Table 3 corresponds to the sequence and run numbers in the short reports appearing in Appendix D.

Table 3. Sequence number, run number and vehicle information for each reportable test. The term "re-test" refers to additional testing following repair or re-flash. The "idle32" represents a double length idle (1,800 seconds total), "creep34" four creep cycles in a row.

E55CRC-(truck)	Test ID	Test Run ID	Engine Manufacturer	Engine Model	Engine Model Year	Odometer Reading	Test Duration (in sec.)	Vehicle model year	Particulate Filter	Driving Schedule
30000										
E55CRC-26	2445	1	Caterpillar	C-10	1998	539553	1800	1999	None	idle32
E55CRC-26	2445	2	Caterpillar	C-10	1998	539553	1032	1999	None	creep34
E55CRC-26	2445	3	Caterpillar	C-10	1998	539553	688	1999	None	trans3
E55CRC-26	2445	4	Caterpillar	C-10	1998	539553	2083	1999	None	cruise3
E55CRC-26	2445	5	Caterpillar	C-10	1998	539553	760	1999	None	hhddt_s
56000										
E55CRC-26	2464	1	Caterpillar	C-10	1998	539980	1039.9	1999	None	TEST_D
E55CRC-26	2465	1	Caterpillar	C-10	1998	539980	1800	1999	None	idle32
E55CRC-26	2465	2	Caterpillar	C-10	1998	539980	1032	1999	None	creep34
E55CRC-26	2465	3	Caterpillar	C-10	1998	539980	688	1999	None	trans3
E55CRC-26	2465	4	Caterpillar	C-10	1998	539980	2083	1999	None	cruise3
66000										
E55CRC-26	2466	1	Caterpillar	C-10	1998	539980	1800	1999	None	idle32
E55CRC-26	2466	2	Caterpillar	C-10	1998	539980	1032	1999	None	creep34
E55CRC-26	2466	3	Caterpillar	C-10	1998	539980	688	1999	None	trans3
E55CRC-26	2466	4	Caterpillar	C-10	1998	539980	2083	1999	None	cruise3
re-test										
E55CRC-26R	2469	1	Caterpillar	C-10	1998	539980	1039.9	1999	None	TEST_D
E55CRC-26R	2470	1	Caterpillar	C-10	1998	539980	1800	1999	None	idle32
E55CRC-26R	2470	2	Caterpillar	C-10	1998	539980	1032	1999	None	creep34
E55CRC-26R	2470	3	Caterpillar	C-10	1998	539980	688	1999	None	trans3
E55CRC-26R	2470	4	Caterpillar	C-10	1998	539980	2083	1999	None	cruise3
30000										
E55CRC-27	2457	1	Detroit	Diesel Series 60	1999	420927	1800	2000	None	idle32
E55CRC-27	2457	2	Detroit	Diesel Series 60	1999	420927	1032	2000	None	creep34
E55CRC-27	2457	3	Detroit	Diesel Series 60	1999	420927	688	2000	None	trans3
E55CRC-27	2457	4	Detroit	Diesel Series 60	1999	420927	2083	2000	None	cruise3
E55CRC-27	2457	5	Detroit	Diesel Series 60	1999	420927	760	2000	None	hhddt_s
56000										
E55CRC-27	2454	1	Detroit	Diesel Series 60	1999	420927	1039.9	2000	None	TEST_D
E55CRC-27	2455	1	Detroit	Diesel Series 60	1999	420927	1800	2000	None	idle32
E55CRC-27	2455	2	Detroit	Diesel Series 60	1999	420927	1032	2000	None	creep34
E55CRC-27	2455	3	Detroit	Diesel Series 60	1999	420927	688	2000	None	trans3
E55CRC-27	2455	4	Detroit	Diesel Series 60	1999	420927	2083	2000	None	cruise3
E55CRC-27	2455	5	Detroit	Diesel Series 60	1999	420927	760	2000	None	hhddt_s
66000										
E55CRC-27	2461	1	Detroit	Diesel Series 60	1999	420927	1800	2000	None	idle32
E55CRC-27	2461	2	Detroit	Diesel Series 60	1999	420927	1032	2000	None	creep34

E55CRC-27	2461	3	Detroit	Diesel Series 60	1999	420927	688	2000	None	trans3
E55CRC-27	2461	4	Detroit	Diesel Series 60	1999	420927	2083	2000	None	cruise3
E55CRC-27	2461	5	Detroit	Diesel Series 60	1999	420927	760	2000	None	hhddt_s
30000										
E55CRC-28	2477	1	Detroit	Diesel Series 60	1998	645034	1800	1999	None	idle32
E55CRC-28	2477	2	Detroit	Diesel Series 60	1998	645034	1032	1999	None	creep34
E55CRC-28	2477	3	Detroit	Diesel Series 60	1998	645034	688	1999	None	trans3
E55CRC-28	2477	4	Detroit	Diesel Series 60	1998	645034	2083	1999	None	cruise3
E55CRC-28	2477	5	Detroit	Diesel Series 60	1998	645034	760	1999	None	hhddt_s
56000										
E55CRC-28	2475	1	Detroit	Diesel Series 60	1998	645034	1039.9	1999	None	TEST_D
E55CRC-28	2476	1	Detroit	Diesel Series 60	1998	645034	1800	1999	None	idle32
E55CRC-28	2476	2	Detroit	Diesel Series 60	1998	645034	1032	1999	None	creep34
E55CRC-28	2476	3	Detroit	Diesel Series 60	1998	645034	688	1999	None	trans3
E55CRC-28	2476	4	Detroit	Diesel Series 60	1998	645034	2083	1999	None	cruise3
E55CRC-28	2476	5	Detroit	Diesel Series 60	1998	645034	760	1999	None	hhddt_s
66000										
E55CRC-28	2480	2	Detroit	Diesel Series 60	1998	645034	1800	1999	None	idle32
E55CRC-28	2480	3	Detroit	Diesel Series 60	1998	645034	1032	1999	None	creep34
E55CRC-28	2480	4	Detroit	Diesel Series 60	1998	645034	688	1999	None	trans3
E55CRC-28	2480	5	Detroit	Diesel Series 60	1998	645034	2083	1999	None	cruise3
E55CRC-28	2480	6	Detroit	Diesel Series 60	1998	645034	760	1999	None	hhddt_s
Re-test 1										
E55CRC-28R1	2556	1	Detroit	Diesel Series 60	1998	645400	1039.9	1999	None	TEST_D
E55CRC-28R1	2557	1	Detroit	Diesel Series 60	1998	645400	1800	1999	None	idle32
E55CRC-28R1	2557	2	Detroit	Diesel Series 60	1998	645400	1032	1999	None	creep34
E55CRC-28R1	2557	3	Detroit	Diesel Series 60	1998	645400	688	1999	None	trans3
E55CRC-28R1	2557	4	Detroit	Diesel Series 60	1998	645400	2083	1999	None	cruise3
E55CRC-28R1	2557	5	Detroit	Diesel Series 60	1998	645400	760	1999	None	hhddt_s
Re-test 2										
E55CRC-28R2	2560	1	Detroit	Diesel Series 60	1998	645400	1039.9	1999	None	TEST_D
E55CRC-28R2	2561	1	Detroit	Diesel Series 60	1998	645400	1800	1999	None	idle32
E55CRC-28R2	2561	2	Detroit	Diesel Series 60	1998	645400	1032	1999	None	creep34
E55CRC-28R2	2561	3	Detroit	Diesel Series 60	1998	645400	688	1999	None	trans3
E55CRC-28R2	2561	4	Detroit	Diesel Series 60	1998	645400	2083	1999	None	cruise3
E55CRC-28R2	2561	5	Detroit	Diesel Series 60	1998	645400	760	1999	None	hhddt_s
Re-test 3										
E55CRC-28R3	2562	1	Detroit	Diesel Series 60	1998	645400	1039.9	1999	None	TEST_D
E55CRC-28R3	2569	1	Detroit	Diesel Series 60	1998	645400	1800	1999	None	idle32
E55CRC-28R3	2569	2	Detroit	Diesel Series 60	1998	645400	1032	1999	None	creep34
E55CRC-28R3	2569	3	Detroit	Diesel Series 60	1998	645400	688	1999	None	trans3
E55CRC-28R3	2569	4	Detroit	Diesel Series 60	1998	645400	2083	1999	None	cruise3
E55CRC-28R3	2569	5	Detroit	Diesel Series 60	1998	645400	760	1999	None	hhddt_s
30000										
E55CRC-29	2489	1	Cummins	1SX475ST2	1999	120000	1800	2000	None	idle32
E55CRC-29	2489	2	Cummins	1SX475ST2	1999	120000	1032	2000	None	creep34

E55CRC-29	2489	3	Cummins	1SX475ST2	1999	120000	688	2000	None	trans3
E55CRC-29	2489	4	Cummins	1SX475ST2	1999	120000	2083	2000	None	cruise3
E55CRC-29	2489	5	Cummins	1SX475ST2	1999	120000	760	2000	None	hhddt_s
56000										
E55CRC-29	2490	1	Cummins	1SX475ST2	1999	120000	1039.9	2000	None	TEST_D
E55CRC-29	2485	1	Cummins	ISX475ST2	1999	120000	1800	2000	None	idle32
E55CRC-29	2485	2	Cummins	ISX475ST2	1999	120000	1032	2000	None	creep34
E55CRC-29	2485	3	Cummins	ISX475ST2	1999	120000	688	2000	None	trans3
E55CRC-29	2485	4	Cummins	ISX475ST2	1999	120000	2083	2000	None	cruise3
E55CRC-29	2485	5	Cummins	ISX475ST2	1999	120000	760	2000	None	hhddt_s
66000										
E55CRC-29	2486	1	Cummins	1SX475ST2	1999	120000	1800	2000	None	idle32
E55CRC-29	2486	2	Cummins	1SX475ST2	1999	120000	1032	2000	None	creep34
E55CRC-29	2486	3	Cummins	1SX475ST2	1999	120000	688	2000	None	trans3
E55CRC-29	2486	4	Cummins	1SX475ST2	1999	120000	2083	2000	None	cruise3
E55CRC-29	2486	5	Cummins	1SX475ST2	1999	120000	760	2000	None	hhddt_s
30000										
E55CRC-30	2591	1	Detroit	Diesel Series 60	1998	138625	1800	1999	None	idle32
E55CRC-30	2591	2	Detroit	Diesel Series 60	1998	138625	1032	1999	None	creep34
E55CRC-30	2591	3	Detroit	Diesel Series 60	1998	138625	688	1999	None	trans3
E55CRC-30	2591	4	Detroit	Diesel Series 60	1998	138625	2083	1999	None	cruise3
E55CRC-30	2591	5	Detroit	Diesel Series 60	1998	138625	760	1999	None	hhddt_s
56000										
E55CRC-30	2587	1	Detroit	Diesel Series 60	1998	138625	1039.9	1999	None	TEST_D
E55CRC-30	2586	2	Detroit	Diesel Series 60	1998	138625	1800	1999	None	idle32
E55CRC-30	2586	3	Detroit	Diesel Series 60	1998	138625	1032	1999	None	creep34
E55CRC-30	2586	4	Detroit	Diesel Series 60	1998	138625	688	1999	None	trans3
E55CRC-30	2586	5	Detroit	Diesel Series 60	1998	138625	2083	1999	None	cruise3
E55CRC-30	2586	6	Detroit	Diesel Series 60	1998	138625	760	1999	None	hhddt_s
66000										
E55CRC-30	2583	1	Detroit	Diesel Series 60	1998	138625	1800	1999	None	idle32
E55CRC-30	2583	2	Detroit	Diesel Series 60	1998	138625	1032	1999	None	creep34
E55CRC-30	2583	3	Detroit	Diesel Series 60	1998	138625	688	1999	None	trans3
E55CRC-30	2583	4	Detroit	Diesel Series 60	1998	138625	2083	1999	None	cruise3
E55CRC-30	2583	5	Detroit	Diesel Series 60	1998	138625	760	1999	None	hhddt_s
30000										
E55CRC-31	2573	1	Cummins	N14-460E+	1997	587389	1800	1998	None	idle32
E55CRC-31	2573	2	Cummins	N14-460E+	1997	587389	1032	1998	None	creep34
E55CRC-31	2573	3	Cummins	N14-460E+	1997	587389	688	1998	None	trans3
E55CRC-31	2573	4	Cummins	N14-460E+	1997	587389	2083	1998	None	cruise3
E55CRC-31	2573	5	Cummins	N14-460E+	1997	587389	760	1998	None	hhddt_s
56000										
E55CRC-31	2534	1	Cummins	N14-460E+	1997	587244	1039.9	1998	None	TEST_D
E55CRC-31	2532	1	Cummins	N14-460E+	1997	587244	1800	1998	None	idle32
E55CRC-31	2532	2	Cummins	N14-460E+	1997	587244	1032	1998	None	creep34
E55CRC-31	2532	3	Cummins	N14-460E+	1997	587244	688	1998	None	trans3

E55CRC-31	2532	6	Cummins	N14-460E+	1997	587244	2083	1998	None	cruise3
E55CRC-31	2532	5	Cummins	N14-460E+	1997	587244	760	1998	None	hhddt_s
66000										
E55CRC-31	2535	1	Cummins	N14-460E+	1997	587244	1800	1998	None	idle32
E55CRC-31	2535	2	Cummins	N14-460E+	1997	587244	1032	1998	None	creep34
E55CRC-31	2535	3	Cummins	N14-460E+	1997	587244	688	1998	None	trans3
E55CRC-31	2535	4	Cummins	N14-460E+	1997	587244	2083	1998	None	cruise3
E55CRC-31	2535	6	Cummins	N14-460E+	1997	587244	760	1998	None	hhddt_s
56000 R										
E55CRC-31R	2684	1	Cummins	N14-460E+	1997	587701	1039.9	1998	None	TEST_D
E55CRC-31R	2685	1	Cummins	N14-460E+	1997	587701	1800	1998	None	idle32
E55CRC-31R	2685	2	Cummins	N14-460E+	1997	587701	1032	1998	None	creep34
E55CRC-31R	2685	3	Cummins	N14-460E+	1997	587701	688	1998	None	trans3
E55CRC-31R	2685	4	Cummins	N14-460E+	1997	587701	2083	1998	None	cruise3
E55CRC-31R	2685	5	Cummins	N14-460E+	1997	587701	760	1998	None	hhddt_s
30000										
E55CRC-32	2595	1	Caterpillar	3406B	1991	596082	1800	1992	None	idle32
E55CRC-32	2595	2	Caterpillar	3406B	1991	596082	1032	1992	None	creep34
E55CRC-32	2595	3	Caterpillar	3406B	1991	596082	688	1992	None	trans3
E55CRC-32	2595	4	Caterpillar	3406B	1991	596082	2083	1992	None	cruise3
E55CRC-32	2595	5	Caterpillar	3406B	1991	596082	760	1992	None	hhddt_s
56000										
E55CRC-32	2539	1	Caterpillar	3406B	1991	595242	1039.9	1992	None	TEST_D
E55CRC-32	2540	1	Caterpillar	3406B	1991	595242	1800	1992	None	idle32
E55CRC-32	2540	2	Caterpillar	3406B	1991	595242	1032	1992	None	creep34
E55CRC-32	2540	3	Caterpillar	3406B	1991	595242	688	1992	None	trans3
E55CRC-32	2540	4	Caterpillar	3406B	1991	595242	2083	1992	None	cruise3
E55CRC-32	2540	5	Caterpillar	3406B	1991	595242	760	1992	None	hhddt_s
66000										
E55CRC-32	2599	1	Caterpillar	3406B	1991	596082	1800	1992	None	idle32
E55CRC-32	2599	2	Caterpillar	3406B	1991	596082	1032	1992	None	creep34
E55CRC-32	2599	3	Caterpillar	3406B	1991	596082	688	1992	None	trans3
E55CRC-32	2599	4	Caterpillar	3406B	1991	596082	2083	1992	None	cruise3
E55CRC-32	2599	5	Caterpillar	3406B	1991	596082	760	1992	None	hhddt_s
30000										
E55CRC-33	2547	1	Caterpillar	3406	1984	988726	1800	1985	None	idle32
E55CRC-33	2547	2	Caterpillar	3406	1984	988726	1032	1985	None	creep34
E55CRC-33	2547	3	Caterpillar	3406	1984	988726	688	1985	None	trans3
E55CRC-33	2547	4	Caterpillar	3406	1984	988726	2083	1985	None	cruise3
E55CRC-33	2547	5	Caterpillar	3406	1984	988726	760	1985	None	hhddt_s
56000										
E55CRC-33	2552	1	Caterpillar	3406	1984	988726	1039.9	1985	None	TEST_D
E55CRC-33	2550	1	Caterpillar	3406	1984	988726	1800	1985	None	idle32
E55CRC-33	2550	2	Caterpillar	3406	1984	988726	1032	1985	None	creep34
E55CRC-33	2550	3	Caterpillar	3406	1984	988726	688	1985	None	trans3
E55CRC-33	2550	4	Caterpillar	3406	1984	988726	2083	1985	None	cruise3

