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Exhaust Emissions From A Heavy-duty Diesel Engine Equipped With A High Pressure Common Rail Fuel Injection System

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TECHNICAL REPORT

EXHAUST EMISSIONS FROM A HEAVY-DUTY DIESEL ENGINE EQUIPPED WITH A HIGH PRESSURE COMMON RAIL FUEL INJECTION SYSTEM

by

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I. INTRODUCTION

In October, 1997 the Environmental Protection Agency (EPA) promulgated new exhaust emission standards for heavy-duty engines[1]. The new standards, to become effective in the year 2004, will help reduce exhaust emissions for oxides of nitrogen (NOx) to approximately 2 g/bhp-hr while maintaining the current standard for particulate matter at 0.1 g/bhp-hr. Although these lower emission levels will present a challenge in the design of new engines, there are technologies available that will allow emission reductions without significantly affecting performance and fuel economy.

Over the last several years, advances in the development of electronic controls and high-pressure fuel injection systems have allowed manufacturers more flexibility in the control of the delivery of the fuel during the combustion event and higher injection pressures. High injection pressures, for example, allow better air/fuel mixing, which result in reduced formation of particulate matter. Common-rail fuel injection systems are one example of the type of technologies that are being introduced in the market and that allow both better engine performance and low emissions[2,3].

Common-rail injection systems today are attracting a lot of attention due to their flexibility by allowing the control of many engine parameters independently. In that type of system the fuel is accumulated in a rail at high pressures and the injection pressure is increased by varying the amount of fuel discharged by the supply pump[4]. Contrary to conventional fuel injections systems, the common-rail type allows to vary the injection pressures independent of engine speed and load. In in-line fuel systems the injection pressure results from the metered fuel quantity being pushed through the nozzle orifice by a piston with a velocity that is proportional to the engine speed[5]. The flexibility in varying fuel injection pressures and fuel quantity allow common-rail systems to produce higher injection pressures and higher torque at low speeds than systems using in-line pumps. Another advantage of common-rail systems is that, since the injectors use electromagnetic valves or solenoids, strategies such as rate shaping, pilot injection or even post injection can be used to further improve performance and exhaust emissions[6].

We have obtained baseline emissions data over a variety of transient and steady state cycles from a heavy-duty diesel engine that utilizes a common-rail fuel injection system. Data show that even though this engine emits NOx and PM levels that are than the 1998 U.S. heavy-duty emission standards on the Federal Test Procedure, the steady-state data show that the engine is capable of achieving NOx emission levels in the order of 3 g/bhp-hr.

II. TESTING PROCEDURES

A. Engine

The engine was in new condition and already undergone break-in. The engine is naturally aspirated, with a total displacement of 7.9 liters and its rated power is 193 hp at 2900 rpm. The engine was setup in a heavy-duty engine test cell at EPA's National Vehicle and Fuel Emissions Laboratory (NVFEL). Inlet depression was set at -7.9 in H_2O at rated point and the exhaust backpressure at 6.4 in. Hg at rated point. The fuel used for this study was diesel No. 2. The fuel specifications are included in the Appendix.

B. Test cycles

The following transient test cycles were performed:

a. Heavy-duty Federal Test Procedure (FTP): cold and hot start.
b. Crawler-tractor cycle
c. Backhoe loader cycle
d. Composite cycle

Cycles b., c. and d. were developed by Southwest Research Institute under separate contracts with the Engine Manufacturers Association (EMA) and the EPA. Although there are no final reports currently available with detailed information about the development of the cycles, the torque and speed traces are shown in the Appendix. The FTP was run by following the procedure outlined in the Code of Federal Regulations (CFR) Title 40, Part 86, Subpart N. Both the ISO 13 mode (UN-ECE R49) test and the C1 (8 mode), which are described in the ISO 8178-4 document, were also performed. In addition, a set of 56 steady-state modes were run twice to develop an emissions map under the torque curve of the engine. Each steady-state mode was run for approximately five minutes, followed by three minutes of exhaust emissions measurements. Figure 1 shows the specific map points tested under the engine's torque curve.

Exhaust emissions were sampled from a dilution tunnel and recorded continuously. The emission sampling procedure is described in 40 CFR Part 86 Subpart N. Brake specific NOx, HC and PM emissions, in g/bhp-hr, were determined from the gas concentrations that were measured continuously. The efficiency and fuel consumption results were obtained from carbon balance calculations. The following carbon balance equations were used:

$$R_2 = \frac{12.011}{12.011 + 1.008\alpha};$$

$$G_s = R_2 HC_{mass} + 0.429 CO_{mass} + 0.273 CO_{2_{mass}};$$

$$M = \frac{G_s}{R_2}\left(\frac{1}{453.6}\right);$$

where α is the hydrogen to carbon ratio, G_s is the total mass of carbon, in grams, and M is the mass of fuel consumed, in pounds.

