START-UP AND IDLING EMISSIONS FROM TWO LOCOMOTIVES

FINAL REPORT

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Submitted to:
Technology Advancement Office
South Coast Air Quality Management District

ENGINE, FUEL, AND EMISSIONS ENGINEERING, INCORPORATED

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<u>Submitted to</u>
Technology Advancement Office
South Coast Air Quality Management District
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EXECUTIVE SUMMARY

The South Coast Air Quality Management District (SCAQMD) is developing regulations to limit idling by locomotive engines. Such regulations would necessarily result in more-frequent starting, including start-up after varying periods of being shut down. The SCAQMD staff has received comments from the railroad industry that increase in the number of start-ups due to idle restrictions could result in a tradeoff of emissions.

To clarify the relationship between start-up and idling emissions, the SCAQMD Technology Advancement Office requested Engine, Fuel, and Emissions Engineering, Inc. (EF&EE) to carry out emission measurements on two locomotives owned by the South Coast Regional Rail Authority – better known as Metrolink. Emission measurements were performed using the Ride Along Vehicle Emission Measurement (RAVEM) system developed and manufactured by EF&EE. Pollutants measured included particulate matter (PM), oxides of nitrogen (NOx), carbon dioxide (CO_2), and total hydrocarbons (HC). CO concentrations were also measured, but the results were below detection levels, and are not reported. The emission measurements were performed during the period from November 3 to 8, 2005, at Metrolink's Central Maintenance Facility (old "Taylor Yard") in Los Angeles.

The two locomotives tested were both produced by the Electromotive Division of General Motors (EMD), and were equipped with 16-cylinder, two-stroke, turbocharged and aftercooled diesel engines. The first locomotive tested, Metrolink No. 804, was an SD60 model – a typical freight locomotive of the last generation – equipped with an EMD 16-710G engine. This unit was also equipped with a computer control system that – among other functions – changed the idle speed from low idle (about 200 RPM) to higher speed in response to low coolant temperature, low battery voltage, or low pressure in the air brake reservoir. The second unit tested was Metrolink No. 800, an F40 locomotive equipped with an EMD 16-645E engine. This unit was equipped with an electromechanical control system, and included a manual switch to select between low and normal idle speeds. Consistent with normal railroad practice, low idle speed was selected during all of the idle and start-up measurements in this test program.

PM emissions at idle from the two locomotives tested were 0.66 and 0.38 grams per minute, respectively; and NOx emissions were 16.7 and 19.8 grams per minute. A significant fraction of the total PM (15% in the first case, and 49% in the second) is not emitted at the time, but retained in the exhaust system as "soup" – semivolatile hydrocarbons and lubricating oil – to be emitted subsequently when the locomotive returns to higher-load operation. The present Federal locomotive test procedure fails to measure these substantially-increased PM emissions during the transient conditions following a period of idle.

The incremental emissions due to engine start-up from these locomotives were small compared to the emissions produced under stabilized idle conditions. In none of the start-up tests conducted did these emissions exceed the equivalent of 8 minutes of idle operation. Based on these data, shutting down the engine and restarting it will result in reduced emissions compared to allowing it to idle, as long as the idle shutdown period is longer than eight minutes. The longer the shutdown period, the greater the emission benefits.

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1. INTRODUCTION

In the railroad industry, it is presently a common practice for locomotive engines to be left idling when the locomotive is not in use – sometimes for very long periods. The South Coast Air Quality Management District (SCAQMD) is developing regulations to limit idling by locomotive engines. Such regulations would necessarily result in more-frequent starting, including start-up after varying periods of being shut down. There was concern, therefore, that the extra emissions due to more-frequent starts – especially starting with the engine cold – might offset the benefits of reduced pollutant emission from the shut down periods.

