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Technical Report

Testing of the Cummins VTB-903 at EPA/MVEL

By

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Standards Development and Support Branch
Emission Control Technology Division
Office of Mobile Source Air Pollution Control
Office of Air, Noise and Radiation
U. S. Environmental Protection Agency

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I. Summary

The Cummins VTB-903 heavy-duty diesel engine was tested at EPA as part of the EMA/EPA correlation program. The purpose of this program is to analyze lab-to-lab variability in emissions measurements and to assess whether or not the large amount of transient emissions data generated at the Southwest Researach Institute (SwRI) was repeatable at other laboratories. This particular engine was first tested at Cummins Engine Company (Cummins) and then at SwRI. This engine was tested next at the MVEL during August 1981, then sent to Detroit Diesel Allison (DDA). It was returned to the MVEL for retesting in February 1982, after which it was sent back to Cummins for the final test in the series.

The initial testing of this engine at the MVEL from August 17th to September 9th resulted in highly variable HC and particulate emissions; however, NOx, CO_2, and CO emissions data were consistent. Inspection of the HC and particulate data from this phase of the testing indicated that there was a serious start-up problem resulting from the manner in which fuel was delivered to the engine. Fuel was pumped from a Flowtron fuel measuring device to the engine fuel pump and through the engine fuel solenoid valve. There was a constant pressure of 6 psig maintained in the fuel line from the Flowtron to the fuel pump. At times the fuel pump solenoid valve was left open during a soak period resulting in fuel (being under pressure) leaking into the cylinders, thus causing start-up problems. There were other, more general problems also associated with this method of fuel delivery since the fuel pump would not see a positive pressure in-use. After correcting for this problem consistent transient and steady state emission results were obtained.

A summary of EPA's initial results together with Cummins', SwRI's and DDA's are reported in Table 1A. It is evident that EPA's HC and particulate results did not correlate well with the other labs. During DDA's testing of this engine (subsequent to EPA's testing), a turbocharger oil leak was accidentially detected by DDA personnel when oil was seen dripping from the turbocharger exhaust/tailpipe connection. After installing a new turbocharger, DDA retested the engine and their results agreed with Cummins' and SwRI's results. DDA also conducted 4 tests with the leaky turbocharger and found that their particulate emissions were 13 percent higher than EPA's and their HC emissions were 36 percent lower than EPA's. For both pollutants the emissions were much higher with the leaky turbocharger than without. EPA retested the engine with the new turbocharger during February 1982 and the results are summarized in Table 1B. As can be seen, the overall variability for transient composite NOx, CO and particulate is very good, 7.8, 3.5 and 2.9 percent, respectively; while HC variability was good, 11.6 percent. EPA's emission measurements also correlate very well with those of the other laboratories; all transient composite and 13-mode measurements are within 7 percent of the mean measurements of all the laboratories, except for the 13-mode particulate measurement, which was 10 percent higher than the mean. This is a characteristic offset for particulates, which has been discussed in previous reports.

II. Introduction

This report discusses the results of testing the Cummins VTB-903 at EPA. This engine was tested as part of the EMA/EPA cooperative test program designed to analyze lab-to-lab variability in emissions measurements. The standard test program followed by all labs consists of: 1) two sets of EPA transient tests, each consisting of one cold start test followed by six hot start tests, 2) two 13-mode steady-state tests, and 3) two measurements of particulate emissions over modes 6 and 11 of the 13-mode test. In addition to being tested at EPA, this engine was also tested at Cummins, SwRI and Detroit Diesel (DDA).

It should be noted that there were three phases of testing conducted at EPA. Inconsistent data were obtained from the first phase as a result of an improper fuel delivery system to the engine. These data will not be presented in this report. The second phase of testing was performed after correction of this problem, but which is now suspect due to the discovery of a defective turbocharger by DDA. The third phase of testing was necessary to provide data after the replacement of the defective turbocharger. In this report, EPA's testing results from both the second and third phases will be presented and compared with Cummins, DDA's and SwRI's results. A review of the problems encountered during all three phases of testing and an examination of variability in particulate results will conclude this report.