E55CRC-33	2550	5	Caterpillar	3406	1984	988726	760	1985	None	hhddt_s
66000										
E55CRC-33	2545	1	Caterpillar	3406	1984	988726	1800	1985	None	idle32
E55CRC-33	2545	2	Caterpillar	3406	1984	988726	1032	1985	None	creep34
E55CRC-33	2545	3	Caterpillar	3406	1984	988726	688	1985	None	trans3
E55CRC-33	2545	4	Caterpillar	3406	1984	988726	2083	1985	None	cruise3
E55CRC-33	2545	5	Caterpillar	3406	1984	988726	760	1985	None	hhddt_s
30000										
E55CRC-34	2610	1	Detroit	Diesel Series 60	2003	19094	1800	2004	None	idle32
E55CRC-34	2610	2	Detroit	Diesel Series 60	2003	19094	1032	2004	None	creep34
E55CRC-34	2610	3	Detroit	Diesel Series 60	2003	19094	688	2004	None	trans3
E55CRC-34	2610	4	Detroit	Diesel Series 60	2003	19094	2083	2004	None	cruise3
E55CRC-34	2610	5	Detroit	Diesel Series 60	2003	19094	760	2004	None	hhddt_s
56000										
E55CRC-34	2607	1	Detroit	Diesel Series 60	2003	19094	1039.9	2004	None	TEST_D
E55CRC-34	2608	1	Detroit	Diesel Series 60	2003	19094	1800	2004	None	idle32
E55CRC-34	2608	2	Detroit	Diesel Series 60	2003	19094	1032	2004	None	creep34
E55CRC-34	2608	3	Detroit	Diesel Series 60	2003	19094	688	2004	None	trans3
E55CRC-34	2608	4	Detroit	Diesel Series 60	2003	19094	2083	2004	None	cruise3
E55CRC-34	2608	5	Detroit	Diesel Series 60	2003	19094	760	2004	None	hhddt_s
66000										
E55CRC-34	2603	1	Detroit	Diesel Series 60	2003	19094	1800	2004	None	idle32
E55CRC-34	2603	2	Detroit	Diesel Series 60	2003	19094	1032	2004	None	creep34
E55CRC-34	2603	3	Detroit	Diesel Series 60	2003	19094	688	2004	None	trans3
E55CRC-34	2603	6	Detroit	Diesel Series 60	2003	19094	2083	2004	None	cruise3
E55CRC-34	2603	7	Detroit	Diesel Series 60	2003	19094	760	2004	None	hhddt_s
30000										
E55CRC-35	2614	1	Detroit	Diesel Series 60	2000	106377	1800	2001	None	idle32
E55CRC-35	2614	2	Detroit	Diesel Series 60	2000	106377	1032	2001	None	creep34
E55CRC-35	2614	3	Detroit	Diesel Series 60	2000	106377	688	2001	None	trans3
E55CRC-35	2614	4	Detroit	Diesel Series 60	2000	106377	2083	2001	None	cruise3
56000										
E55CRC-35	2616	1	Detroit	Diesel Series 60	2000	106377	1039.9	2001	None	TEST_D
E55CRC-35	2617	1	Detroit	Diesel Series 60	2000	106377	1800	2001	None	idle32
E55CRC-35	2617	2	Detroit	Diesel Series 60	2000	106377	1032	2001	None	creep34
E55CRC-35	2617	3	Detroit	Diesel Series 60	2000	106377	688	2001	None	trans3
E55CRC-35	2617	4	Detroit	Diesel Series 60	2000	106377	2083	2001	None	cruise3
66000										
E55CRC-35	2621	1	Detroit	Diesel Series 60	2000	106377	1800	2001	None	idle32
E55CRC-35	2621	2	Detroit	Diesel Series 60	2000	106377	1032	2001	None	creep34
E55CRC-35	2621	3	Detroit	Diesel Series 60	2000	106377	688	2001	None	trans3
E55CRC-35	2621	4	Detroit	Diesel Series 60	2000	106377	2083	2001	None	cruise3
30000										
E55CRC-36	2645	1	Caterpillar	C-15	2001	284553	1800	2001	None	idle32
E55CRC-36	2645	2	Caterpillar	C-15	2001	284553	1032	2001	None	creep34
E55CRC-36	2645	3	Caterpillar	C-15	2001	284553	688	2001	None	trans3

E55CRC-36	2645	4	Caterpillar	C-15	2001	284553	2083	2001	None	cruise3
E55CRC-36	2645	5	Caterpillar	C-15	2001	284553	760	2001	None	hhddt_s
56000										
E55CRC-36	2638	1	Caterpillar	C-15	2001	284553	1039.9	2001	None	TEST_D
E55CRC-36	2639	1	Caterpillar	C-15	2001	284553	1800	2001	None	idle32
E55CRC-36	2639	2	Caterpillar	C-15	2001	284553	1032	2001	None	creep34
E55CRC-36	2639	3	Caterpillar	C-15	2001	284553	688	2001	None	trans3
E55CRC-36	2639	4	Caterpillar	C-15	2001	284553	2083	2001	None	cruise3
E55CRC-36	2639	5	Caterpillar	C-15	2001	284553	760	2001	None	hhddt_s
66000										
E55CRC-36	2641	1	Caterpillar	C-15	2001	284553	1800	2001	None	idle32
E55CRC-36	2641	2	Caterpillar	C-15	2001	284553	1032	2001	None	creep34
E55CRC-36	2641	3	Caterpillar	C-15	2001	284553	688	2001	None	trans3
E55CRC-36	2641	4	Caterpillar	C-15	2001	284553	2083	2001	None	cruise3
E55CRC-36	2641	5	Caterpillar	C-15	2001	284553	760	2001	None	hhddt_s
IDLE										
E55CRC-37	2771	1	Cummins	ISX-500	2004	2404	1779.9	2004	None	idle32
30000										
E55CRC-38	2841	1	Cummins	ISX	2003	2829	1800	2004	None	idle32
E55CRC-38	2841	2	Cummins	ISX	2003	2829	1032	2004	None	creep34
E55CRC-38	2841	3	Cummins	ISX	2003	2829	688	2004	None	trans3
E55CRC-38	2841	4	Cummins	ISX	2003	2829	2083	2004	None	cruise3
E55CRC-38	2841	5	Cummins	ISX	2003	2829	760	2004	None	hhddt_s
56000										
E55CRC-38	2852	1	Cummins	ISX	2003	2829	1039.9	2004	None	TEST_D
E55CRC-38	2853	1	Cummins	ISX	2003	2829	1800	2004	None	idle32
E55CRC-38	2853	2	Cummins	ISX	2003	2829	1800	2004	None	idle32
E55CRC-38	2853	3	Cummins	ISX	2003	2829	1800	2004	None	idle32
E55CRC-38	2855	1	Cummins	ISX	2003	2829	1800	2004	None	idle32
E55CRC-38	2855	2	Cummins	ISX	2003	2829	1032	2004	None	creep34
E55CRC-38	2855	3	Cummins	ISX	2003	2829	688	2004	None	trans3
E55CRC-38	2855	6	Cummins	ISX	2003	2829	2062.9	2004	None	cruise3
E55CRC-38	2855	5	Cummins	ISX	2003	2829	760	2004	None	hhddt_s
66000										
E55CRC-38	2846	1	Cummins	ISX	2003	2829	1800	2004	None	idle32
E55CRC-38	2846	2	Cummins	ISX	2003	2829	1032	2004	None	creep34
E55CRC-38	2850	1	Cummins	ISX	2003	2829	667.9	2004	None	trans3
E55CRC-38	2850	2	Cummins	ISX	2003	2829	2083	2004	None	cruise3
E55CRC-38	2850	3	Cummins	ISX	2003	2829	760	2004	None	hhddt_s

Correlation

The analytic trailer and previous chassis dynamometer test bed of the TransLab (as used in Phase 1 of this program) have been verified in a previous CRC funded effort [2] to agree sufficiently well in emissions prediction with an ensemble of laboratories across

North America. The WVU researchers have verified that the new chassis dynamometer test bed (used for the present Phase 1.5 research) correlates with the previous test bed (used in Phase 1 research) with respect to loading the vehicle in the following two ways:

First, for all vehicles, it was verified that coastdowns at 56,000 lbs. test weight matched closely the coastdowns recorded during Phase 1 of the program. This assured the field engineer that the drag to inertia characteristics was set appropriately and that the trucks were loaded in the same way on Phases 1 and 1.5.

Second, for two vehicles in the Phase 1.5 program, the vehicle hub speeds were shown to match closely the hub speeds of two class 8 tractors in Phase 1. For the same two vehicles, the integrated axle power was compared between the Phase 1 and Phase 1.5 cases.

The first pair of trucks used for comparison was E55CRC-3 (Phase 1, 1985, 300 hp) and E55CRC-33 (Phase 1.5, 1984, 310 hp) and the second pair was E55CRC-10 (Phase 1, 1998, 470 hp) and E55CRC-30 (Phase 1.5, 1998, 500 hp). Figure 7 compares the first pair on the Transient Mode and Figure 8 the first pair on the Cruise Mode. Figure 9 compares the second pair on the Transient Mode and Figure 10 compares the second pair on the Cruise Mode.

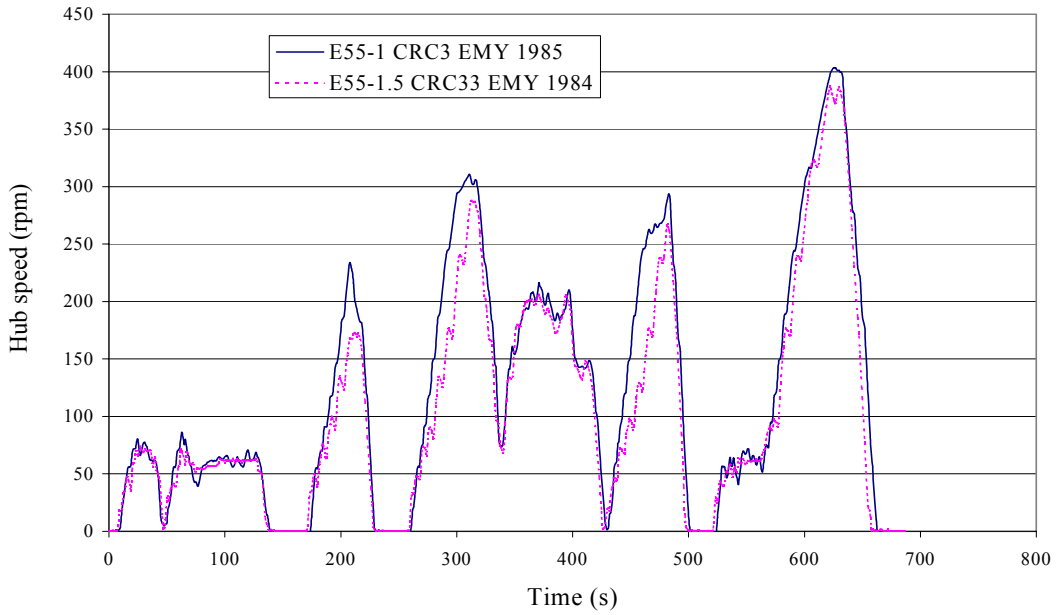


Figure 7. Hub speed for the "older" Phase 1 and Phase 1.5 vehicle pair for the Transient Mode (56,000 lbs.).

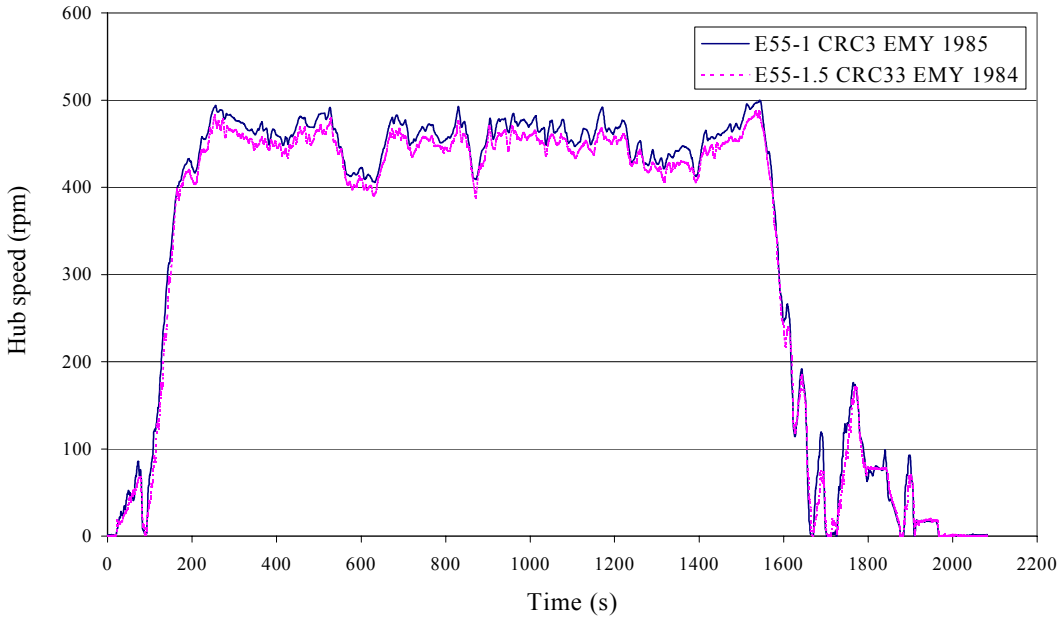


Figure 8. Hub speed for the "older" Phase 1 and Phase 1.5 vehicle pair for the Cruise Mode (56,000 lbs.).