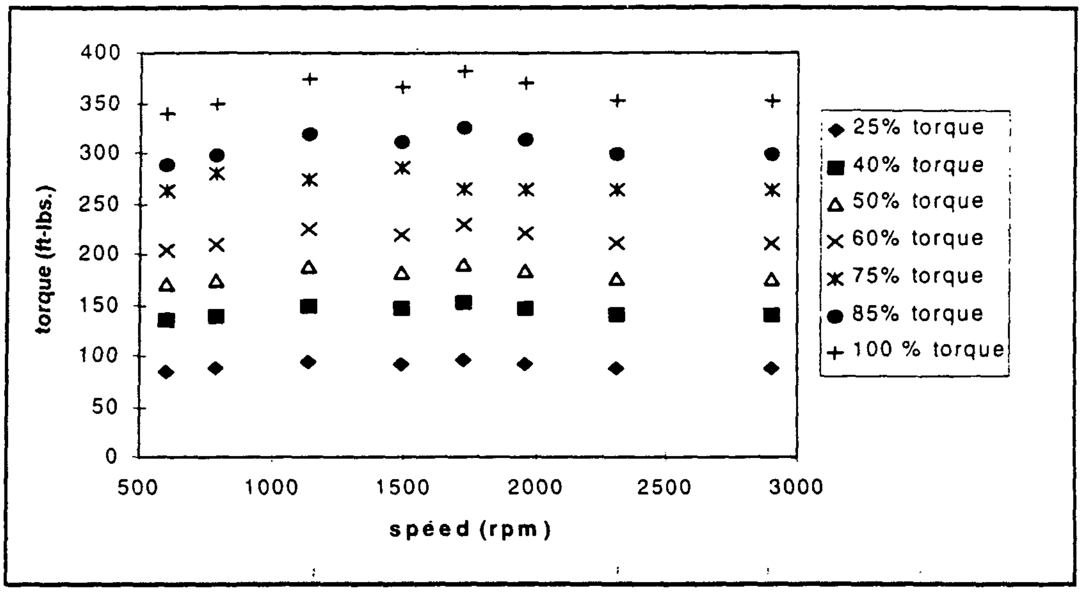


Figure 1. Steady-state emission points under the engine's torque curve.

III. RESULTS AND DISCUSSION

The table below shows the emissions results from the transient test cycles. The backhoe, crawler and composite cycles results are the average of three runs. The reproducibility of the results was good as shown in the Appendix, and the standard deviation was consistently within 5 percent of the average values. The Hot Start of the FTP was performed twice and the brake specific results were also within 5 percent from the averaged values.

Cycle	bhp-hr	NOx (g/bhp-hr)	HC (g/bhp-hr)	PM (g/bhp-hr)	BSFC (lb/bhp-hr)	Efficiency	g NOx/kg of fuel
Backhoe	4.5	5.14	0.89	0.20	0.376	0.37	30.1
Crawler	16.6	3.42	0.37	0.16	0.320	0.43	23.6
Composite	20.9	4.11	0.41	0.19	0.377	0.37	24.0
FTP (HS)	12.2	4.48	0.60	0.22	0.406	0.34	24.3
FTP (CS)	12.2	4.67	0.62	0.25	0.428	0.32	24.1

Table I. Emission results for various transient cycles.

It is worth noting that the 43% thermal efficiency calculated for the Crawler cycle was much higher than the efficiencies on the other transient cycles. Furthermore, the thermal efficiency determined from steady-state data reaches a maximum of 42% at one point only. Since the overall fuel consumption, and as a result the thermal efficiency, during the Crawler cycle was very consistent for all three cycles run, it is not possible to explain at this point the reason for such high thermal efficiency. Results for the 13 mode and ISO C1 steady state cycles are shown in Table II. The weighted brake-specific NOx and PM values were similar for both cycles as can be seen from the Table. Detailed emissions data is presented in the Appendix.

Cycle	NOx (g/bhp-hr)	HC (g/bhp-hr)	PM (g/bhp-hr)
ISO C1 (8 mode)	4.66	0.29	0.28
ISO 13 mode	4.73	0.29	0.34

Table II. Emission results from two steady-state cycles.

Results from the steady state modes sampled under the torque curve were plotted as contour graphs. Figures 2 to 6 show the brake-specific emissions, fuel consumption and thermal efficiency plots. As shown in Figure 2, the lowest NOx values occur from 1300 to almost 2000 rpm across almost the entire operating torque range. The lowest NOx value was 2.61 g/bhp-hr at 1725 rpm and 153 ft-lb. The PM emissions map shown in Figure 3 exhibit its lowest values at low speeds and high loads. Overall, however, PM emissions are higher than the current 0.1 g/bhp-hr U.S. standard. Both the BSFC and thermal efficiency maps display, as expected, similar trends: the lowest BSFC's and highest efficiencies occur at the low speed-high torque regions while the opposite is true at the high speed-low torque region.

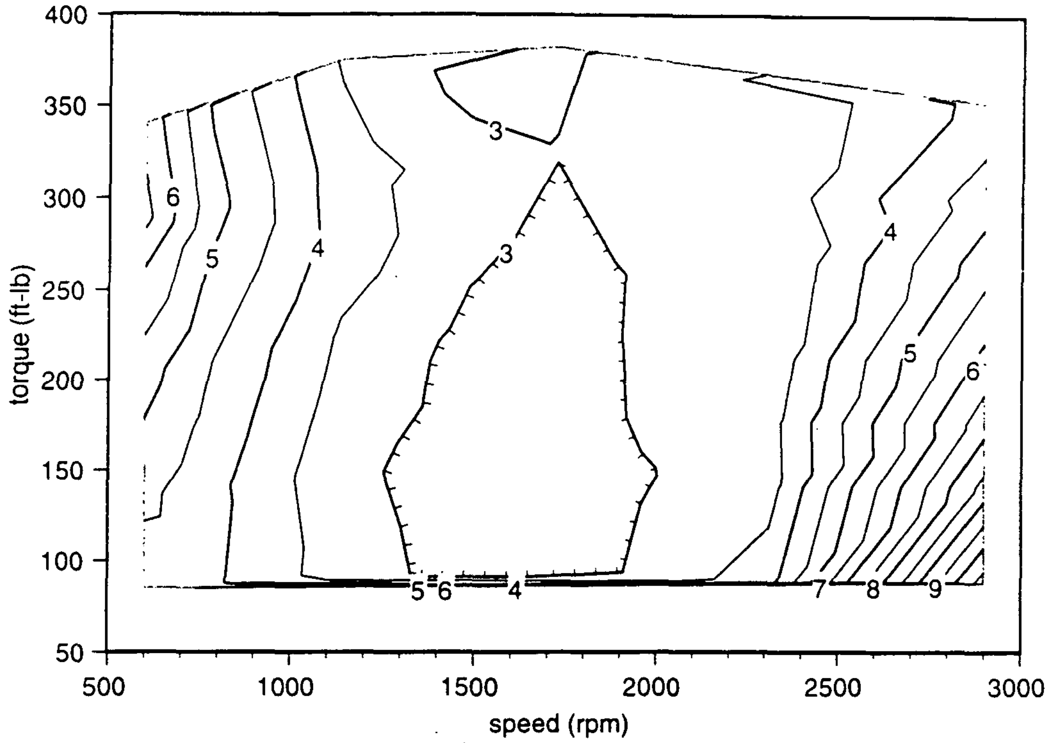


Figure 2. NOx emissions (g/bhp-hr) map.