III. EPA Test Results and Correlation with Other Laboratories

A. Test Results

Table 1A presents data from the second phase of testing with EPA data excluded from calculations of $\bar{\bar{x}}$. NOx data were not available during the second phase of testing, as the NOx probe was used for single dilution particulate results to aid in the discovery of the causes of high variability and high particulate measurements relative to other manufacturers. The 13-mode data was actually obtained during the initial phase of testing of the engine; time constraints did not allow 13-mode testing during the second testing phase.

The results from the third phase of testing are presented in Table 1B, again with the data from Cummins, SwRI, and DDA. This table shows that transient emissions results from all labs agree well for particulate, CO and NOx emissions; whereas the differences in HC measurements are somewhat higher. Inspection of the coefficients of variation for emission results obtained from the three laboratories shows that the emission measurements at each laboratory were very repeatable.

Variability for 13-mode and mode-6 particulate was 13.3 and 9.9 percent, respectively; while mode-11 variability was very low, 3.7 percent. Variability for 13-mode HC and NOx emissions was 7.9 and 5.0 percent, respectively.

B. Variability at EPA

Twenty-nine transient tests were conducted during the first phase of testing with inconsistent HC and particulate emission results. The primary reason for the large number of tests is that the instantaneous HC strip charts were ignored; these readings would have indicated a problem during the first few tests.

The HC variability problem was solved by noting that HC emissions during the first 5-minute portion of the transient test were extremely high. Noticeably high variability in HC levels was still occuring into the "Bag 3" portion of the test which indicated that the engine was taking over 10 minutes to reach independence from initial start-up. Therefore, a series of tests was designed to analyze the effect of fuel delivery method on initial HC emissions. It was determined that our fuel delivery method was the cause of the variability. Discussions with Cummins' engineers confirmed this. After modification of our fuel delivery system, repeatable results were obtained. Correction of this problem reduced emissions by up to 3 g/BHP-hr of HC and over 1 g/BHP-hr of particulate.

The initial fuel delivery configuration involved pumping fuel to the engine fuel pump. There was a constant pressure of about 6 psig on the engine fuel pump. Whenever the engine fuel pump solenoid valve was mistakenly left open during a soak period or overnight, fuel would leak into the cylinders and cause high initial HC's. During one cold start a thick cloud of white smoke was visible in the test cell, caused by the excess fuel. The modified fuel delivery system simply allows the engine fuel pump to do all the work in drawing fuel from the fuel tank. This is identical to the "on road" fuel delivery method.

The initial fuel delivery configuration had been used on all previous engines tested at MVEL including the Cummins NH-250 and NTC-290, which were not sucessfully tested. Of the engines tested at MVEL only the Cummins' engines were sensitive to our fuel delivery system. This is because their engines' fuel injection systems are based on different design concepts than those of the other manufacturers.

C. Correlation

During the second phase of testing, after correcting the fuel delivery problem, it soon became apparent that there was still a correlation problem between EPA, SwRI and Cummins. During this time, it was not known that there was a turbocharger oil leak and EPA had no reason to suspect any engine problems. Therefore, the EPA test cell and equipment were investigated to determine the correlation problem.

Since EPA's repeatability was acceptable, the investigation focused on inter-lab differences. An important point appeared to be that both HC's and particulate were significantly higher than those from the other two labs and that the difference for HC was the greater of the two. It was postulated that the reason for the high particulate may be the high HC level. This was further confirmed when comparing filter efficiencies from EPA and SwRI for transient tests.

	EPA	SwRI
Cold	85	90
Hot	92	95

The fact that EPA had lower efficiencies could indicate that EPA's filters were experiencing higher hydrocarbon concentrations, based on the hypothesis that the non-volatile HC's soak the back-up filter, causing the measured inefficiency. With previous engines, EPA's filter efficiencies were always greater than 95 percent.

In comparing EPA's HC emissions with those from Cummins and SwRI for the hot start portion of the cycle, it appeared that EPA's hydrocarbons were approximately twice as high as the other labs. When the hot start HC emissions from all three labs were subdivided into "bag 1-4" portions (each "bag" consists of the hydrocarbon emissions of a 5-minute segment of the 20-minute cycle), it was found that any given bag represented the same fraction of total hydrocarbons for each lab. These results are presented in Table 2. This implied that the additional hydrocarbons being generated by EPA were appearing throughout the cycle and indicated the presence of a miscalibration somewhere in the system.