In order to clarify the relationship between start-up and idling emissions, the SCAQMD Technology Advanced Office requested Engine, Fuel, and Emissions Engineering, Inc. (EF&EE) to carry out emission measurements on two locomotives owned by the South Coast Regional Rail Authority – better known as Metrolink. Emission measurements were performed using the Ride Along Vehicle Emission Measurement (RAVEM) system developed and manufactured by EF&EE. Pollutants measured included particulate matter (PM), oxides of nitrogen (NOx), carbon dioxide (CO_2), and total hydrocarbons (HC). CO concentrations were also measured, but the results were below detection levels. The emissions measurements were performed during the period from November 3 to 8, 2005, at Metrolink's Central Maintenance Facility (old "Taylor Yard") in Los Angeles.

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2. EMISSION MEASUREMENT SYSTEM INSTALLATION AND OPERATION

Emission measurements were performed using EF&EE's "Ride Along Vehicle Emission Measurement" (RAVEM) system[1,2]. Conventional vehicle emission measurement methods defined by the U.S. EPA[3] and California ARB[4] utilize *full-flow* constant volume sampling (CVS), in which the entire exhaust flow is extracted and diluted. RAVEM measurements use *partial flow* CVS. This is similar to the EPA and CARB methods, except that the sampling system extracts and dilutes only a small, constant fraction of the total exhaust flow. The RAVEM system is further described in the Appendix.

Although the RAVEM system is designed to measure emissions while "riding along" on the vehicle under test, it can also be used for stationary tests in those cases where the source being measured does not need to move. For this program, the RAVEM system unit was placed on a table next to the locomotive. Figure 1 and Figure 2 show these installations for locomotives 804 and 800, respectively.

In the RAVEM system, as in conventional CVS systems, particulate matter is normally collected on filters of Teflon-coated borosilicate glass. For the testing in this program, the SCAQMD requested that EF&EE also collect particulate matter from some tests on quartz filters, to allow the content of organic and elemental carbon to be determined. Thus, two sets of PM sample filters were collected for most of these tests. The sample filter plumbing was modified to allow two filter holders to be installed in parallel, and flow through the quartz filter was controlled by an auxiliary mass flow controller slaved to the mass flow controller for the Teflon/borosilicate glass filters.

The RAVEM system normally does not measure gaseous HC emissions, as experience has shown that diesel engines emit very low quantities of HC. For these tests, it was considered possible that HC emissions would be significant, so a heated sample probe, heated line, and heated FID analyzer were added to the measurement system. Background HC concentrations cannot be determined reliably from the RAVEM's background bag samples, due to HC hangup in the bag system. Thus, background HC concentrations were measured before and/or after each test. The variability in these background measurements was comparable in magnitude to the net HC concentrations measured in the dilution tunnel, so that the HC results reported here should be considered only approximate.

Figure 1: Emission measurement system installation on Metrolink No. 804

Figure 2: Emission measurement system installation on Metrolink No. 800

Inspection of the locomotive exhausts showed that both units discharge almost directly from the turbocharger to the atmosphere via a very short, tapered exhaust stack. While the mixing due to passage of the exhaust through the turbine would have helped to provide homogeneity, there was concern that the distribution of pollutants could be affected by the crankcase vent discharging into the right side of each stack. In addition, it would have been difficult to find a single probe location in the existing stacks for which the exhaust velocity would be equal to the average velocity of the exhaust as a whole, as required by the isokinetic proportional sampling system. To increase the opportunity for mixing, and to help provide a uniform velocity profile in the exhaust, EF&EE extended each locomotive's stack by 7.5 feet, using rectangular sheet metal extensions cut to fit around the edge of the existing stack. The RAVEM probe was attached to a crossbar at the top center of the stack extension, and the insulated one-half inch sample line was led from the probe to the sample inlet on the CVS.

Figure 3: Inside of exhaust stack on Metrolink No. 804, showing the crankcase vent discharge on the right side

As a check on the accuracy of the sampling system, a system for measuring mass fuel consumption was installed on locomotive 800. This system consisted of a 55-gallon drum, a drum scale, and a pair of three-way valves inserted in the fuel supply and return lines, with supply and return tubes leading to the 55-gallon drum. By opening and closing the three-way valves, it was possible to switch the locomotive's fuel supply and return from its own tank to the drum mounted on the scale, and thus to measure the fuel consumed during a given emission test. A similar installation was planned to be made on locomotive no. 804, but this proved to be impractical. The fuel system on no. 804 had been rebuilt at some time in the past, and was assembled with non-standard fittings in such a way that the three-way valves could not be installed without damaging it.