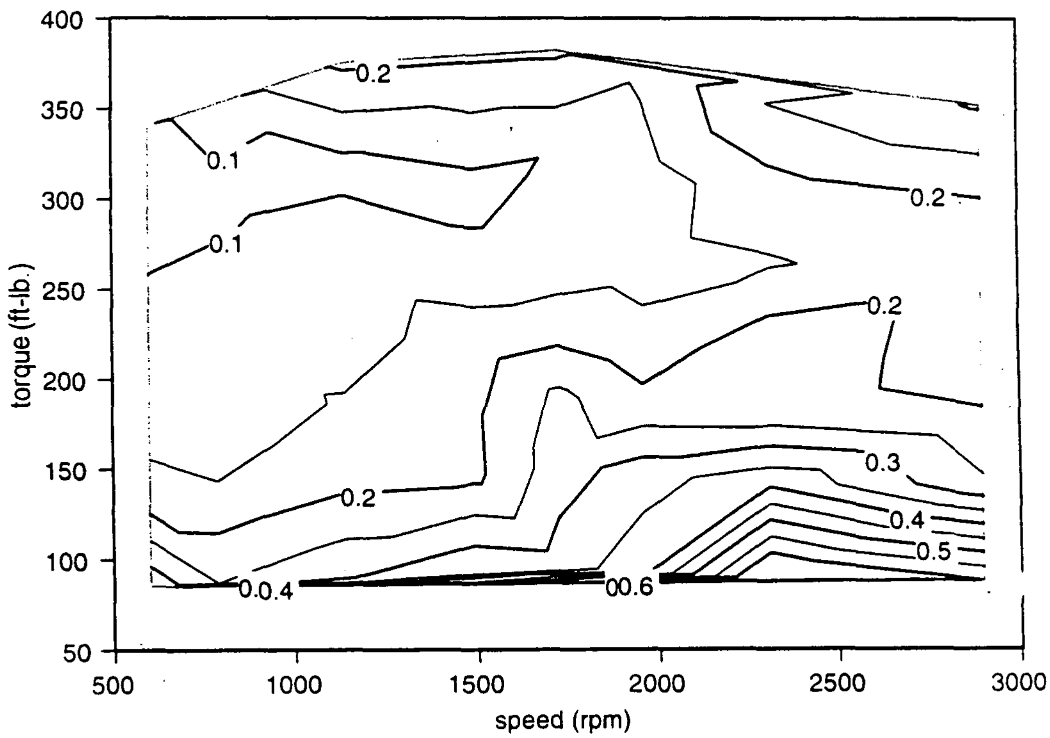


Figure 3. PM emissions (g/bhp-hr) map.

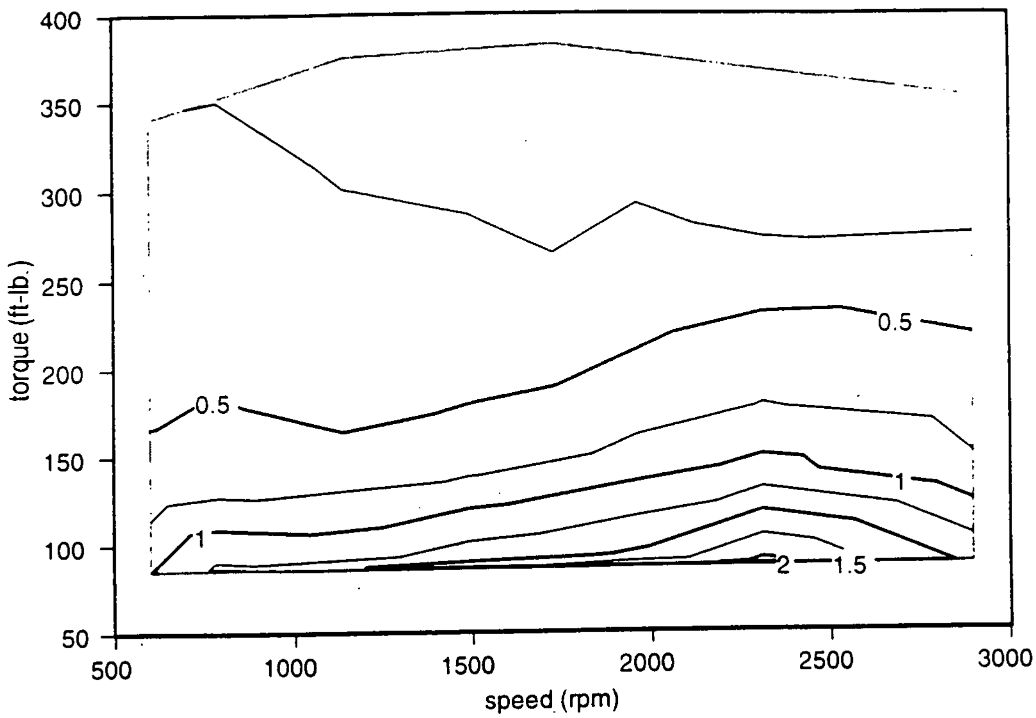


Figure 4. HC emissions (g/bhp-hr) map.