EPA's HC system was then analyzed thoroughly. Both software and hardware were inspected. A known amount of HC was injected into the dilution tunnel and compared with the real-time value. Both values were nearly the same, which indicated that our HFID was not the problem. Numerous other parameters were investigated. Cummins was contacted and the calculation procedure was discussed with them. No differences were found in the calculation procedures. Cummins' real time emissions data was sent to EPA and inspected. EPA's idling HC level was abcut twice that of Cummins, again indicating a constant percentage offset throughout the test. All three labs use the same Beckman 402 HFID analyzer. However, each lab has slightly different response times and sample line lengths.

Both DDA and SwRI correlated well on HC and particulate on a previous DDA engine and EPA had correlated reasonably well with SwRI on HC emissions on four baseline engines. Thus, we were confident that the DDA tests would reveal where the problem lay.

Since this investigation had not turned up the problem and further effort promised little results, it was decided discontinue any further testing of the engine and to ship it to DDA. Their results would confirm whether or not the engine had shifted or been damaged, or if there was a problem with the EPA HC system.

As has been noted elsewhere in this report, a turbocharger oil leak was discovered at DDA and the turbocharger was replaced. The subsequent test results confirmed the contention that the high measurements observed during earlier tests at EPA were indeed engine related, and not a function of defective equipment or procedures.

IV. Conclusions

The Cummins VTB-903 heavy-duty diesel engine has been tested at EPA as part of the EMA/EPA testing program. Four labs have tested this engine: Cummins, SwRI, DDA and EPA, with Cummins and EPA testing the engine twice. Valid data accumulated during tests at the above labs has shown that variability for transient combined (one cold start with one hot start) NOx, CO, and particulate emissions was very good, 7.8, 3.5, and 2.9 percent, respectively; while HC variability was good, 11.6 percent. Steady state test results also showed a simiilar correlation. Variability for 13-mode HC, NOx, and particulates was, 7.9, 5.0, and 13.3 percent, respectively; and mode-6 and mode-11 particulate variabilty was, 9.9 and 3.7 percent, respectively.

VII. Recommendations

Recommendations regarding the test program and procedures are outside the scope of this report, and will be covered in detail in the Technical Report prepared at the end of the test program.

Table 1A

Cummins VTB-903 Emission Results, g/BHP-hr

Transient Testing

Testing Laboratory	HC	NOx	Particulate	CO	CO_2	BHP-hr
	Composite Results					
Cummins	1.69±3.3	5.63±2.7	0.67±8.1	2.06±46	--	--
SwRI	2.24±5.0	5.57±3.9	0.67±2.9	2.00±2.4	654±0.7	16.5±0.9
EPA	3.46±3.9	4.9±9.2	0.99±4.2	2.25±3.6	641±3.0	17.5±0.8
DDA	1.91±6.8	4.87±2.6	0.65±8.6	--	--	--
*x̄	1.95±14.2**	5.36±7.9	0.66±1.7			
	Hot Start Results					
Cummins	1.50±3.3	5.63±2.7	0.63±8.12	1.98±46.4	--	17.50
SwRI	1.87±5.0	5.7±3.92	0.61±2.9	1.86±2.4	648.9±0.7	16.48±0.9
EPA	3.04±3.7	4.95±8.6	0.88±3.2	2.132±3.7	636.5±3.1	17.50±0.9
DDA	1.61±6.8	5.01±2.6	0.58±8.6	--	--	--
	Cold Start Results					
Cummins	2.79	5.68	1.02	2.54	--	--
SwRI	4.42	4.95	1.02	2.89	684	16.56
EPA	5.95±5.6	4.65±12.9	1.65±10.5	2.98±3.1	670±2.5	17.44±0.4
DDA	3.41	4.74	0.96	--	--	--

Steady-State Testing

Testing Laboratory	HC	NOx	Particulate	CO	CO_2	Particulate Mode 6	Particulate Mode 11
	13-Mode Results						
Cummins	0.81	6.07	0.44	1.52	--	0.25	0.72
SwRI	0.95	6.39	0.38	2.00	--	0.29	0.72
EPA	1.23	6.52	0.45	1.57	--	0.32	0.813
DDA	0.84	6.36	0.33	--	--	0.23	0.71
*x̄	0.87±8.5	6.27±2.8	0.38±14.4			0.25±13.3	0.73±4.4

* Excludes EPA's results because tests were conducted with a suspected turbocharger oil leak.