3. EMISSION RESULTS

The planned emission test sequence was as follows:

1. Precondition the engine and check the accuracy of the RAVEM sampling system using carbon balance. Begin an emission test using the RAVEM system. With the RAVEM system recording data, start the engine, and allow it idle for 10 minutes. Increase the throttle to notch 2 for 10 minutes, and then to notch 4 for 10 minutes. Note the weight indicated by the drum scale at the beginning and end of each segment. End the emission test, reduce the throttle to notch 3, read the sample bags, and change the PM filters. Confirm that the fuel consumption rate calculated by carbon balance from the RAVEM measurements matches that calculated from the change in weight of the fuel drum.
2. "Soup" test baseline – This test, carried out after the exhaust system has been cleaned of "soup" (accumulated heavy HC and lube oil), establishes the baseline for the "soup" test at the end of the program. Reduce the throttle from notch 4 to idle. Start the emission test after no more than 5 minutes at idle. After 60 seconds, return the throttle to notch 3. Measure emissions for 20 minutes. End the emission test, change PM filters, and read bags while continuing to run the engine in notch 3.
3. Cooldown idle. Reduce the locomotive throttle from notch 3 to idle. After ten seconds, begin the emission test. Measure emissions and fuel consumption and monitor cooling water temperature for 30 minutes. Change filters and read bags while the engine continues to idle. If the engine coolant temperature has not stabilized by the end of the test, perform additional 30 minute tests until stability is reached. (i.e. the rate of change in cooling water temperature is less than 1 degree C per 5 minutes.)
4. Stabilized idle. Measure stabilized emissions for 30 minutes.
5. Restart ½ hour. Shut down the locomotive for 30 minutes. Begin the emission test, wait 30 seconds, and then restart the engine. Allow the engine to idle for 29 minutes before shutting it down. End the emission test 30 seconds after shutting down.
6. Restart 1 hour. Shut down the locomotive engine for 60 minutes. Begin the emission test, wait 30 seconds, and then restart the engine. Allow the engine to idle for 29 minutes before shutting it down. End the emission test 30 seconds after shutting down.
7. Cold Restart. Shut down the locomotive engine for 12 to 16 hours. Begin the emission test, wait 30 seconds, and then restart the engine. Allow the engine to continue idling while reading bags and changing filters for the next test. If the engine coolant temperature has not stabilized by the end of the test, perform additional 30 minute tests until stability is reached. (i.e. the rate of change in cooling water temperature is less than 1 degree C per 5 minutes.)
8. Stabilized idle. Measure emissions for 30 minutes.

9. Restart 2 hours. Shut down the locomotive engine for 120 minutes. Begin the emission test, wait 30 seconds, and then restart the engine. Allow the engine to idle for 29 minutes before shutting it down. End the emission test 30 seconds after shutting down.
10. Restart 4 hours. Shut down the locomotive engine for 240 minutes. Begin the emission test, wait 30 seconds, and then restart the engine. Allow the engine to idle for 29 minutes before shutting it down.
11. "Soup" Test -- Start the emission test with the engine at idle. After 60 seconds, increase the throttle to notch 3. Measure emissions for 20 minutes. During this time, the increased exhaust temperature will drive off the "soup" that has accumulated in the exhaust system during the preceding idle tests, allowing it to be measured.
12. Shut down the locomotive, remove the stack extension, probe, thermocouple, and three-way valves.

Because of scheduling issues (primarily involving the availability of the locomotives and the scheduling of the cold start), it was necessary to change the order of the emission tests somewhat. Also, system problems led to repeating some tests on locomotive 804. Table 1 shows the emission tests performed on that locomotive, in the order they were performed.