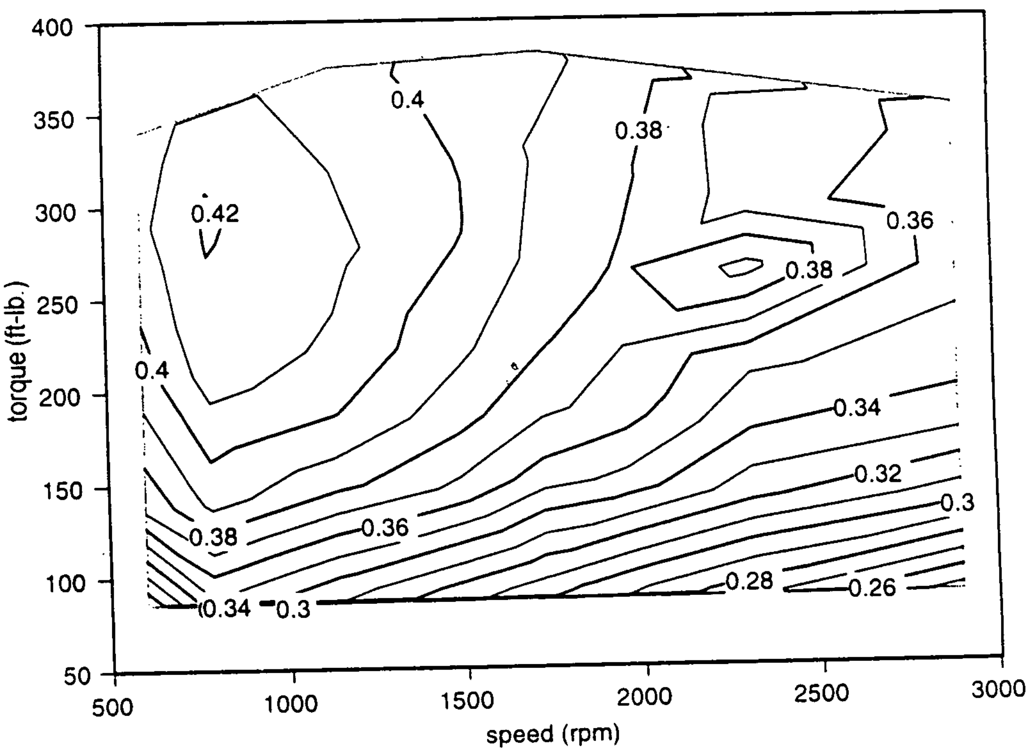


Figure 5. Thermal efficiency map .

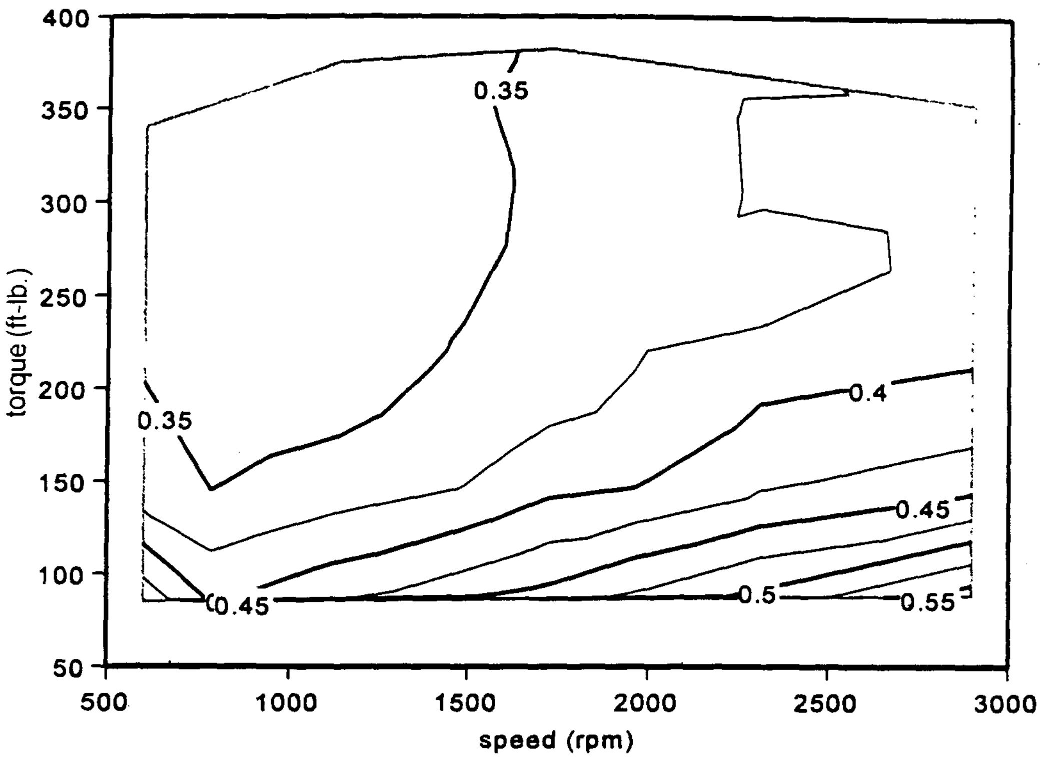


Figure 6. Brake-specific fuel consumption (in lb/bhp-hr) map.

It was attempted to compare the emission test results from this engine with other commercially available engines of similar displacement and power rating. Unfortunately there are almost no naturally-aspirated heavy-duty engines currently available since most engines sold in the U.S. for the heavy-duty truck market are turbocharged.

IV. SUMMARY AND CONCLUSIONS

We have obtained baseline emission data from a common-rail heavy-duty diesel engine. The engine uses a very flexible common-rail fuel injection system that is controlled electronically and is capable of very high injection pressures. For the transient cycles, the brake-specific emissions were relatively high when compared to the 1998 US highway standard of 4.0 g/bhp-hr NOx. On the FTP, for example, the resulting NOx emission level was 4.48 g/bhp-hr. PM emissions were also high relative to the 0.1 g/bhp-hr U.S. standard. Steady-state emissions and efficiency maps were also produced from the test data. The maps show that the lowest NOx region (of about 3.0 g/bhp-hr) occur at intermediate speeds, while at rated speed the NOx can increase to 4.15 g/bhp-hr at full load.

V. REFERENCES

1. *Federal Register*, Vol. 62, No. 203, October 21, 1997, pp.54694-54730.

2. S. Ashley, "Diesel Cars Come Clean", Mechanical Engineering, Vol. 119, No.8. August 1997, pp. 52-56, ASME.

3.G. Stumpp and Mario Ricco, "Common Rail-An Attractive Fuel Injection System for Passenger Car DI Diesel Engines", SAE 960870.