** x.xx ± xx.x = $\bar{x} \pm s/\bar{x} \times 100$

Table 1B

Cummins VTB-903 Emission Results, g/BHP-hr

Transient Testing

Composite Results

Testing Laboratory	HC	NOx	Particulate	CO	CO_2	BHP-hr
Cummins	1.69±3.3	5.63±2.7	0.67±8.1	2.06±46	--	--
SwRI	2.24±5.0	5.57±3.9	0.67±2.9	2.00±2.4	654±0.7	16.5±0.9
EPA**	2.01±0.94	4.92±2.9	0.63±3.0	1.92±5.4	645±1.8	17.4±0.3
DDA	1.91±6.8	4.87±2.6	0.65±8.6	--	--	--
*x	1.96±11.6	5.24±7.8	0.66±2.9	1.99±3.5	650±0.98	17.0±.03

Hot Start Results

Testing Laboratory	HC	NOx	Particulate	CO	CO_2	BHP-hr
Cummins	1.50±3.3	5.63±2.7	0.63±8.12	1.98±46.4	--	17.50
SwRI	1.87±5.0	5.7±3.92	0.61±2.9	1.86±2.4	648.9±0.7	16.48±0.9
EPA**	1.61±5.8	5.14±4.7	0.54±5.2	1.69±6.3	647.5±.04	17.49
DDA	1.61±6.8	5.01±2.6	0.58±8.6	--	--	--

Cold Start Results

Testing Laboratory	HC	NOx	Particulate	CO	CO_2	BHP-hr
Cummins	2.79	5.68	1.02	2.54	--	--
SwRI	4.42	4.95	1.02	2.89	684	16.56
EPA**	3.65	4.74	0.91	2.50	667	--
DDA	3.41	4.74	0.96	--	--	--

Steady-State Testing

13-Mode Results

Testing Laboratory	HC	NOx	Particulate	CO	CO_2	Particulate Mode 6	Particulate Mode 11
Cummins	0.81	6.07	0.44	1.52	--	0.25	0.72
SwRI	0.95	6.39	0.38	2.00	--	0.29	0.77
EPA**	0.94	5.73	0.44	1.36	--	0.25	0.72
DDA	0.84	6.36	0.33	--	--	0.23	0.71
*x	0.89±7.9	6.14±5.0	0.40±13.3			0.26±9.9	0.73±3.7

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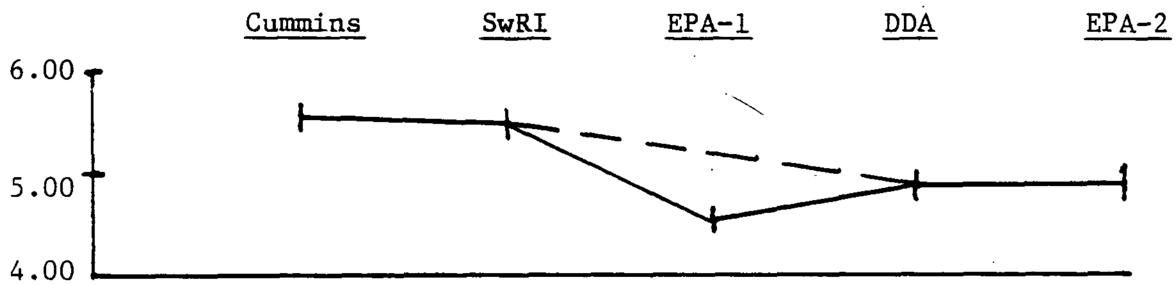
* x.xx ± xx.x = $\bar{x} \pm s/\bar{x} \times 100$