Table 1: Summary of Emission Tests on Metrolink No. 804

Test No.	Start Date/Time	Test Conditions	Coolant °C		Run Min.	Total Emissions (g)			
			Start	End		PM	CO_2	NOx	HC
T0759	11/3/05 8:02	Warm-Start Idle	#N/A	#N/A	29.5	18.4	19,864	559	33
T0760	11/3/05 9:00	Idle-Notch 2-Notch 4	#N/A	#N/A	30.0	59.9	73,061	1,753	85
T0761	11/3/05 9:49	Soup Test Baseline - Notch 3	#N/A	#N/A	20.0	38.9	65,231	1,532	28
T0762	11/3/05 10:24	Cooldown Idle from Notch 3	#N/A	#N/A	30.0	9.4	14,632	473	12
T0763	11/3/05 11:31	Restart after 30 minutes	#N/A	#N/A	29.0	12.5	13,520	449	26
T0764	11/3/05 13:01	Restart after 1 hour	#N/A	#N/A	29.0	13.8	13,008	426	13
T0765	11/3/05 16:01	Restart after 2 hours	#N/A	#N/A	29.0	18.6	13,199	436	22
T0767	11/3/05 20:34	Restart after 4 hours	#N/A	#N/A	29.0	18.6	19,629	484	20
T0769	11/4/05 9:03	Restart after 12 hours	32.3	52.8	29.5	19.3	24,132	632	33
T0770	11/4/05 9:42	Warmup Idle after Cold Start	56.3	60.0	30.0	13.5	17,695	518	31
T0771	11/4/05 10:25	Semi-stabilized idle	61.2	64.1	30.0	#N/A	16,199	495	12
T0772	11/4/05 11:13	Stabilized Idle after Cold Start	65.3	67.5	30.0	16.9	15,449	484	30
T0773	11/4/05 12:00	Soup Test	68.1	81.2	20.0	70.9	70,147	1,654	88
T0774	11/4/05 12:38	Cooldown Idle after Notch 4	84.7	75.9	30.0	12.9	16,188	533	9
T0775	11/4/05 13:43	Restart after ½ h our	71.1	74.3	29.0	11.4	13,835	485	18
T0776	11/4/05 15:13	Restart after 1 hour	66.7	71.4	29.0	9.9	14,391	476	20
T0777	11/4/05 17:43	Restart after 2 hours	58.7	65.9	29.0	#N/A	15,975	506	23
Soup Test Minus Baseline					324	32.0	4,915	123	60

In addition to the summary results shown in Table 1, detailed second-by-second data and plots of gaseous pollutant concentrations, exhaust temperature, and coolant temperature are given in the Excel files produced by the RAVEM system for each test. These files also contain background pollutant concentrations and environmental data such as ambient temperature, humidity, and barometric pressure.

During the first day of testing, a software error prevented the coolant temperature data from being stored with the rest of the test data, although some limited data were recorded manually by another participant. During test 771, the primary PM sample filter stuck to the filter holder and tore, invalidating the weight results. During test 777, the sample filter holder was not pushed all the way into its receptacle, and this was not noticed until most of the way through the test.

Table 2 summarizes the emission tests performed on locomotive 800. With the increased experience of the sample team, no significant problems were experienced during this testing. In one deviation from the planned procedure, test 779 – preconditioning – was performed with the engine throttle set to notches 2 and 4, but without the self-load system in operation. This was because no-one available at the time knew how to apply the self-load system. The resulting exhaust temperatures were lower than if the self-load had been in effect, but still exceeded 100 ^{o}C. We believe that this adequately preconditioned the engine and exhaust system for the subsequent tests.