4. Y. Yamaki, et al, "Application of Common Rail Fuel Injection System to a Heavy-Duty Diesel Engine", SAE 942294.

5. See endnote 2--S. Ashley, "Diesel Cars Come Clean", 1997.

6.W. Boehner and K. Hummel, "Common Rail Injection System for Commercial Diesel Vehicles", SAE 970345.

VI. ACKNOWLEDGMENTS

Special thanks to the Engine Testing Group in the Testing Services Division at U.S. EPA's National Vehicles and Fuel Emissions Laboratory for their technical suppport of this project. Also we appreciate the help of Dr. Joe Norbeck, from the University of California-Riverside for his suggestions and comments on this report.

VI. Appendix

A1. Backhoe Cycle

A2. Crawler Tractor Cycle

A3. Composite Cycle

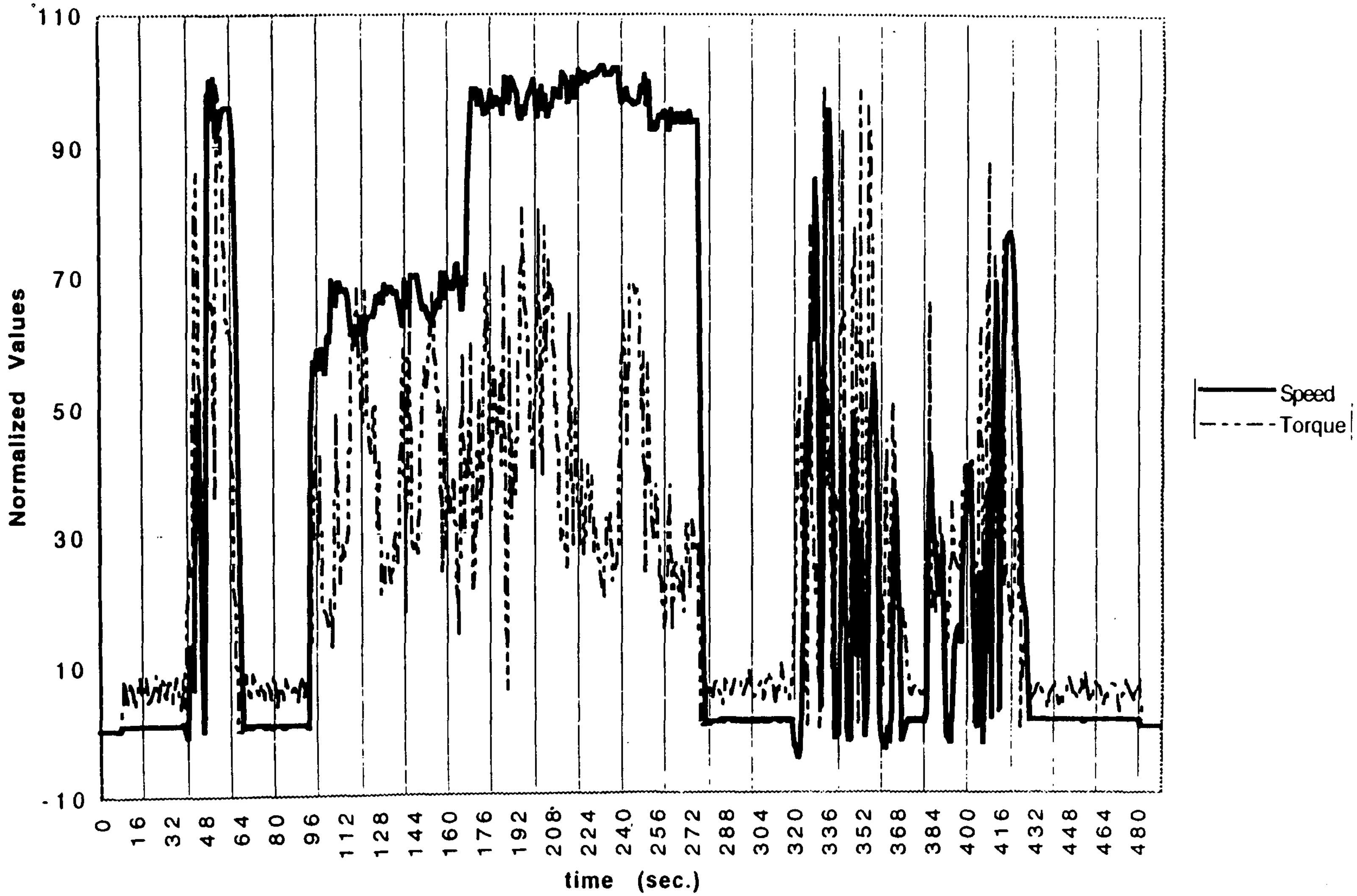
A4. Fuel Specifications

A5. Steady-state emissions data.