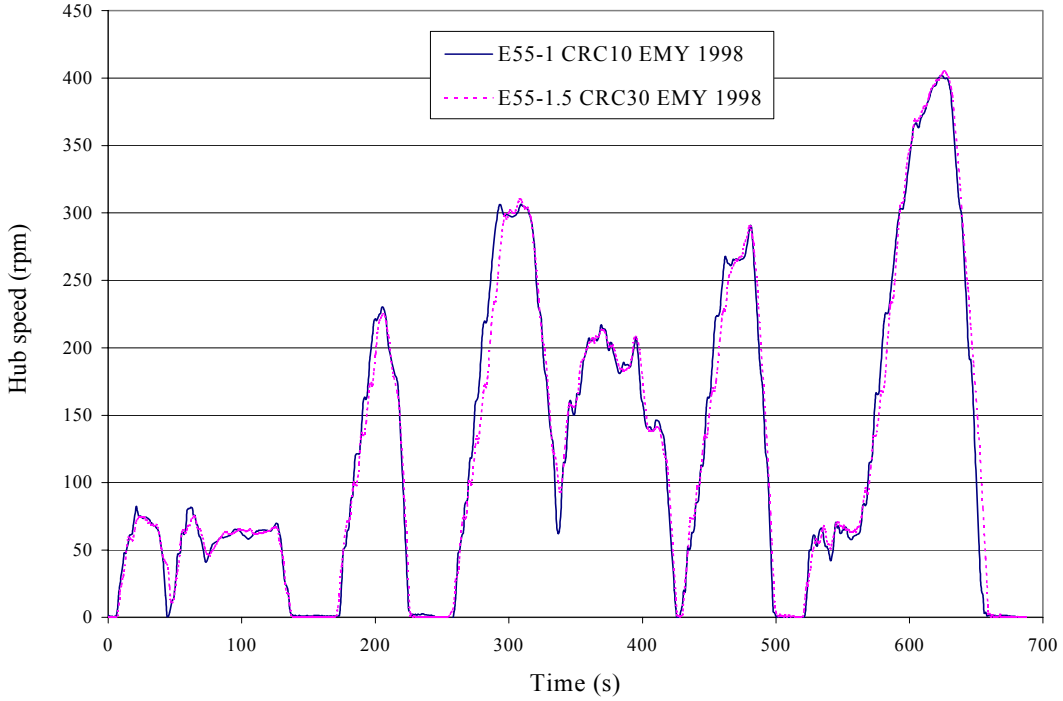


Figure 9. Hub speed for the "newer" Phase 1 and Phase 1.5 vehicle pair for the Transient Mode.

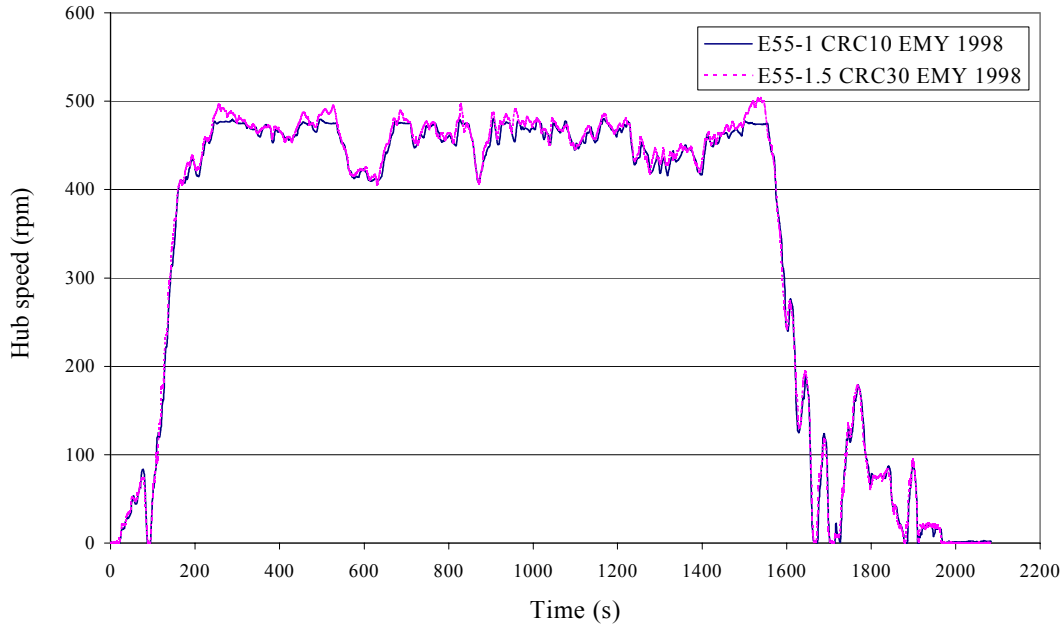


Figure 10. Hub speed for the "newer" Phase 1 and Phase 1.5 vehicle pair for the Cruise Mode.

Table 4 shows the integrated hub work for these two pairs of trucks on the Transient Mode and the Cruise Mode, at 56,000 lbs. It is not possible to compare transient torque or power between two runs because differences in gear ratios, engine torque curves, and driver behavior can cause substantial instantaneous torque differences at the same point in a schedule. Table 4 and Figure 7 show that the greatest difference occurs for the older trucks on the Transient Mode, and it appears that the Phase 1.5 older truck (E55CRC-33) was unable to accelerate rapidly. Otherwise there is good agreement between the Phase 1 and Phase 1.5 operation.

Table 4. Two tractors from Phase 1 were matched with two tractors of similar power from Phase 1.5 and total axle energy was compared favorably. Data are for a 56,000 lbs. test weight.

Phase	Truck Number	Engine Model Year	Engine Rated Power	Transient	Cruise
			hp	ahp-hr	ahp-hr
1	E55CRC-3	1985	300	9.2	45.4
1.5	E55CRC-33	1984	310	8.0	42.7
1	E55CRC-10	1998	470	8.6	48.1
1.5	E55CRC-30	1998	500	8.4	48.0

Vehicle Inspection

Each truck, when received at the test site, was inspected for safety, tampering or malmaintenance and engine control unit (ECU) status. The safety inspection was conducted by the truck's test driver (who in most instances also drove the vehicle from its source). The vehicle was inspected for:

- Exhaust leaks
- Air leaks in the brake system
- Other visible brake problems (including frayed lines, damaged slack adjusters)
- Damaged drive tires
- Drivetrain damage (including worn universal joints)
- Loose fan bearing or worn engine drive belts
- Damaged vehicle controls

Vehicle information was collected on the WVU Test Vehicle Information Sheets and they are included in Appendix E. The vehicle safety inspection was verified by the completion of WVU Vehicle Inspection Report. These sheets appear in Appendix F. Vehicle E55CRC-31 required subsequent repairs during testing, but no vehicle in the program failed this initial check. One of the repairs to E55CRC-31 was for an exhaust leak, which can affect the accuracy of mass emissions rate measurements. The WVU field engineer communicated with the WVU investigators: "The leak was in the section of exhaust behind the panel under the passenger door. It was only detectable by sound." The exhaust leak was repaired after it was detected. Vehicle E55CRC-31 also suffered clutch failure on two occasions, and was sent for repairs that were effected by the owner. Clutch repairs are not considered by the investigators to influence emissions behavior. Vehicle E55CRC-31 also had an injector fail during the test program, causing it to run on five cylinders. The injector was replaced. The vehicle was retested after all these repairs were completed. Vehicle E55CRC-31 is discussed in detail in a separate section below.

Each vehicle was also visually inspected for Tampering and Malmaintenance (T&M). This inspection was the same as that developed and used in Phase 1 of this program. Items for inspection appeared in the WVU Tampering and Malmaintenance (T&M) Issues sheet for each vehicle. Copies of the WVU Tampering and Malmaintenance (T&M) Issues Sheets appear in Appendix G of this report. This E-55/59-1.5 program test plan did not originally include a provision for repair and retest of vehicles that were identified during the T&M inspection or were determined to have abnormally high emissions. However, the sponsors were notified of high PM emissions from two vehicles, E55CRC-28 and E55CRC-29, and they elected to authorize repair and retest of E55CRC-28. This repair and retest information is discussed in a separate section devoted to vehicle E55CRC-28.

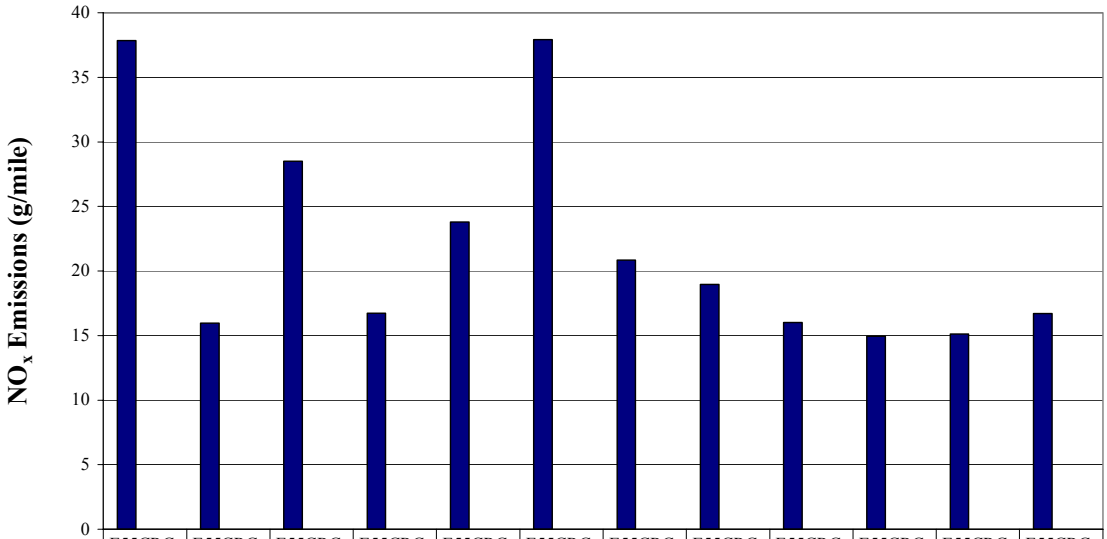
The ECU of each vehicle in the program was interrogated. WVU used the interface and software developed for the Mobile Emissions Measurement System (MEMS) used in other programs by WVU for on-board vehicle emissions measurement [3]. The field engineer transmitted interrogation results to WVU-Morgantown electronically as soon as they were available. In some cases it was not possible to read the engine ECU, and in

some cases problems were experienced with the system used to read the data. All available ECU downloads are presented in Appendix H**.** In the case that the same vehicle ECU download was performed on two occasions (and was identical), only the first download is shown in the Appendix.

Data Gathered

The cycle or mode-averaged data, in units of g/mile (except for idle, which is in time-specific units) are all presented in Appendix D in the form of "short reports." These data have also been translated into graphical representations in Appendix I**.** Data in units of g/mile, g/cycle, g/minute, g/ahp-hr and g/gallon have been gathered into summary tables in Appendix J**.** The full database containing continuous data has been made available to CRC separately in electronic form.

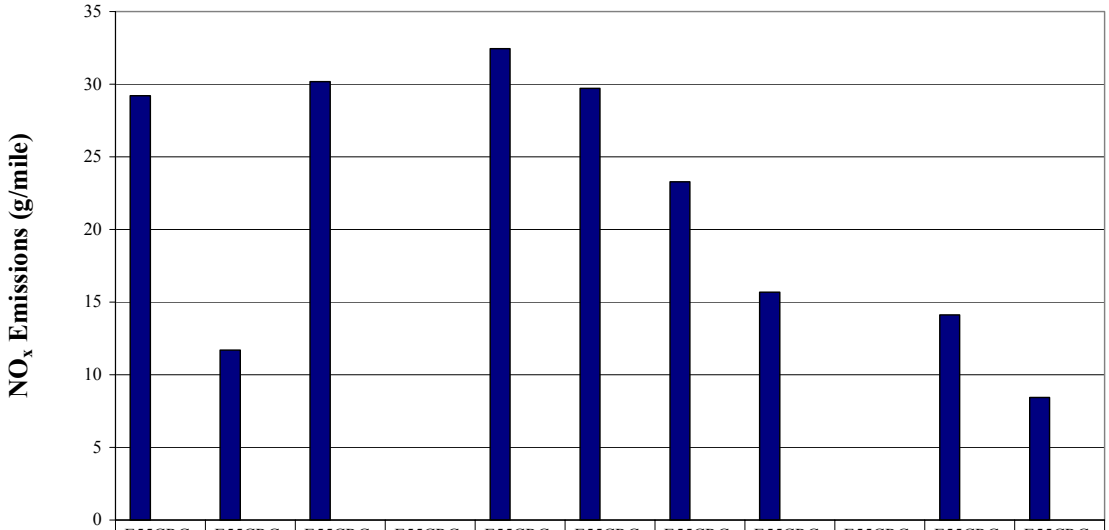
Discussion of individual truck emissions within the body of this report has emphasized two species, NO_x and PM, for two modes, Transient and HHDDT_S, since these data are assumed to be of greatest interest to the sponsors. E55CRC-26 and E55CRC-35 were not tested for the HHDDT_S because the vehicles were "speed limited" and were not able to follow the schedule trace. Figure 11 presents the NO_x emissions for all of the trucks on the Transient Mode of the HHDDT. Years on appearing in Figure 11 correspond to years of engine certification. The emissions of NO_x prior to 1999 are variable, but all of the post-1999 vehicles show NO_x levels of about 15 g/mile. The 2003 truck, though equipped with EGR and certified to a 2.5 g/bhp-hr level, shows similar NO_x emissions to the 2000 and 2001 trucks, certified to a 4 g/bhp-hr level. It is important to note that the Transient Mode does involve substantial time outside of the not-to-exceed zone, so that this equality is plausible.



	E55CRC-33	E55CRC-32	E55CRC-31	E55CRC-26	E55CRC-28	E55CRC-30	E55CRC-27	E55CRC-29	E55CRC-35	E55CRC-36	E55CRC-34	E55CRC-38
Transient	37.83	15.96	28.50	16.73	23.79	37.92	20.85	18.97	16.02	14.96	15.11	16.70
EMY	1984	1991	1997	1998	1998	1998	1999	1999	2000	2001	2003	2003
Test ID	2550	2540	2532	2465	2476	2586	2455	2485	2617	2639	2608	2855

Figure 11. NO_x emissions for the Transient Mode (56,000lbs.).