Table 2: Summary of Emission Tests on Metrolink No. 800

Test	Start	Test	Coolant ^{o}C		Run	Total Emissions (g)			
No.	Date/Time	Conditions	Start	End	Min.	PM	CO_2	NOx	HC
T0778	11/7/05 21:58	Stabilized Normal Idle	72.1	78.8	20.0	12.2	28,214	573	42
T0779	11/7/05 23:24	Idle-Notch 2-Notch 4 Prep	81.1	76.3	30.0	25.4	51,084	991	104
T0780	11/8/05 10:11	Cold Start after 10 hours	37.4	54.2	29.5	9.3	24,066	545	60
T0781	11/8/05 10:58	Warmup idle after cold start	58.1	63.4	30.0	10.0	23,721	578	53
T0782	11/8/05 11:45	Stabilized Idle	65.5	68.4	30.0	8.0	23,539	627	66
T0783	11/8/05 13:15	1 hour restart	59.0	67.0	29.0	8.5	22,315	589	32
T0784	11/8/05 14:16	30 Minute Restart	62.5	67.6	29.0	6.4	22,731	621	44
T0785	11/8/05 17:00	2.25 hour restart	51.8	63.5	29.0	7.0	21,878	565	37
T0786	11/8/05 21:30	4 hour restart	42.5	56.7	29.0	9.6	20,143	498	38
T0787	11/8/05 22:18	Soup Test	56.5	77.8	20.0	102.6	114,541	1,862	62
T0788	11/8/05 22:57	Soup test baseline	76.1	82.4	20.0	54.3	117,218	2,004	84
T0789	11/8/05 23:33	Cooldown idle after Notch 3	77.4	75.8	30.0	5.4	21,910	612	35
T0790	11/9/05 0:15	Stabilized Idle	74.8	72.7	30.0	3.8	21,314	594	38
Soup Test Minus Baseline					259	48.3	(2,677)	-142	-21

Fuel consumption measurements and carbon balance checks were conducted on all but the last two emission tests on locomotive no. 800. During the course of this testing, it was found that the locomotive fuel system is not closed, but includes air vents or leaks that allow it to "drain down" when the fuel pump is not running. This requires that the system be "primed" by running the fuel pump for about 15 seconds before attempting to start the engine. The amount of fuel entering and leaving the weighed drum during these processes amounted to about three kilograms – a substantial fraction of the 7-8 kilograms consumed during a half-hour idle. Because of these effects, carbon balance during the start-up and shutdown events was poor.

Carbon balance checks were conducted during preconditioning at notches 2 and 4 (test 779), and during the soup test baseline at notch 3 (test 788), resulting in fuel carbon recoveries of 98.3% and 101.0%, respectively. Unlike the start-up tests, the engine was not started or stopped during these tests, so that the transient effects discussed above had little effect on the results. Another carbon balance test was attempted during the "soup test" at notch 3 (test 787), but the fuel level in the drum fell below the entry to the fuel supply hose, allowing air to enter the fuel system.

A carbon balance calculation can also be conducted on the two-hour period covering tests 780 through 782. During this period, the locomotive underwent a cold start, followed by 123 minutes of idle, after which the locomotive was shut down for one hour. The 123 minutes of run time included 89.5 minutes during the three tests, as well as the roughly 15 minute periods between the tests. Allowing for these periods, total fuel consumption during the 123 minutes of idle is calculated at 30.93 kg. Fuel drum weight prior to the cold start was 92.4 kg, and it was 63.6 kg after the engine had been shut down for 55 minutes, giving total consumption of 28.8 kg over the period. Thus, calculated fuel consumption was 107% of the measured fuel consumption over the time period.

4. ANALYSIS AND DISCUSSION

The main purpose of this test program was to determine the tradeoff in emissions between more-frequent restarting and continuous idling of locomotive engines. Table 3 shows how the incremental emissions due engine restarting were calculated.

In calculating PM emissions at idle, the effects of exhaust system "souping" turned out to be very significant. Although this particulate matter is not emitted immediately, it accumulates until the next time the locomotive goes to a higher power setting, and is emitted then. Since the amount emitted depends on the amount accumulated, it is appropriate to attribute it to the idling period rather than the high-power operation when it actually comes out the stack. These substantial PM emissions are not measured by the Federal locomotive test procedure, since this procedure does not measure during the transition between test modes.