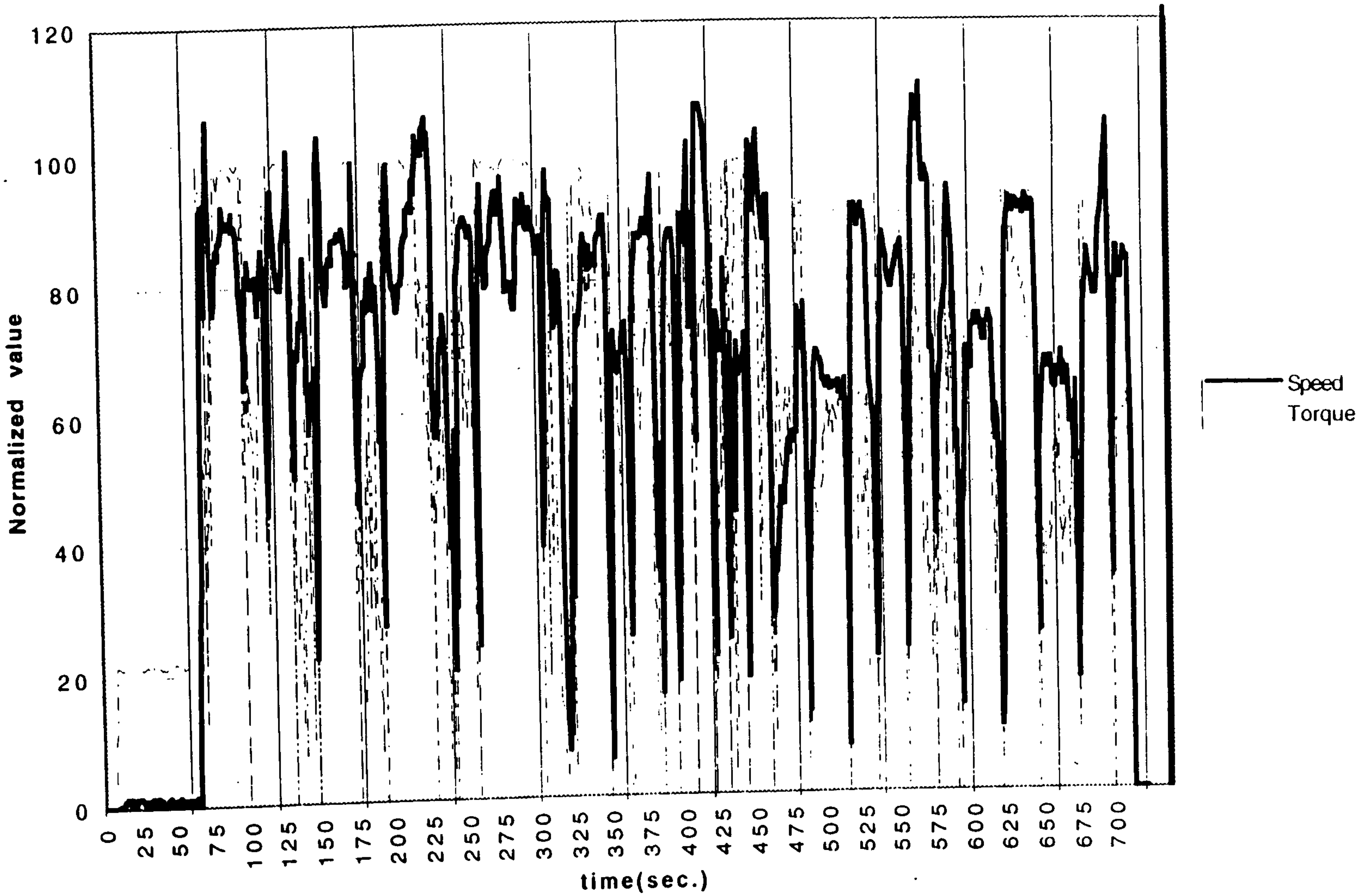
A7. ISO 13 mode and C1 data.

A8. Transient cycle data.