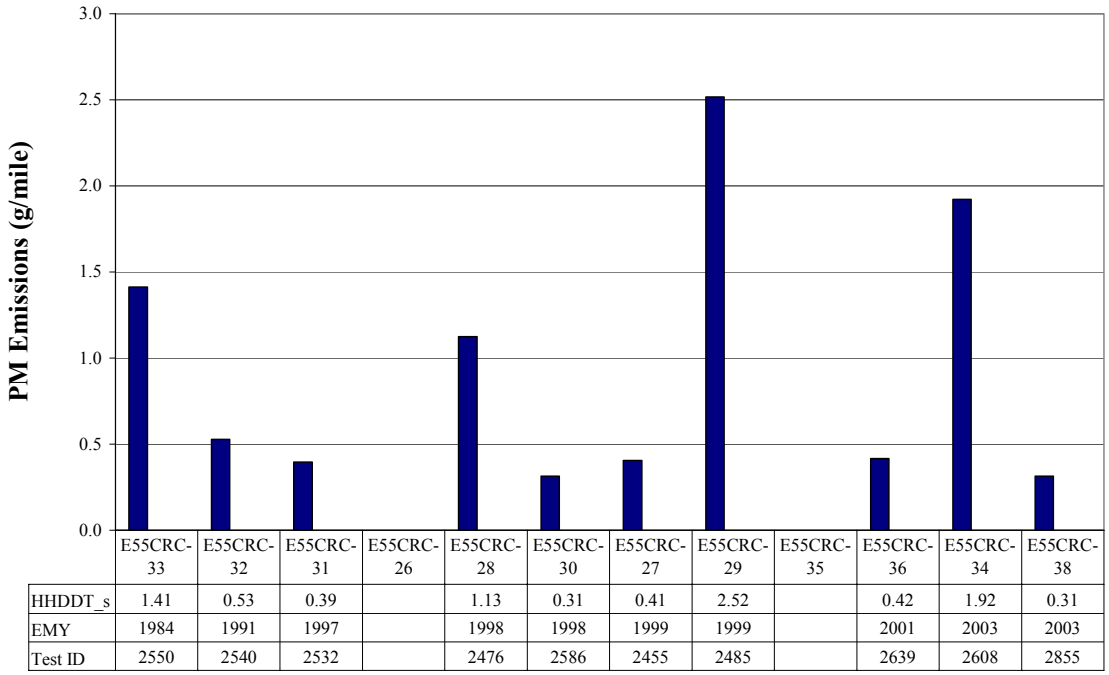
Figure 12 shows NO_x emissions for all trucks operated through the HHDDT_S mode at 56,000 lbs. test weight. For this mode, which has a high content of near-steady high-speed freeway operation, the HHDDT with the 2003 year engine exhibited lowest NO_x, at 8.44g/mile. All the remaining vehicles, but for a truck with a 1991 engine (at 11.69 g/mile NO_x) produced NO_x at over 15 g/mile.



	E55CRC-33	E55CRC-32	E55CRC-31	E55CRC-26	E55CRC-28	E55CRC-30	E55CRC-27	E55CRC-29	E55CRC-35	E55CRC-36	E55CRC-34
HHDDT_s	29.20	11.69	30.17		32.45	29.71	23.27	15.67		14.11	8.44
EMY	1984	1991	1997		1998	1998	1999	1999		2001	2003
Test ID	2550	2540	2532		2476	2586	2455	2485		2639	2608

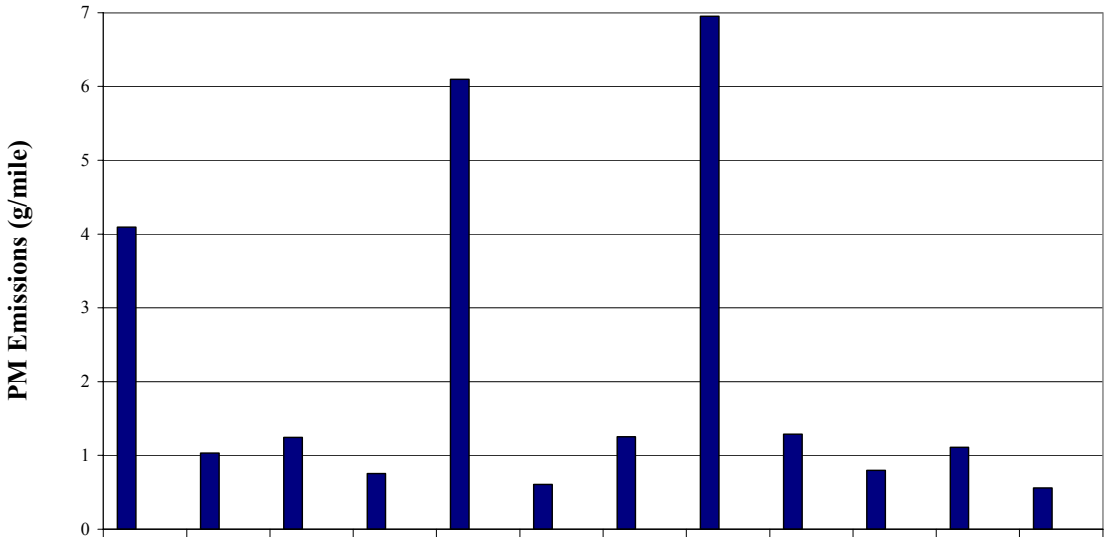
Figure 12. NO_x emissions for the HHDDT_S Mode (56,000lbs.).

Figure 13 shows PM emissions for all trucks operated through the HHDDT_S Mode at 56,000 lbs. test weight. Unexpectedly, two of the newest trucks (engine years 1999 and 2003) produced the highest PM levels. The 1999 truck was E55CRC-29, identified as a high emitter on the Transient Mode. The newest (2003 engine year) truck, E55CRC-34, was confirmed to have high PM by examining TEOM data. There was good agreement between PM filter and TEOM masses at all three test weights for the HHDDT_S Mode, and the TEOM mass for the HHDDT_S at 56,000 lbs. was higher than for other vehicles tested. High CO is also often associated with high PM, because both can arise from insufficiently lean combustion. One might expect this association to hold true for EGR equipped vehicles.



	E55CRC-33	E55CRC-32	E55CRC-31	E55CRC-26	E55CRC-28	E55CRC-30	E55CRC-27	E55CRC-29	E55CRC-35	E55CRC-36	E55CRC-34	E55CRC-38
HHDDT_s	1.41	0.53	0.39		1.13	0.31	0.41	2.52		0.42	1.92	0.31
EMY	1984	1991	1997		1998	1998	1999	1999		2001	2003	2003
Test ID	2550	2540	2532		2476	2586	2455	2485		2639	2608	2855

Figure 13. PM emissions for the HHDDT_S Mode (56,000lbs.). Two trucks, E55CRC26 and E55CRC35 have no HHDDT_S data because the trucks were governed at too low a speed to complete the mode successfully.



	E55CRC-33	E55CRC-32	E55CRC-31	E55CRC-26	E55CRC-28	E55CRC-30	E55CRC-27	E55CRC-29	E55CRC-35	E55CRC-36	E55CRC-34	E55CRC-38
Transient	4.09	1.03	1.24	0.76	6.10	0.61	1.26	6.95	1.29	0.80	1.11	0.56
EMY	1984	1991	1997	1998	1998	1998	1999	1999	2000	2001	2003	2003
Test ID	2550	2540	2532	2465	2476	2586	2455	2485	2617	2639	2608	2855

Figure 14. PM emissions for the Transient Mode (56,000 lbs.).

NO_x – PM Plots

Figure 14 shows PM emissions for all trucks operated through the Transient Mode at 56,000 lbs. test weight. Some trucks (E55CRC-26 and E55CRC-35) were not operated on the HHDDT_S Mode because they could not reach the high speed required. The oldest truck (engine year 1984) produced 4.09 g/mile of PM. Of the remaining trucks, two (E55CRC-28 and E55CRC-29) were identified as high emitters, and the remainder all emitted PM in the range of 0.76 to 1.29 g/mile. In other words, PM levels remained similar for all trucks with engines from 1991 to 2003, except for two high emitters that were over 6 g/mile.

Plots have been prepared showing a point for the distance-specific emissions on all modes at 30,000 lbs., 56,000 lbs., and 66,000 lbs. Figure 15, Figure 16, and Figure 17 show the Creep Mode yielding the highest distance specific emissions in most cases.

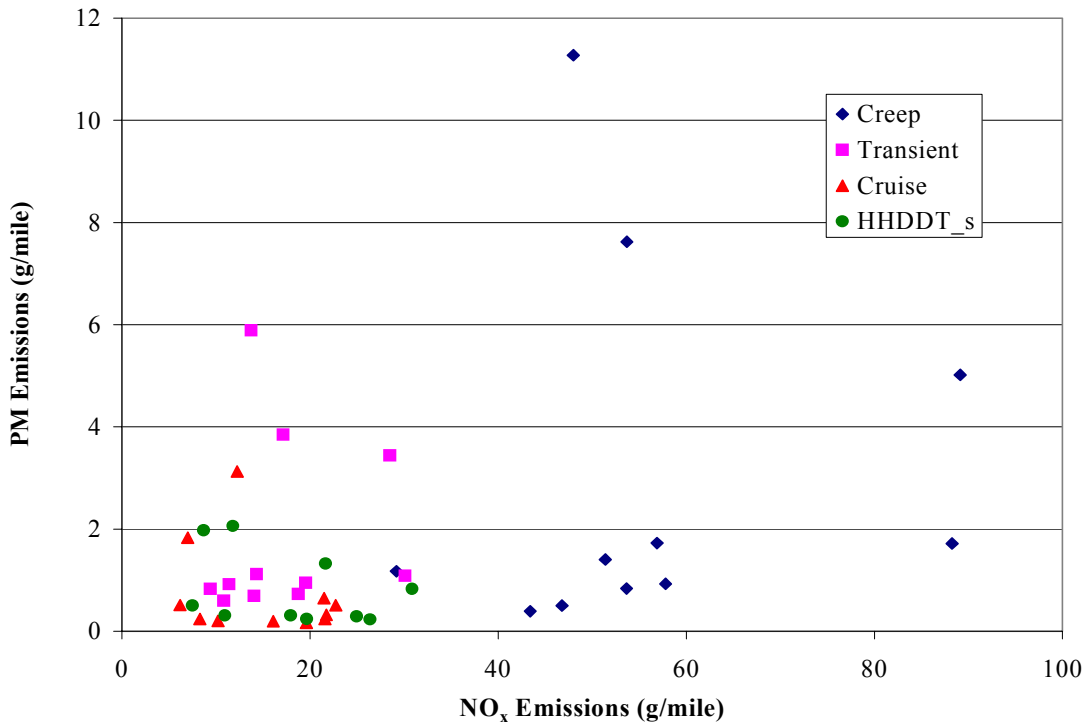


Figure 15. PM versus NO_x for the HHDDT Modes (excluding idle) for all Phase 1.5 trucks at 30,000 lbs. test weight.

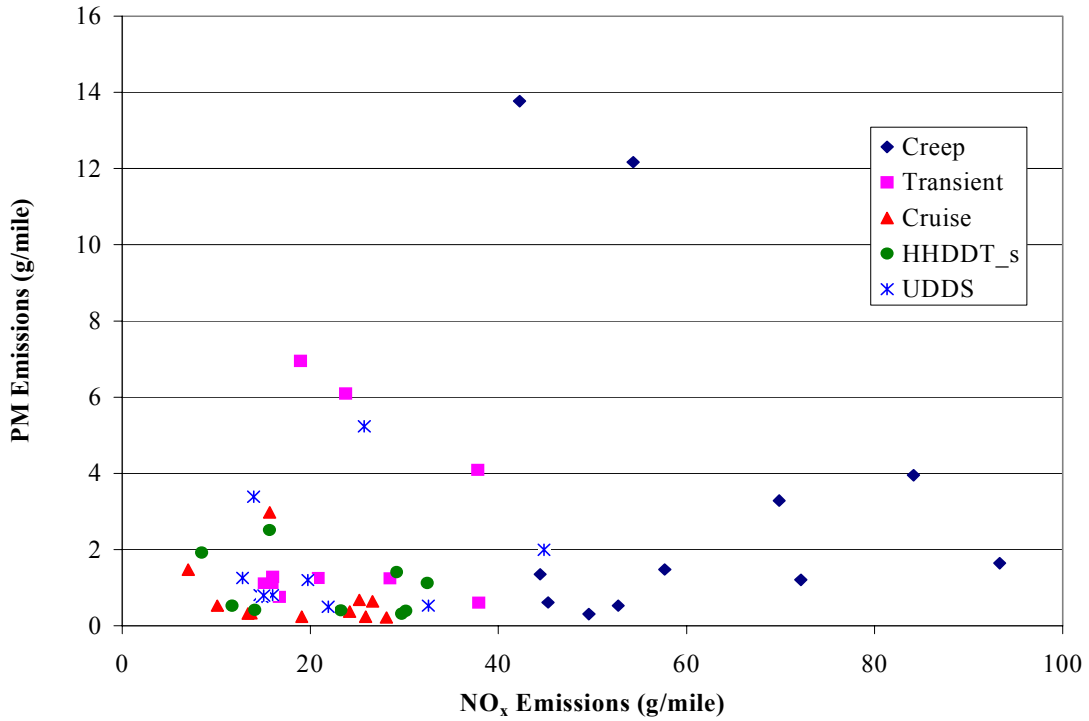


Figure 16. PM versus NO_x for the HHDDT Modes (excluding idle) for all Phase 1.5 trucks at 56,000 lbs. test weight.

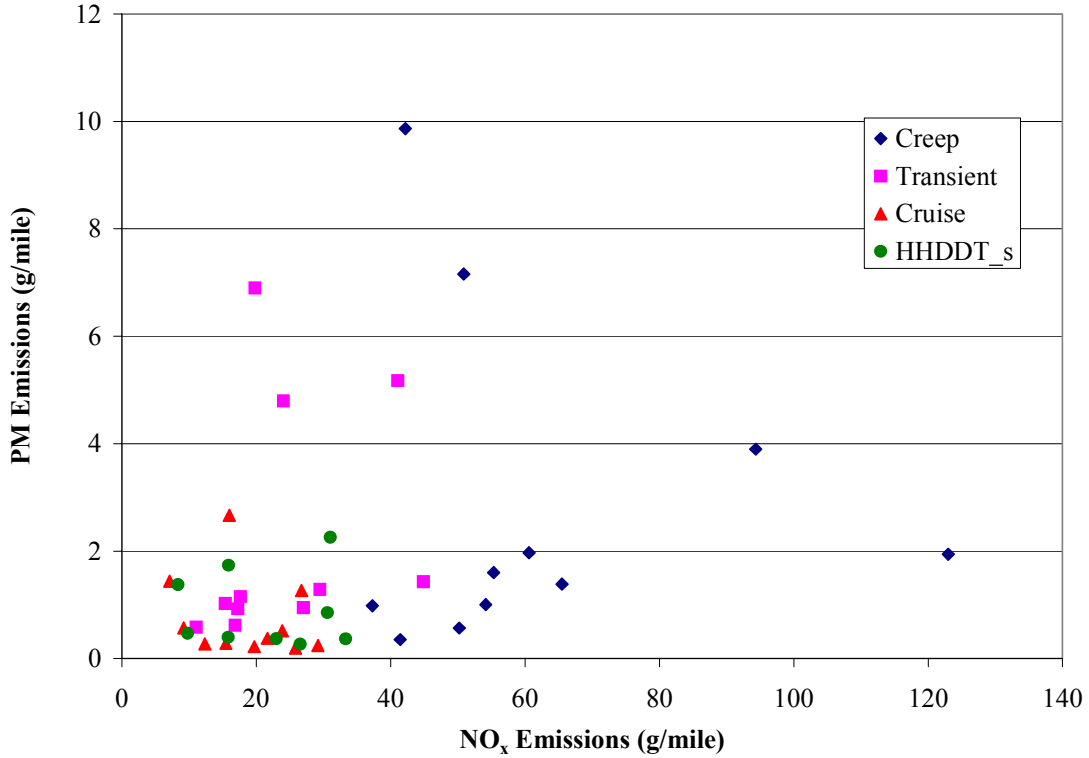


Figure 17. PM versus NO_x for the HHDDT Modes (excluding idle) for all Phase 1.5 trucks at 66,000 lbs. test weight.