** Results from second set of tests after turbocharger replacement.

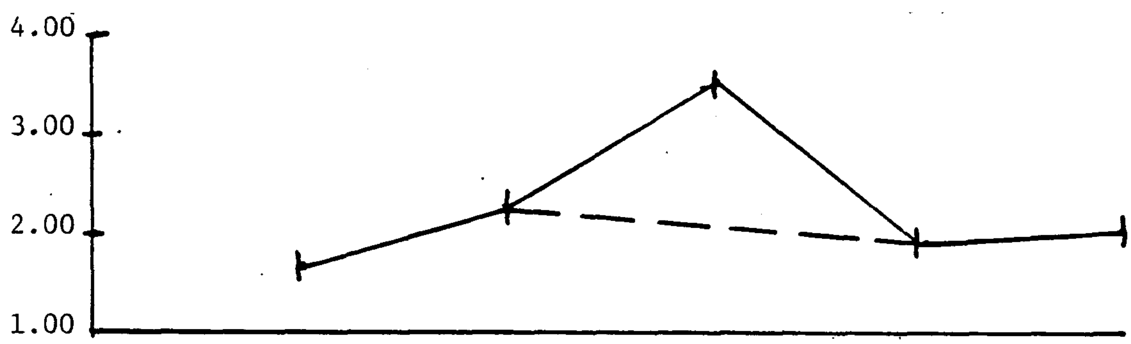
Table 1C

Cummins VTB-903

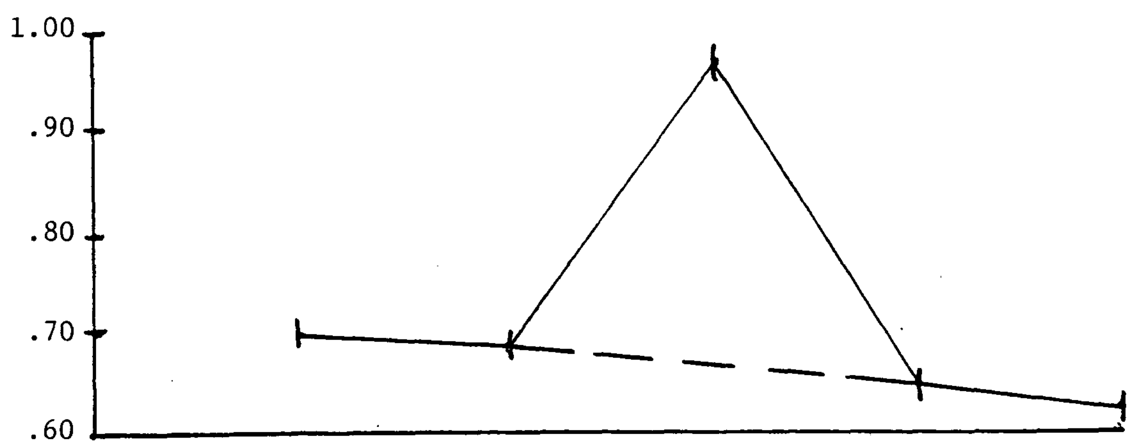
Transient Test Emissions
(g/BHP-hr)



NOx Combined $\bar{x}$



HC Combined $\bar{x}$



Particulate Combined $\bar{x}$

Table 2

Comparison of Inter-Lab HC Emissions

	Cummins		SwRI		EPA*		EPA**	
Bag	Grams	% Total Grams	Grams	% Total Grams	Grams	% Total Grams	Grams	% Total Grams
1	5.7	20.6	5.9	18.6	12.1	21.8	5.8	20.6
2	9.0	32.5	10.2	32.2	18.2	32.8	9.2	32.6
3	6.3	22.7	8.2	25.9	13.9	25.1	7.0	24.8
4	6.7	24.2	7.4	23.3	11.2	20.2	6.2	22.0
	27.7	100.0	31.7	100.0	55.4	100.0	28.2	100.0

* EPA first test run.

** EPA second test run after turbocharger replacement.

Table 3

Steady-State Particulate Results - Mode 6 and Mode 11

	Mode 6		Mode 11	
	Date of Test	g/BHP-hr	Date of Test	g/BHP-hr
First Testing Phase	8/7/81	0.272	8/7	0.749
	8/11	0.44	8/11	0.785
	8/11	0.472	8/11	0.754
	9/10	0.513	9/10	0.911
	9/11	0.435	9/11	0.874
	9/11	0.370	9/14	0.756
	9/14	0.282	9/15	0.994
	9/14	0.378	9/15	0.986
	9/15	0.363		
Second Testing Phase	9/25	0.304	9/25	0.830
	9/25	0.420	9/25	0.795
	9/28	0.340		
Third Testing Phase	2/5/82	0.463	2/5	0.784
	2/5	0.260		
	2/10	0.473		
	2/12	0.235	2/12	0.693