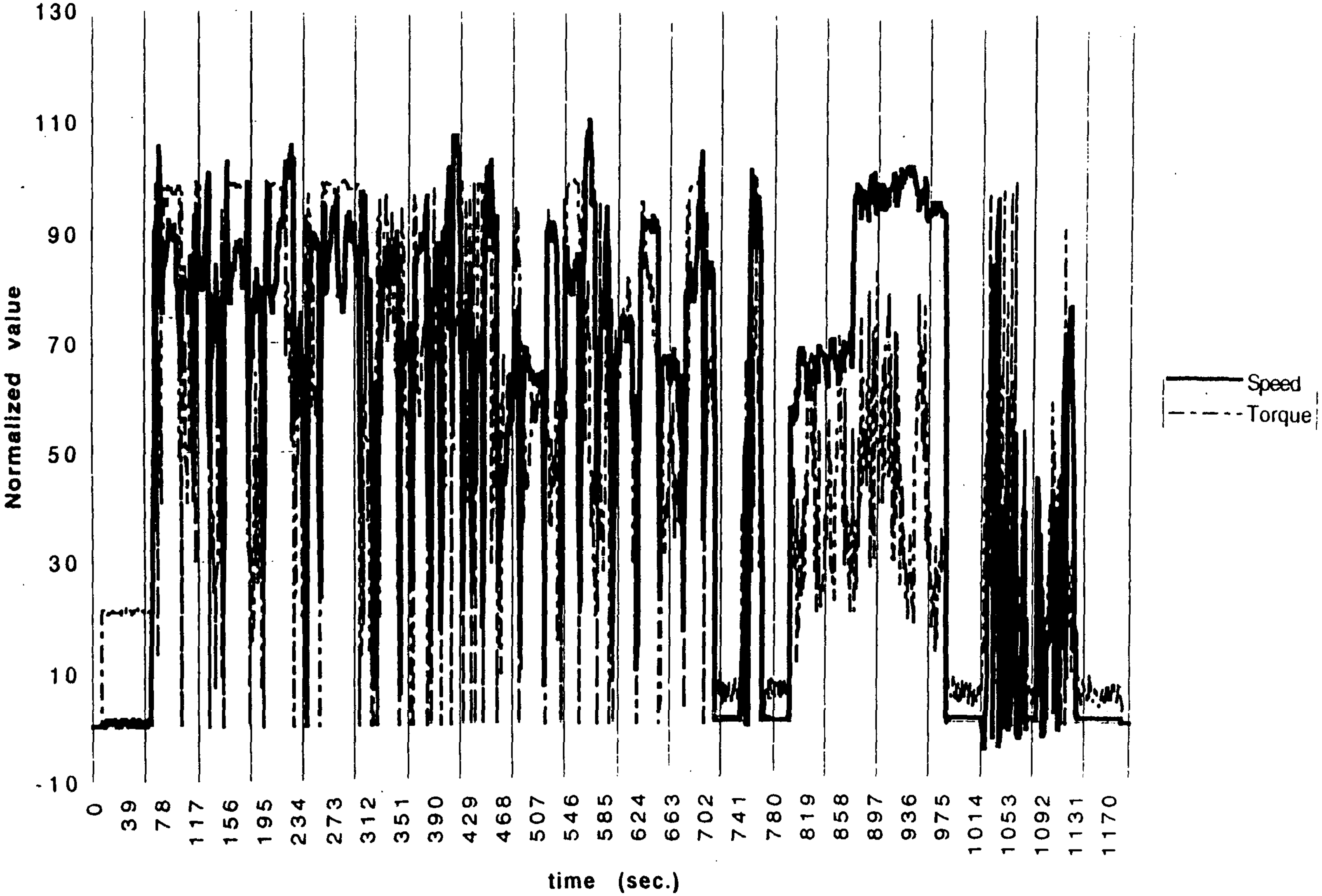
Backhoe Cycle



Crawler Tractor Cycle



Composite Cycle



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CONTAINER NO.
TRLR #358

0.05 SULFUR DIESEL FUEL
LOT S-946X

TESTS	RESULTS	SPECIFICATIONS	METHOD
Corrosion	1A	Report	ASTM D-130
Specific Gravity, 60/60	.8468	Report	ASTM D-4052
API Gravity	35.6	32-37	ASTM D-1298
Sulfur, Wt%	.036	0.03 - 0.05	ASTM D-2622
Flash Point, °F, PM	171	130 Min.	ASTM D-93
Pour Point, °F	-6	Report	ASTM D-97
Cloud Point, °F	0	Report	ASTM D-2500
Viscosity, cs 40C	2.67	2.0 - 3.4	ASTM D-445
Carbon, wt%	*	Report	
Hydrogen, wt%	*	Report	
Ash, wt%	0.01	Report	ASTM D-482
Net Heat of Combustion, BTU/lb.	18434	Report	ASTM D-3338
Particulate Matter(mg/l)	8	15 Max.	ASTM D-2276
Cetane Index	47.0	40-48	ASTM D-976
Cetane Number	46.5	40-48	ASTM D-613
*TO BE REPORTED LATER			
DISTILLATION, °F			ASTM D-86
IBP	374	340-400	
5%	410		
10%	427	400-460	
20%	453		
30%	472		
40%	486		
50%	502	470-540	
60%	516		
70%	533		
80%	556		
90%	588	560-630	
95%	615		
EP	642	610-690	
Loss	0.6		
Residue	0.7		
HYDROCARBON TYPE, VOL%			ASTM D-1319
Aromatics	32.0	27 Min.	
Olefins	3.8		
Saturates	64.2		

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Steady-state emissions

Mode	Speed (rpm)	Torque (ft-lb)	hp	NOx (g/bhp-hr)	NOx (g/hr)	HC (g/bhp-hr)	PM (g/bhp-hr)	fuel cons.	bsfc (lb	th. effic.	g NOx/kg fuel
1	600	85	9.7	4.16	40.35	1	0.316	4.3	0.44	0.31	19.91
2	600	136	15.6	4.63	72	0.53	0.173	5.79	0.37	0.37	27.34
3	600	170	19.6	4.93	96.39	0.45	0.144	6.98	0.36	0.38	29.07
4	600	204	23.3	5.21	121.3	0.38	0.131	8.15	0.35	0.39	32.27
5	600	262	29.9	6	179.6	0.31	0.096	10.21	0.34	0.4	38.32
6	600	289	33.0	6.63	219	0.31	0.085	11.18	0.34	0.41	43.17
7	600	340	38.8	6.34	246.1	0.27	0.108	13.29	0.34	0.4	41.23
8	785	87	13.4	4.09	55	1.37	0.25	5.15	0.4	0.35	22.48
9	785	140	20.9	4.15	86.89	0.61	0.161	7.35	0.35	0.39	26.29
10	785	175	26.1	4.33	113.2	0.51	0.155	8.94	0.34	0.4	28.32
11	785	210	31.4	4.49	140.8	0.41	0.132	10.44	0.33	0.41	29.96
12	785	281	42.0	5.07	213	0.32	0.093	13.78	0.33	0.42	34.74
13	785	297	44.4	5.18	230.1	0.28	0.086	14.54	0.33	0.42	34.93
14	785	350	52.3	4.93	258	0.21	0.115	17.4	0.33	0.41	32.48
15	1137	94	20.3	3.25	66.12	1.15	0.259	8.37	0.41	0.34	17.37
16	1137	150	32.5	3.14	101.9	0.5	0.157	11.68	0.36	0.38	18.88
17	1137	188	40.7	3.31	134.6	0.38	0.133	14.02	0.34	0.4	20.86
18	1137	225	48.7	3.44	167.6	0.33	0.13	16.45	0.34	0.41	22.46
19	1137	275	59.4	3.76	223.4	0.28	0.115	19.91	0.33	0.41	24.32
20	1137	319	69.1	3.71	256.2	0.23	0.092	23.25	0.34	0.41	23.97
21	1137	375	81.3	3.44	279.6	0.12	0.19	27.75	0.34	0.4	21.67
22	1490	92	26.1	2.79	72.72	1.47	0.366	11.38	0.44	0.32	14.26
23	1490	146	41.4	2.72	112.7	0.72	0.203	15.57	0.38	0.37	16.07
24	1490	183	51.9	2.82	146.3	0.53	0.203	18.7	0.36	0.38	17.02
25	1490	220	62.4	2.86	178.6	0.43	0.184	21.97	0.35	0.39	17.66
26	1490	287	81.5	3.16	257.6	0.26	0.103	27.99	0.34	0.4	20.2
27	1490	311	88.3	3.27	288.7	0.2	0.089	30.36	0.34	0.4	20.76
28	1490	366	122.2	2.81	343.5	0.08	0.156	36.13	0.35	0.4	14.38
29	1725	96	31.5	2.66	83.67	1.46	0.374	14.11	0.45	0.31	13.2
30	1725	153	50.2	2.61	130.9	0.72	0.316	19.48	0.39	0.36	14.84
31	1725	191	62.7	2.62	164.3	0.55	0.293	23.21	0.37	0.37	15.79
32	1725	229	75.4	2.65	199.7	0.38	0.189	27.15	0.36	0.38	16.12
33	1725	265	87.1	2.83	246.6	0.29	0.133	31.07	0.36	0.39	17.54
34	1725	325	106.9	3.02	322.8	0.13	0.104	37.88	0.35	0.39	18.7
35	1725	382	125.8	2.89	363.5	0.01	0.181	44.11	0.35	0.39	17.93
41	1960	93	34.8	3.09	107.4	1.71	0.408	16.34	0.47	0.29	14.19
42	1960	148	55.3	2.96	163.8	0.9	0.308	22.03	0.4	0.35	16.03
43	1960	185	69.1	3.08	212.9	0.63	0.213	26.18	0.38	0.36	17.56
44	1960	222	83.0	3.1	257.2	0.5	0.162	30.61	0.37	0.37	17.96
45	1960	264	98.7	3.08	303.9	0.35	0.139	35.89	0.36	0.38	18.52
46	1960	315	117.7	3.24	381.3	0.2	0.126	42.47	0.36	0.38	19.65
47	1960	370	138.0	3.24	447.1	0.05	0.151	49.31	0.36	0.39	19.94