Continuous Data

All dynamometer speeds and torques, all regulated gaseous emissions, exhaust and tunnel temperatures, and TEOM data are available on a continuous basis. These data are available to the sponsors separately from this report. Figure 18, Figure 19, and Figure 20 present examples of continuous NO_x, HC and CO emissions from E55CRC-31 on the Transient Mode at 56,000 lbs. test weight and Figure 21 shows the exhaust temperature of this vehicle.

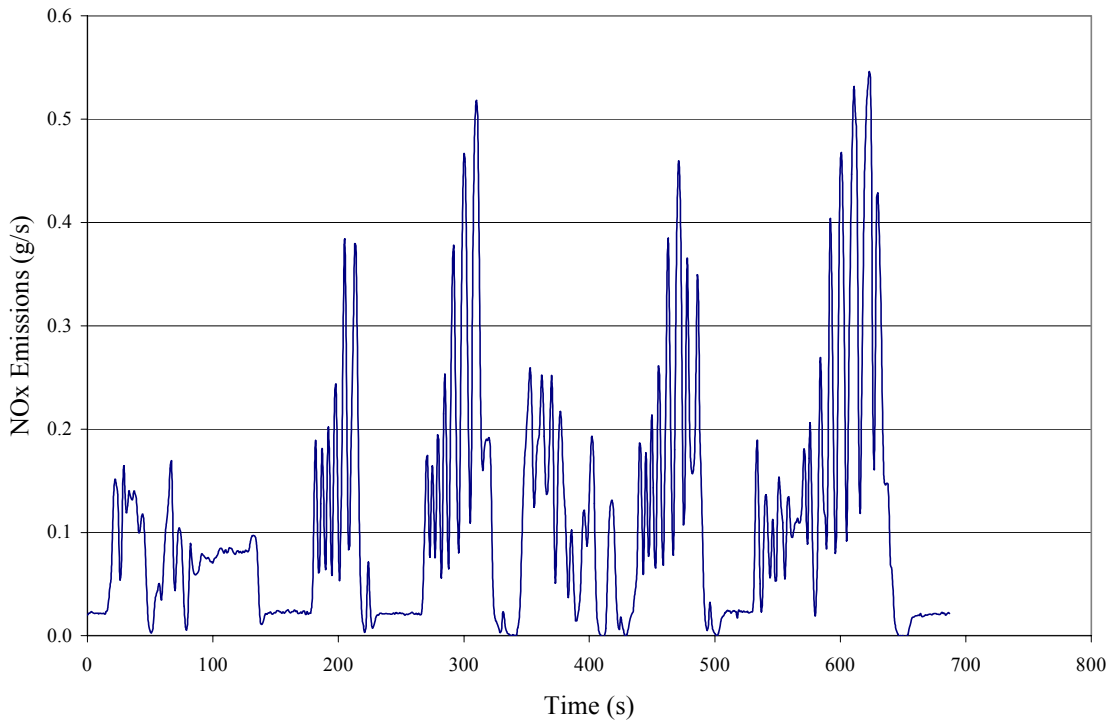


Figure 18. Example of a continuous NO_x emissions plot in g/second for E55CRC-31 at 56,000 lbs. following the Transient Mode schedule.

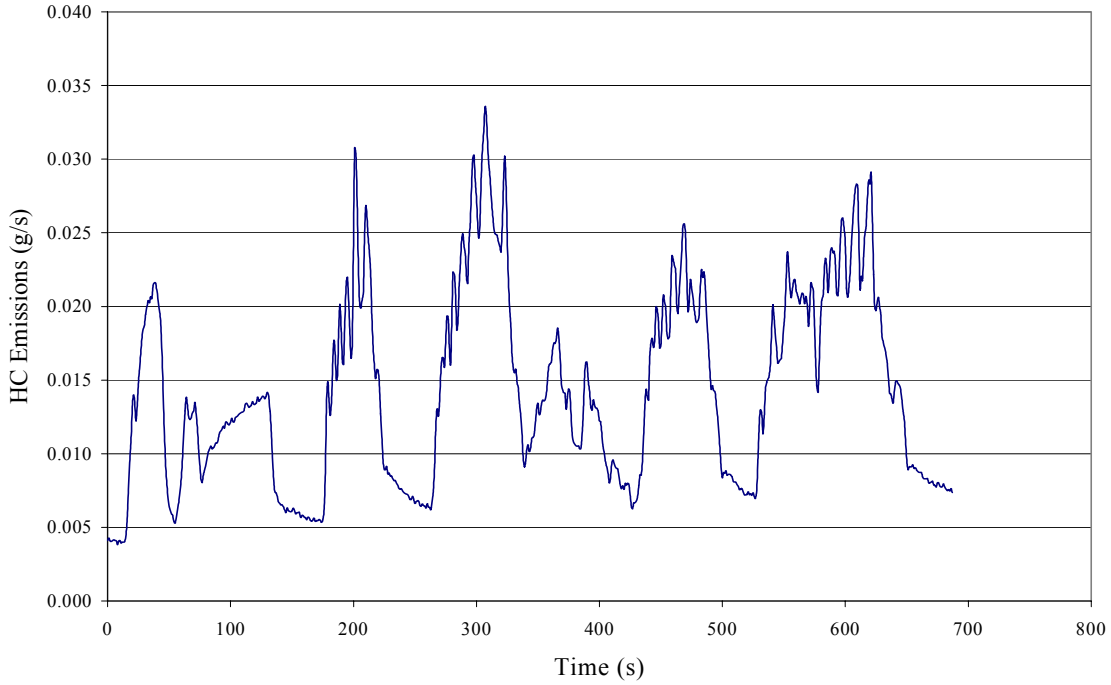


Figure 19. Example of a continuous HC emissions plot in g/second for E55CRC-31 at 56,000 lbs. following the Transient Mode schedule.

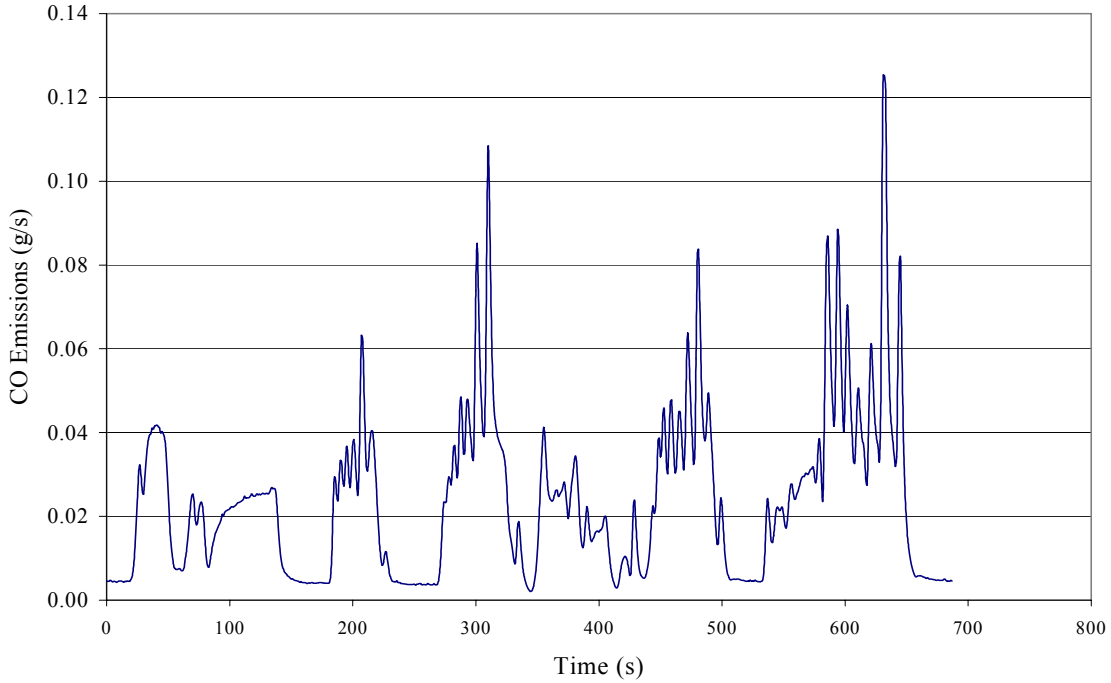


Figure 20. Example of a continuous CO emissions plot in g/second for E55CRC-31 at 56,000 lbs. following the Transient Mode schedule.

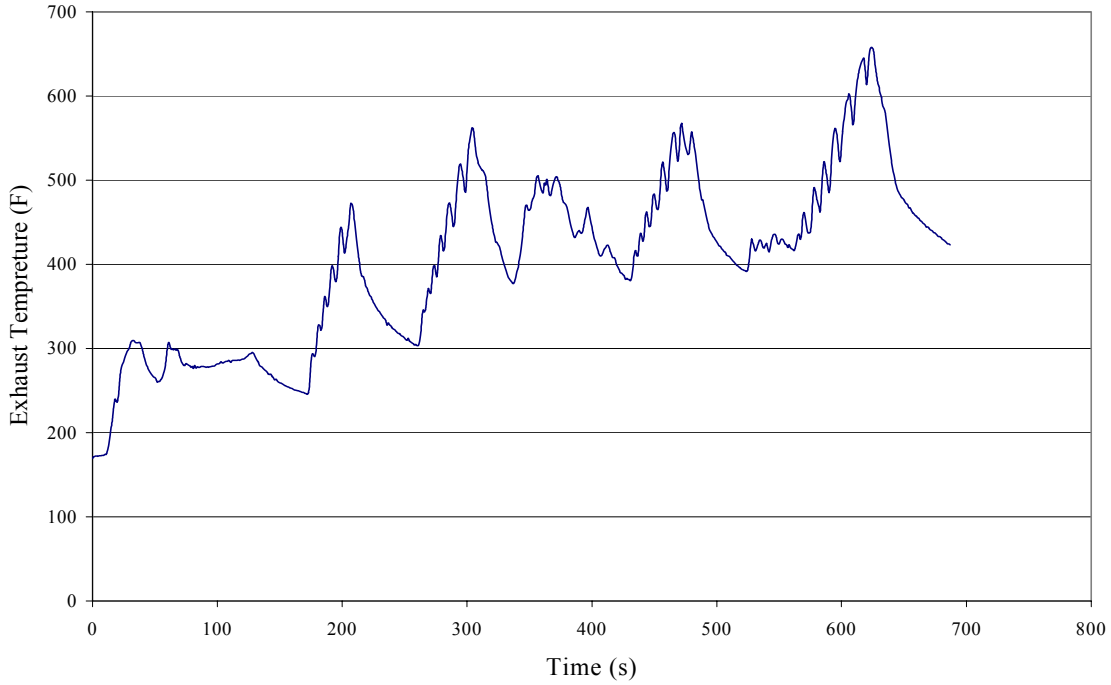


Figure 21. Example of a continuous exhaust temperature reading for E55CRC-31 at 56,000 lbs. following the Transient Mode schedule.

Group A (re-flash) vehicles

E55CRC-26, E55CRC-28 and E55CRC-31 were tested using the full baseline test program discussed immediately above. At the end of the baseline test program, all three vehicles were re-flashed to a "low-NO_x" ECU map, and re-tested. After the re-flash, the vehicle was retested using a limited set of schedules, as follows. After warming the vehicle and dynamometer, the researchers conducted a coastdown, a UDDS at 56,000 lbs., a HHDDT Idle, a HHDDT 56,000 lbs. Creep Mode, a HHDDT 56,000 lbs. Transient Mode and a HHDDT 56,000 lbs. Cruise Mode.

E55CRC-28 was also identified as a high emitter, and was tested (i) as received, (ii) without repair but with re-flash, (iii) with repair and re-flash, and (iv) without repair but with re-flash. E55CRC-31 was a vehicle that required mechanical attention during testing, as discussed in a section below.

Each of the three re-flash vehicles is discussed separately below. Figure 22 and Figure 23 show the NO_x versus hub power plots for all three re-flash vehicles on the Cruise Mode. Reduction of NO_x due to re-flash is evident.

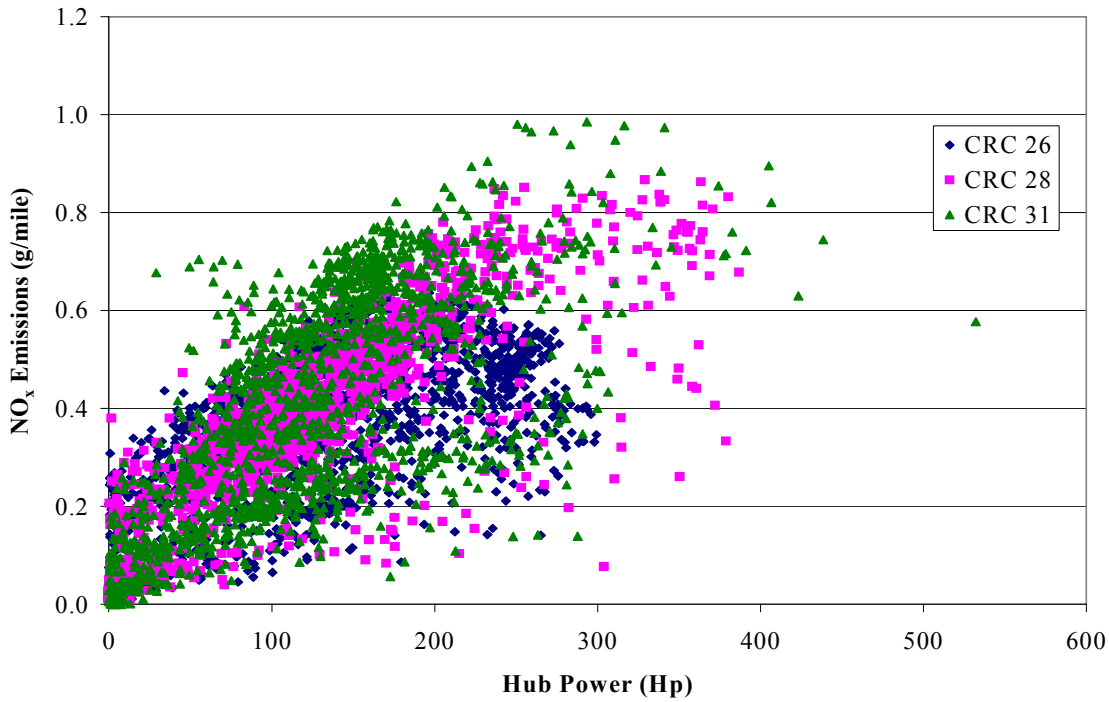


Figure 22. NO_x emissions on Cruise Mode at 56,000 lbs. test weight for three vehicles before re-flash. NO_x emissions and hub power were time-aligned before plotting. Test weight was 56,000 lbs.

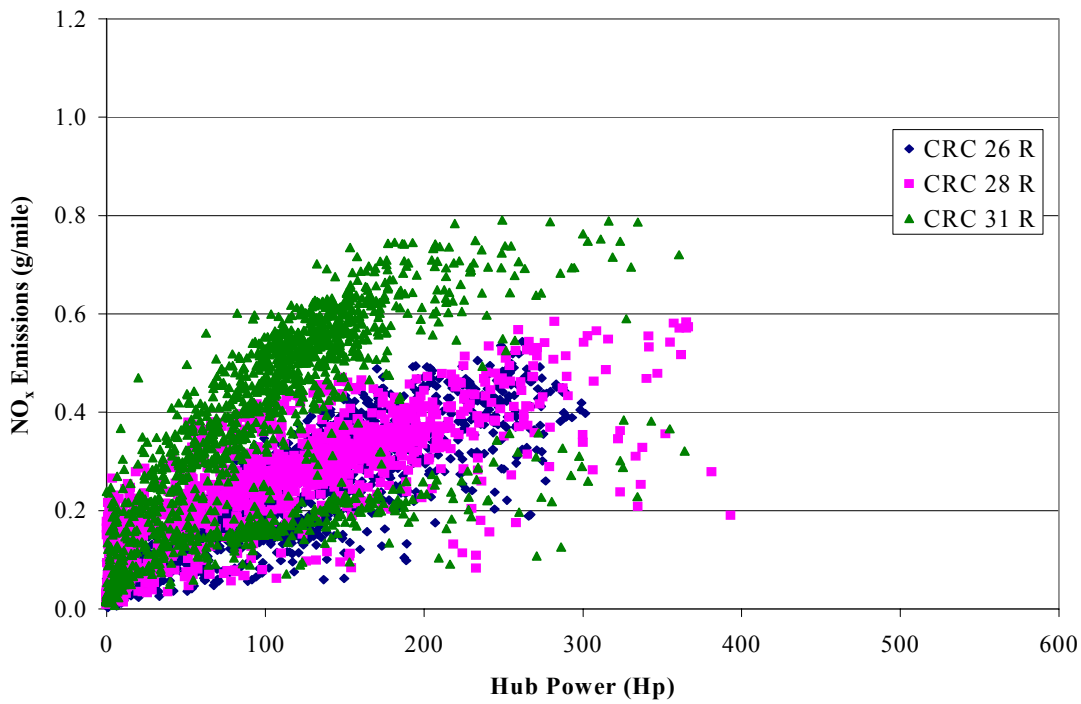
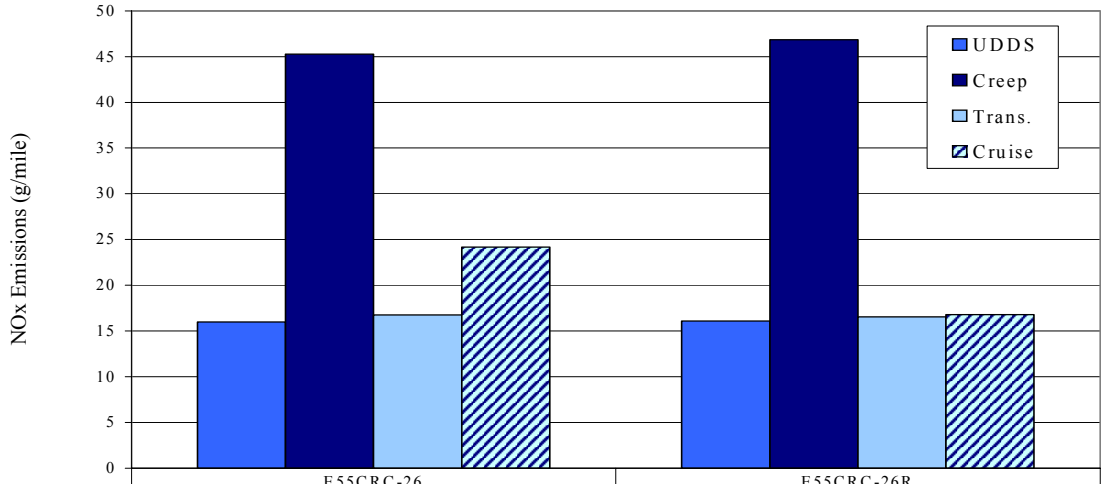


Figure 23. NO_x emissions on the three re-flash vehicles were reduced in Cruise Mode after re-flash. Test weight was 56,000 lbs.

E55CRC-26

As-received and re-flash data for NO_x for E55CRC-26 are presented in Figure 24. As might be expected, transient operation was not affected by the re-flash, and the NO_x data for the UDDS, Creep Mode and Transient Mode did not change appreciably due to re-flash.



	E55CRC-26	E55CRC-26R
UDDS	15.99	16.10
Creep	45.27	46.84
Trans.	16.73	16.53
Cruise	24.19	16.77

Figure 24. As-received and retest after re-flash NO_x data for E55CRC-26 at 56,000 lbs. test weight.

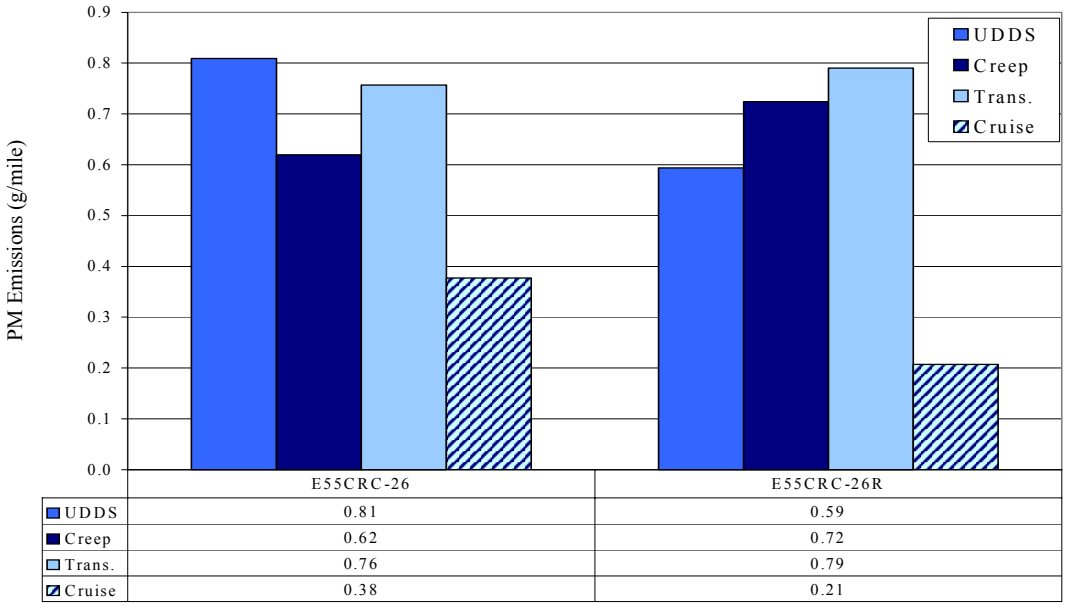


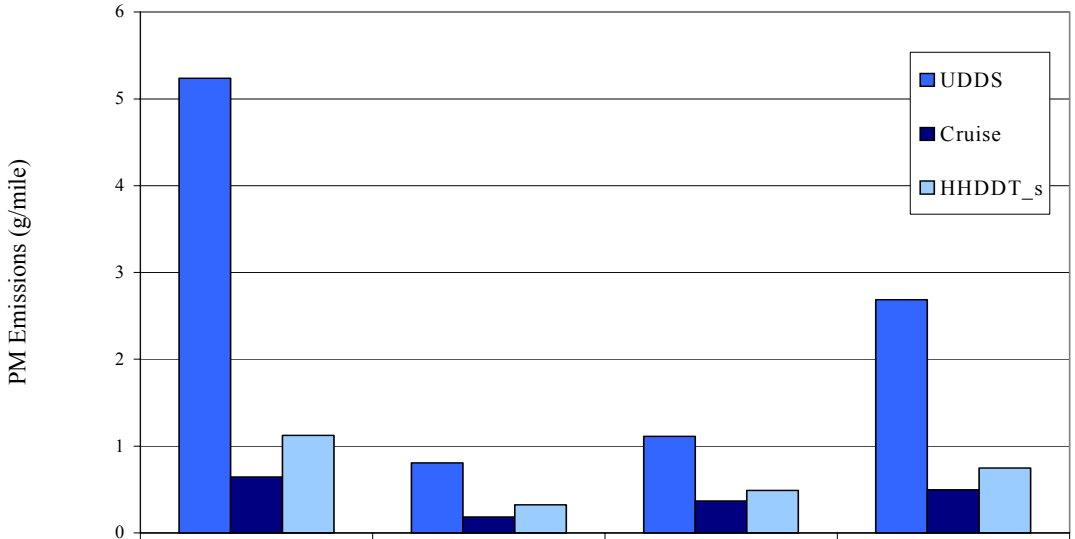
Figure 25. As-received and retest after re-flash PM data for E55CRC-26 at 56,000 lbs. test weight.

The Cruise Mode, however, exhibited a reduction in NO_x from 24.19 to 16.77 g/mile due to the re-flash. PM data for the Creep Mode, and Transient Mode were not changed appreciably by the re-flash, but the PM for the UDDS was 27% lower and the PM for the Cruise Mode dropped from 0.38 to 0.21 g/mile after the re-flash. One might expect PM values to rise slightly after a re-flash as part of the NO_x-PM tradeoff, but TEOM data (0.37 g/mile as-received, 0.20 g/mile after re-flash) were consulted and found to support the substantial reduction in PM filter mass on the Cruise Mode after re-flash.

E55CRC-28

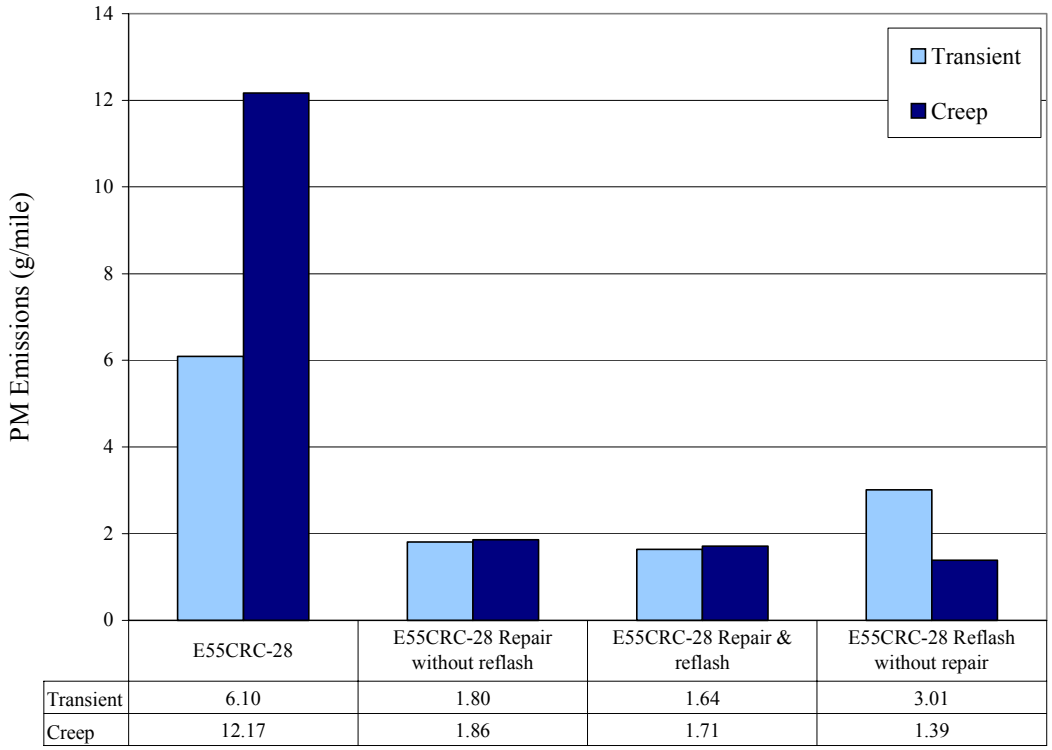
E55CRC-28, selected as a re-flash vehicle, was also identified as a high PM emitter. The researchers suggested that the cause might be a failed manifold air pressure (MAP) sensor. The MAP sensor is used in the engine control strategy to limit fueling in sympathy with rising turbocharger boost during transients that demand rise in torque. Without fueling limitation, the combustion becomes insufficiently lean and elemental carbon is produced in rich zones during combustion. High CO is also produced by failure to limit fueling during transients, and E55CRC-28 was also observed to have high CO emissions. Valley Detroit Diesel, a dealership in Fontana, CA, confirmed that the MAP sensor had failed, and were able to provide a new sensor. These sensors are readily changed.

PM was the species of interest for the repair. Figure 26 and Figure 27 show the PM levels produced by E55CRC-28 on the UDDS and HHDDT (four modes) at 56,000 lbs. test weight with and without re-flash and with and without MAP sensor replacement (repair).



	E55CRC-28	E55CRC-28 Repair without reflash	E55CRC-28 Repair & reflash	E55CRC-28 Reflash without repair
UDDS	5.24	0.81	1.11	2.69
Cruise	0.65	0.19	0.37	0.50
HHDDT_s	1.13	0.32	0.49	0.75

Figure 26. PM emission for E55CRC-28 for the UDDS, Cruise and HHDDT_S



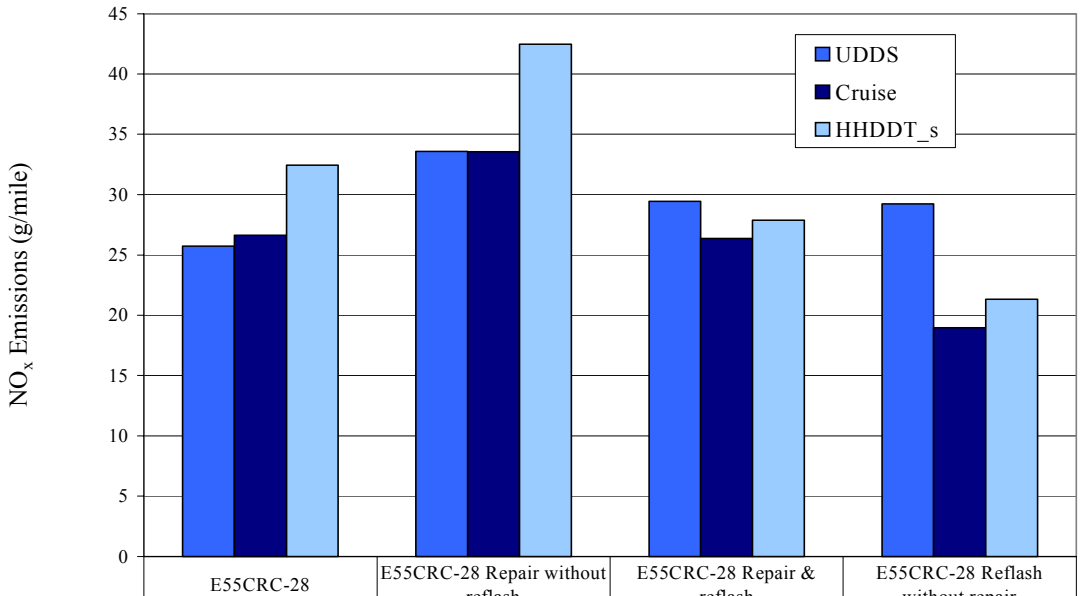
	E55CRC-28	E55CRC-28 Repair without reflash	E55CRC-28 Repair & reflash	E55CRC-28 Reflash without repair
Transient	6.10	1.80	1.64	3.01
Creep	12.17	1.86	1.71	1.39

Modes.