Steady-state emissions

48	2312	88	38.7	3.8	147.2	1.96	0.541	19.65	0.51	0.27	16.52
49	2312	141	62.1	3.28	203.7	1	0.326	26.56	0.43	0.32	17.21
50	2312	177	77.9	3.31	257.9	0.69	0.211	31.6	0.41	0.34	18.27
51	2312	212	93.1	3.16	294.2	0.53	0.204	36.61	0.39	0.35	17.93
52	2312	264	116.4	3.01	350.4	0.27	0.154	40.79	0.35	0.39	18.53
53	2312	300	132.2	3.21	424.4	0.14	0.165	49.89	0.38	0.37	18.67
54	2312	353	155.5	3.11	483.6	0.02	0.237	58.84	0.38	0.36	18.28
55	2900	88	48.6	9.75	474.1	1.55	0.584	27.33	0.56	0.25	37.98
56	2900	141	77.9	7.66	596.7	0.89	0.276	35.2	0.45	0.31	37.2
57	2900	176	97.2	6.79	660	0.7	0.212	40.64	0.42	0.33	35.64
58	2900	211	116.5	6.15	716.6	0.56	0.169	46.61	0.4	0.34	33.62
59	2900	264	145.8	5.26	766.8	0.3	0.175	56.95	0.39	0.35	29.63
60	2900	299	165.0	4.77	787.1	0.12	0.212	64.68	0.39	0.35	27.07
61	2900	352	189.4	4.15	786	0.02	0.326	74.98	0.39	0.36	23.37

Steady state cycles

ISO 13 mode

mode	speed	% torque	hp	NOx g/hr	NOx g/bhp-hr	HC g/hr	HC g/bhp-hr	PM g/hr	PM g/bhp-hr	BSFC lb/bhp-hr	Efficiency	g NOx/kg fuel
1	550	0	0.2	11.40	54.08	14.32	66.33	2.04	8.95	6.78	0.02	17.6
2	2900	100	189.1	758.87	4.01	3.213	0.02	71.70	0.38	0.41	0.34	21.8
3	2900	75	144.8	743.91	5.14	22.48	0.16	31.73	0.22	0.41	0.34	27.7
4	2900	50	96.2	650.32	6.76	44.84	0.47	16.97	0.18	0.44	0.31	34.0
5	2900	25	48.2	478.90	9.93	61.88	1.28	19.17	0.40	0.60	0.23	36.7
6	2900	10	19.4	357.00	18.36	80.35	4.14	25.92	1.32	1.11	0.12	36.6
7	550	0	0.1	14.28	113.10	17.7	139.90	2.63	20.67	11.75	0.01	21.2
8	1740	100	123.5	347.40	2.81	10.24	0.08	27.11	0.22	0.36	0.39	17.4
9	1740	75	93.4	278.20	2.98	21.86	0.23	11.68	0.13	0.38	0.37	17.5
10	1740	50	62.0	161.60	2.61	27.75	0.45	16.19	0.26	0.39	0.36	14.9
11	1740	25	31.0	86.05	2.78	46.37	1.50	11.18	0.36	0.48	0.29	12.8
12	1740	10	12.3	48.63	3.96	57.99	4.73	10.72	0.87	0.78	0.18	11.2
13	550	0	0.2	14.80	66.75	15.06	62.57	2.91	12.76	6.70	0.02	22.0
Weighted:	ISO 13 mode		88.33	417.73	4.73	25.59	0.29	29.77	0.34			
	ISO C1		94.37	439.41	4.66	26.95	0.29	26.53	0.28			

Baseline Emissions Data

Cycle: Crawler Test No.	1	2	3	avg.	std. dev.
NOx (g/bhp-hr)	3.386	3.408	3.467	3.420	0.042
HC (g/bhp-hr)	0.386	0.371	0.351	0.369	0.018
CO (g/bhp-hr)	0.792	0.789	0.803	0.795	0.007
PM (g/bhp-hr)	0.159	0.167	0.153	0.160	0.007
BSFC (lb/bhp-hr)	0.313	0.319	0.329	0.320	0.008

Cycle: Backhoe	1	2	3	avg.	std. dev.
NOx	5.196	5.256	4.979	5.144	0.146
HC	0.815	0.891	0.960	0.889	0.073
CO	2.521	2.496	2.398	2.472	0.065
PM	0.201	0.204	0.205	0.203	0.002
BSFC (lb/bhp-hr)	0.387	0.381	0.361	0.376	0.014

Cycle: Composite	1	2	3	avg.	std. dev.
NOx	4.285	4.159	3.891	4.112	0.201
HC	0.423	0.413	0.387	0.408	0.019
CO	1.211	1.104	1.181	1.165	0.055
PM	0.198	0.186	0.201	0.195	0.008
BSFC (lb/bhp-hr)	0.382	0.380	0.368	0.377	0.008

Cycle: FTP-HS	1	2	3	avg.	std. dev.
NOx	4.532	4.429		4.481	
HC	0.577	0.626		0.602	
CO	1.673	1.674		1.674	
PM	0.216	0.222		0.219	
BSFC (lb/bhp-hr)	0.409	0.403		0.406	

Cycle: FTP-CS	1	2	3	avg.	std. dev.
NOx	4.671				
HC	0.626				
CO	1.883				
PM	0.251				
BSFC (lb/bhp-hr)	0.428				