Figure 27. PM emissions for the Transient and Creep Modes for E55CRC-28.

In all cases, repair lowered PM substantially, whether with or without re-flash of the ECU. However, PM was also lowered in general for the re-flash without repair. In the case of the Creep Mode, the PM from re-flash without repair was below even the values for PM with repair. However, PM is known to be variable on the Creep Mode. It is possible to curb PM production even if the MAP sensor fails by adding a time-based fueling limitation to the ECU strategy. However, the authors have no direct information as to whether the re-flash code may have contained this added strategy.

The re-flash would be expected to influence NO_x more than other species. Figure 28 and Figure 29 show the NO_x levels before and after re-flash. The repair without the re-flash raised NO_x values by about 30% for the UDDS and the four HHDDT modes. The re-flash did little to abate NO_x for the Transient and Creep Modes, but offered modest reductions for the Cruise and HHDDT_S Modes and the UDDS for the repaired condition. NO_x on the UDDS was actually found to rise slightly on the UDDS for the case without repair.



	E55CRC-28	E55CRC-28 Repair without reflash	E55CRC-28 Repair & reflash	E55CRC-28 Reflash without repair
UDDS	25.73	33.57	29.43	29.22
Cruise	26.63	33.57	26.36	18.95
HHDDT_s	32.45	42.46	27.88	21.33

Figure 28. NO_x emissions for E55CRC-28 at 56,000 lbs. on the UDDS and the Creep and HHDDT_S Modes.

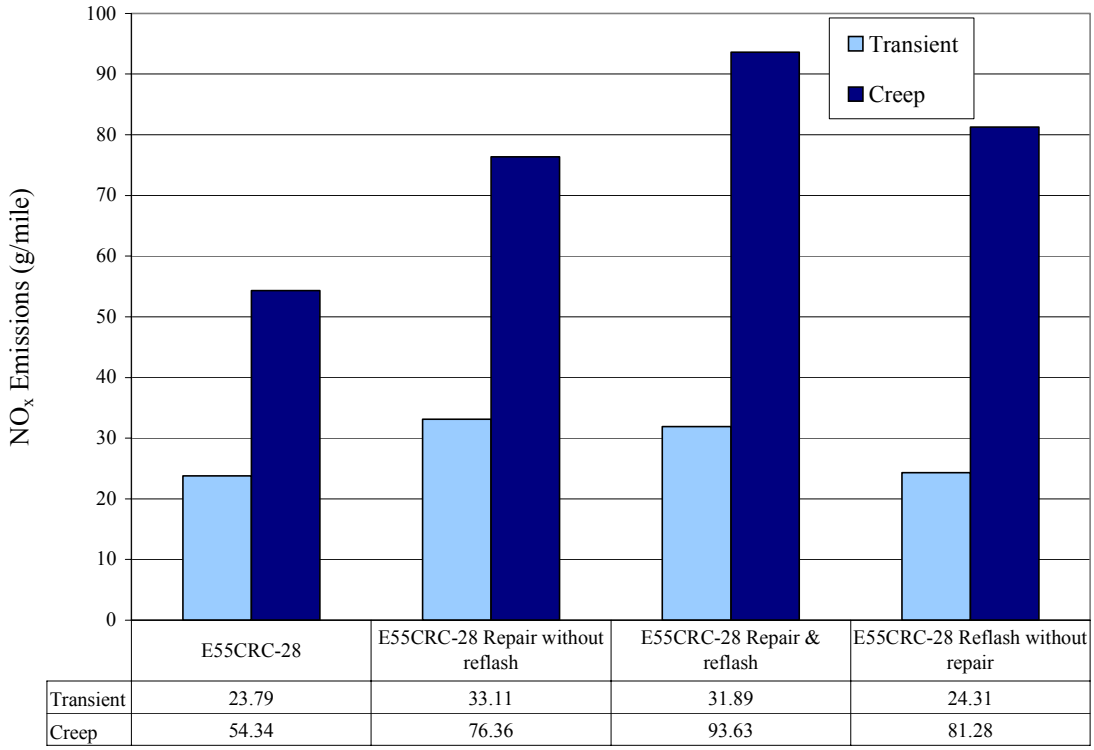


Figure 29. NO_x emissions for E55CRC-28 at 56,000 lbs. on the Transient and Creep Modes.

E55CRC-31

E55CRC-31 was subjected to as-received testing and testing after re-flash. The vehicle suffered from a clutch failure, an exhaust leak, and a fuel injector failure during testing.

The initial testing of vehicle E55CRC-31 was conducted on 7/2/03 during the time of the speciation sampling. HHDDT and UDDS tests were performed at 56,000 lbs. and an HHDDT at 66,000 lbs. The vehicle was re-procured on 7/15/03 for the HHDDT 30,000 lbs. test to complete the as-received testing.

The vehicle was then sent to a local dealership to be "re-flashed" for a low NO_x calibration. On 7/16/03, the vehicle was retested with the re-flash. One HHDDT at 56,000 lbs. was completed but the required UDDS was not performed.

The vehicle was brought back on 7/28/03 to complete the re-flash testing. While conducting the retest with the low NO_x re-flash of vehicle E55CRC-31, a significant exhaust leak developed. The vehicle was removed from the test bed to repair the exhaust leak and testing continued with other vehicles. When vehicle E55CRC-31was procured again, a problem with the clutch prevented testing. WVU staff adjusted the clutch but this did not solve the problem. A technician from the rental company was called to service the vehicle. Both the clutch-brake and the clutch were found to need replacement. While testing the vehicle after changing the clutch, an engine mis-fire was

detected that was not present during prior testing. The technician determined the problem to be a faulty injector. The fuel injector was replaced. Testing was completed. Table 5 shows the sequences of repairs and retests. These repairs were not treated as Tampering and Malmaintenance repairs.

Table 5. Sequence of testing for E55CRC-31

Date	Tests performed	Seq. No.	Action
7/2/03	56,000 HHDDT 56,000 UDDS 66,000 HHDDT	2532 2534 2535	Tests reported
7/15/03	30,000 HHDDT	2573	Tests reported
7/16/03	56,000 HHDDT re-flash did not do the 56,000 UDDS	2577/78	Tests not reported
7/28/03	56,000 HHDDT re-flash (Trans3, Cruise3) to verify data from 7/16/03 56,000 UDDS re-flash (significant exhaust leak developed) Found problems with the clutch, clutch brake, and fuel injector	2625 2626	Tests not reported Truck repaired
8/19/03	56,000 HHDDT re-flash 56,000 UDDS re-flash	2685 2684	Tests reported

As-received and re-flash emissions are shown in Figure 30 and Figure 31. The re-flash reduced NO_x emissions (in g/mile) for the UDDS and the Creep, Transient and Cruise modes of the HHDDT. PM emissions (in g/mile) rose slightly on the UDDS, and dropped from 1.24 g/mile to 0.76 g/mile on the Transient Mode, but were otherwise changed little. However, it was found that CO_2 emissions were also reduced, (as shown in the short reports in Appendix D) which was not expected. Since fuel consumption is calculated from a carbon balance, which is dominated by CO_2 emissions, this difference in CO_2 would lead to changes in the miles per gallon values. As a result conclusions made in the g/gallon domain will differ slightly from conclusions made in the distance specific (g/mile) domain.

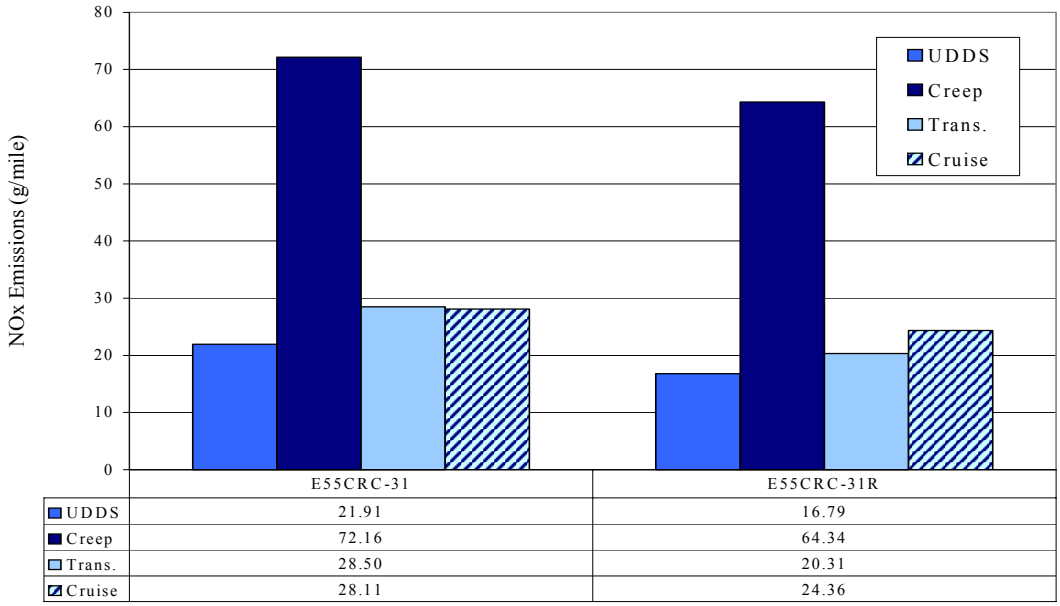


Figure 30. As-received and re-flash emissions for NO_x emissions for E55CRC-31 tested at 56,000 lbs.

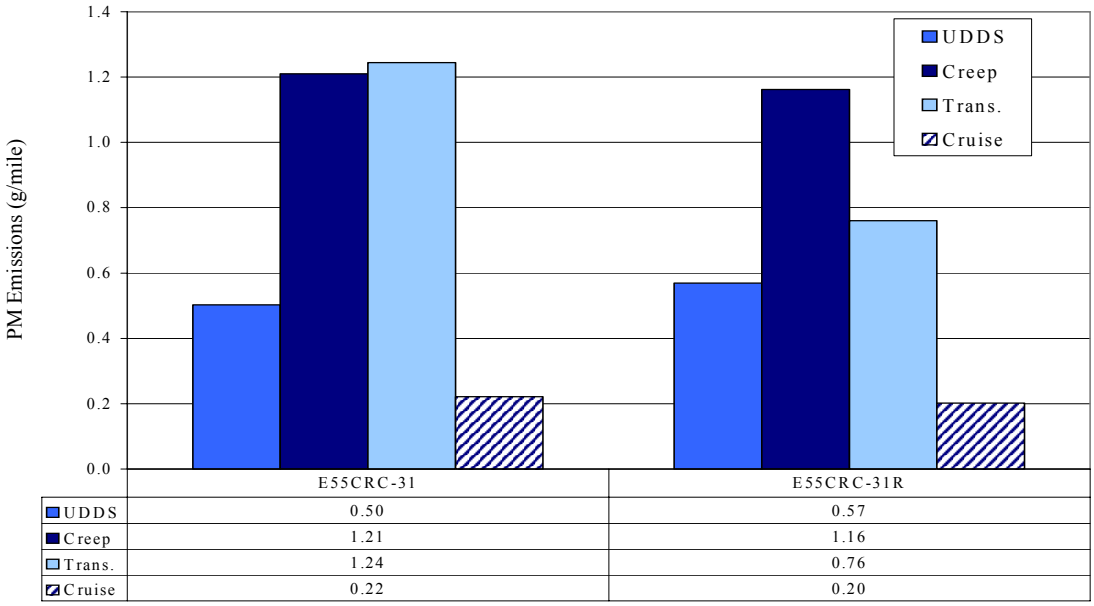


Figure 31. As-received and re-flash emissions for PM emissions for E55CRC-31 tested at 56,000 lbs.

Correlation of PM Filter and TEOM Data

TEOM data, taken as the difference between the TEOM filter end weight and beginning weight, were compared with the 70mm filter data. Agreement was generally good as shown in Figure 32.

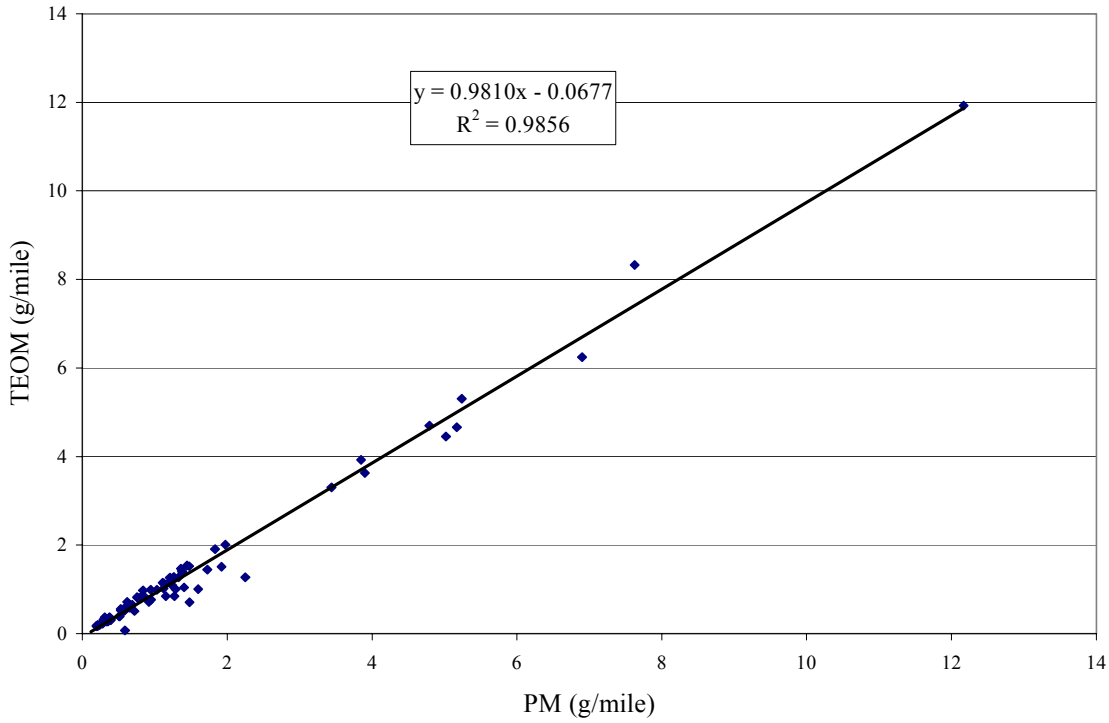


Figure 32. Comparison of TEOM filter weight to 70mm filter weight.

Correlation of NO_x Data from two Analyzers

Figure 33 compares the data between the two NO_x analyzers for every run. Only one point on the plot indicates unacceptable disagreement between the two analyzers. The deviation of other points was small, typically differing by less than 5%.

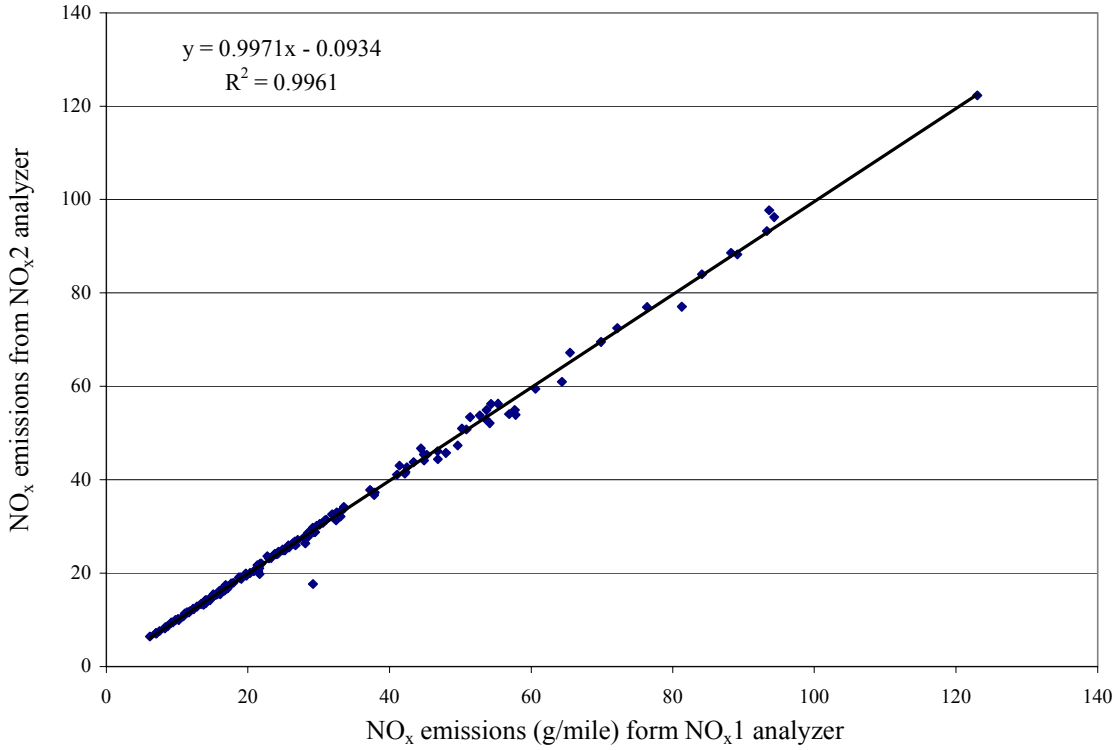


Figure 33. Comparison of NO_x readings from the two TransLab analyzers.

Effect of Test Weight

Data in Figure 34, Figure 35, and Figure 36 provide a partial view of the effect of test weight on emissions. While there were substantial truck-to-truck variations, the average effect of weight across the Phase 1.5 fleet was a rise in NO_x of 29% for the Transient Mode and 14% for the HHDDT_S as the weight increased from 30,000 lbs. to 66,000 lbs. The average effect on PM indicated an increase for two cycles (25% for the Transient Mode, 31% for HHDDT_S) from 30,000 lbs. to 56,000 lbs., but no further increase from 56,000 lbs. to 66,000 lbs.

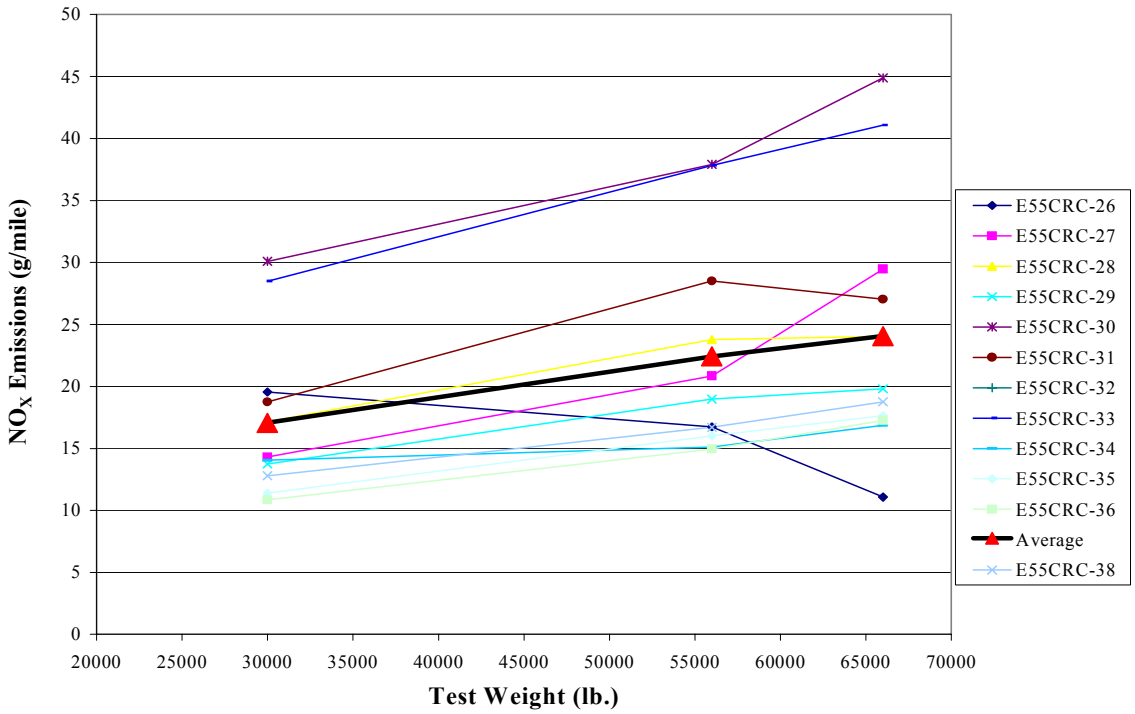


Figure 34. NO_x emissions for the Transient Mode tested at 30,000 lbs., 56,000 lbs. and 66,000 lbs.

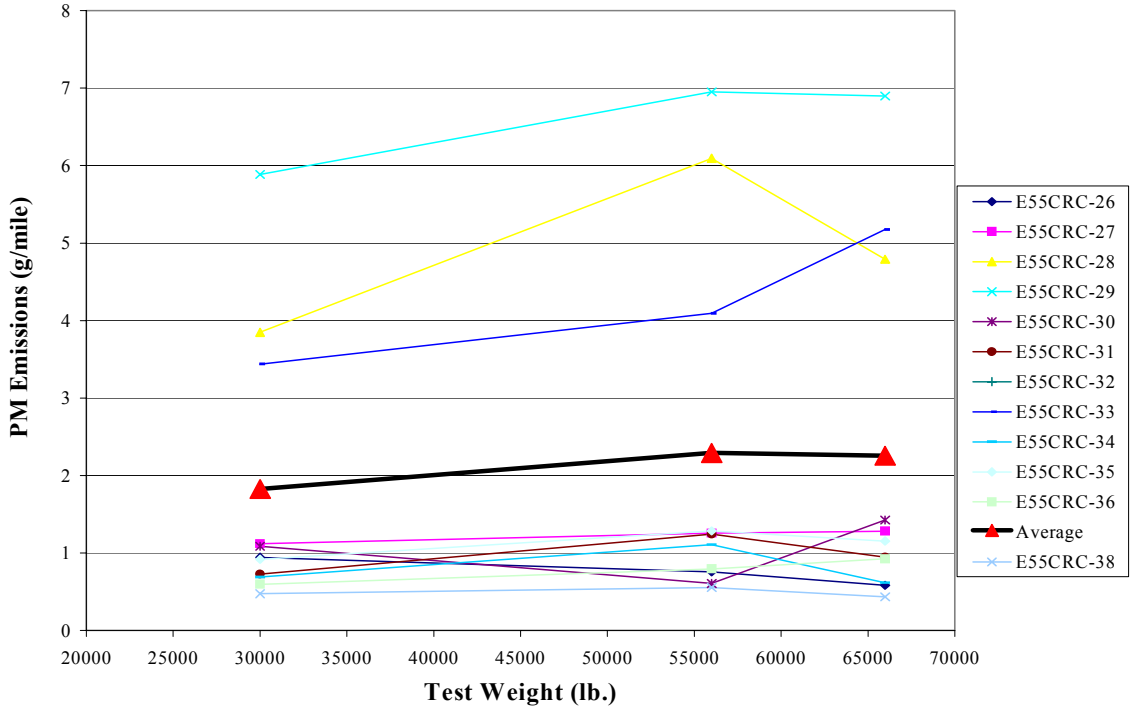


Figure 35. PM emissions for the Transient Mode tested at 30,000 lbs., 56,000 lbs. and 66,000 lbs.

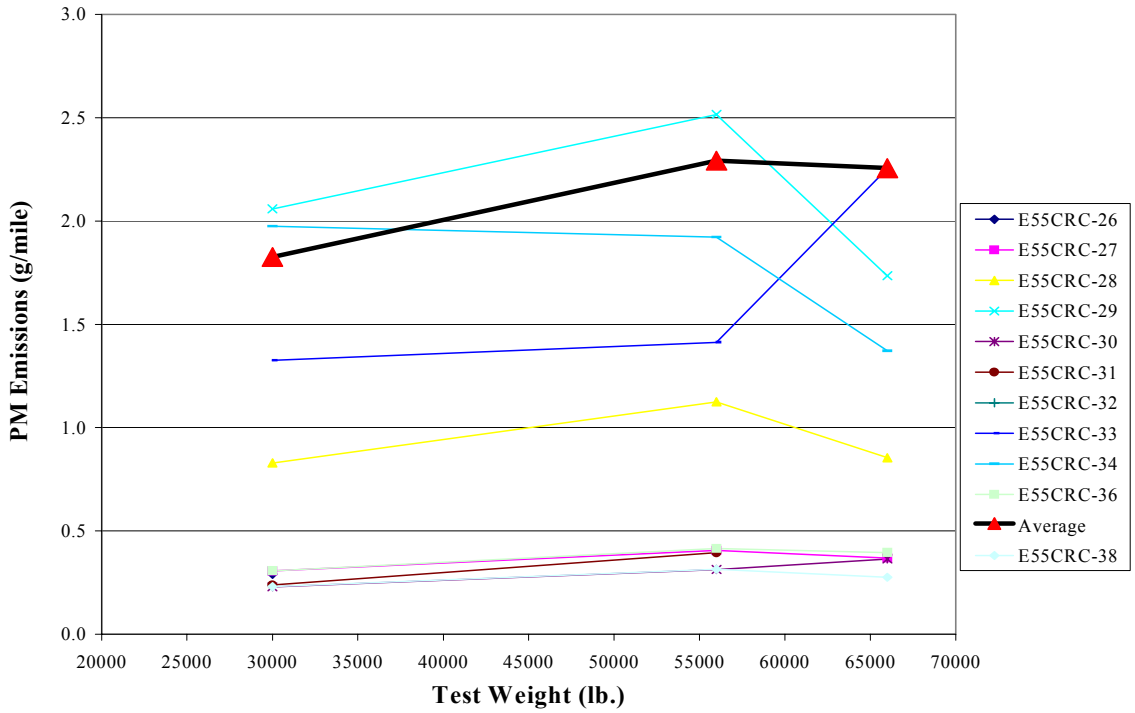


Figure 36. PM emissions for the HHDDT_S Mode tested at 30,000 lbs., 56,000 lbs. and 66,000 lbs.

Cooperation with ARB Researchers

The WVU researchers cooperated with ARB contractors, Dr. M. Judith Charles (UC Davis), Dr. Michael Kleeman (UC Davis) and Dr. Kimberly Prather (UC San Diego), who were engaged at the test site in the collection and measurement of unregulated emissions species from five vehicles E55CRC-26, E55CRC-30, E55CRC-31, E55CRC-32, and E55CRC-33. These researchers were provided with a slipstream of dilute exhaust from the tunnel so that they were able to characterize unregulated species in the diesel exhaust. They have been provided with vehicle data, and with tunnel flow rates and dilution factors for each relevant sequence and run number (see Appendix K).

Examination of Procedures

Inspection of Tampering and Malmaintenance Sheets highlighted the need for more rigorous examination of the trucks. In particular, some air filters were not inspected because they proved difficult to access. Also, some data, such as the reduction of CO_2 emissions after re-flash for E55CRC-31 remain anomalous. This reduces confidence in data obtained from a single test run. On the other hand, confidence in NO_x data was buoyed by the excellent agreement between data from the two separate NO_x analyzers in the TransLab. Also, TEOM data agreed well enough with PM data to help confirm that some unexpected PM findings were justified.

The quality control procedure at WVU was able to react to data in many cases only after the truck was released from the test site. This was particularly true with PM data, where

filter conditioning times delay results. The following actions, related to rapid data quality control, are therefore recommended for Phase 2 of this program:

1) All truck inspection sheets, all gaseous emissions data, all dynamometer data, all ECU data and TEOM data should be transmitted from the test site to WVU on each test day, and they will be examined the following morning at WVU. The truck will not be released if data anomalies are noted. TEOM data will be a surrogate for PM data until PM data are available.
2) Improved hardware and software should be employed to obtain ECU download and identify engine malfunctions.
3) The data from each truck should be compared to the growing WVU database to see whether data appear anomalous or reasonable. This is a powerful tool for verifying CO_2 emissions as they become available.

If a truck is being re-tested for any reason, the original data should be compared with the new data as they become available.

Conclusions

Thirteen HHDDT were subjected to chassis dynamometer testing using a West Virginia TransLab located in Riverside, CA. A substantial set of emissions data arose from this study, in units of g/mile, g/cycle, g/minute, g/ahp-hr, and g/gallon for each schedule or mode at each test weight. Distance-specific (g/mile) vehicle emissions depended on the test cycle or mode that was used. The emissions of NO_x from trucks prior to 1999 model year on the Transient Mode were variable, but after 1999 the levels were all about 15 g/mile for the limited number of vehicles tested. The 2003 engine year truck did not show lower NO_x on the Transient Mode than the 2000 and 2001 trucks. On the HHDDT_S, the 2003 engine year truck showed lowest emissions of NO_x. Except for the oldest truck and two trucks identified as high emitters of PM, all the PM emissions on the Transient Mode were in the 0.76 to 1.29 g/mile range. For the case of vehicles operated on the HHDDT_S, two of the newest trucks yielded the highest PM emissions.

Three of the trucks were subjected to re-flash. One truck (E55CRC-28, that also had a malfunctioning MAP sensor before and after reflash) showed a reflash NO_x reduction on the Cruise Mode and HHDDT_S, but a NO_x increase on the UDDS and no significant change on the Transient mode. Another (CRCE55-26), which could not be tested on the HHDDT_S due to speed governing, showed a reduction on the Cruise Mode, but not on the UDDS or the Transient Mode. The third truck (E55CRC-31) showed reduction on all test cycles, although NO_x reduction was only from 28.11 g/mile to 24.36 g/mile on the HHDDT Cruise Mode at 56,000 lbs. test weight. One of the trucks was also subjected to repair because it had high PM emissions. A manifold air pressure sensor was replaced and PM was reduced.

Increasing test weight from 30,000lb. to 66,000lb. caused an increase in distance-specific NO_x emissions on the Transient Mode and HHDDT_S. PM emissions increased on the Transient mode and HHDDT_S when the test weight was increased from 30,000 to 56,000 lb., but not when weight was increased from 56,000lb. to 66,000lb.

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