The first line in the table shows the stabilized exhaust emissions measured from locomotive 804, in grams per minute. Emissions from "souping" were calculated by subtracting the emissions during the soup test baseline from those during the soup test, and then dividing by the number of minutes of idle operation between the two tests. The results came to 0.10 g/minute of PM for locomotive 804 and 0.19 g/min for locomotive 800. These amounted to 15% and 49%, respectively, of the total PM emissions at idle. Incremental emissions of CO_2, NOx, and HC attributable to "souping" were very small, and probably reflect test-to-test variability rather than any actual accumulation in the exhaust.

Having calculated the emissions – including "soup" buildup – attributable to a 29-minute period of stabilized idle, we then added the same allowance for "soup" buildup to the 29-minute idle period in each of the start-up tests (29.5 minutes in the case of the cold-starts). Incremental start-up emissions were obtained by subtracting the stabilized idle emissions from those observed during each start-up.

As Table 3 shows, the incremental emissions due to start-up were relatively small, even for the ten and twelve-hour shut down periods. In the case of locomotive 804, the incremental emissions from start-up after one-half hour and one hour were negative. In no case did the incremental PM emissions due to start-up exceed the emissions produced during eight minutes of stabilized idle. The maximum incremental NOx emissions were observed in the 12-hour test for locomotive 804, and were equivalent to 10 minutes of stabilized idle.

Table 3: Calculation of Incremental Emissions Due to Locomotive Restart

	Emissions				Start-Idle Equivalence (min)	
	PM	CO_2	NOx	HC	From PM	From NOx
Locomotive #804 (SD-60)						
Stabilized Idle (g/minute)	0.56	527	16.3	0.7		
Addl Emissions from Soup Test (g/min)	0.10	15	0.4	0.2		
Total Stabilized Idle Emissions/Min	0.66	542	16.7	0.9		
Stabilized Idle (g/29 minutes)	19.2	15,725	484	25		
Emissions From Restart + Plus 29 min Idle (including "Soup")						
After 1/2 hour	14.8	14,118	478	27		
After 1 hour	14.7	14,139	462	22		
After 2 hours	21.5	15,027	482	28		
After 4 hours	21.5	20,069	495	26		
After 12 hours	22.2	24,572	643	39		
Incremental Emissions From Restart						
After 1/2 hour	-4.4	-1,608	-6	2	-6.7	-0.4
After 1 hour	-4.5	-1,586	-22	-4	-6.8	-1.3
After 2 hours	2.2	-698	-2	2	3.4	-0.1
After 4 hours	2.2	4,344	12	0	3.4	0.7
After 12 hours	3.3	9,118	168	14	5.0	10.1
Locomotive #800 (F-40)						
Stabilized Idle (g/minute)	0.20	747	20.3	1.7		
Addl Emissions from Soup Test g/min	0.19	(10)	-0.5	-0.1		
Total Stabilized Idle Emissions/Min	0.38	737	19.8	1.6		
Stabilized Idle (g/29 minutes)	11.1	21,361	574	48		
Emissions From Restart + Plus 29 min Idle (including "Soup")						
After 1/2 hour	11.8	22,431	605	42		
After 1 hour	13.9	22,015	573	30		
After 2 hours	12.4	21,578	549	34		
After 4 hours	12.4	20,583	509	43		
After 12 hours	12.1	24,506	556	65		
Incremental Emissions From Restart						
After 1/2 hour	0.6	1,069	31	-6	1.7	1.6
After 1 hour	2.8	654	-1	-18	7.2	0.0
After 2 1/4 hours	1.3	216	-25	-13	3.3	-1.3
After 4 hours	1.3	-778	-65	-5	3.4	-3.3
After 10 hours	1.2	3,513	-8	18	3.0	-0.4

5. SUMMARY AND CONCLUSIONS

Emission tests were performed on two locomotives equipped with engines typical of those used in older line-haul locomotives in the U.S. These tests focused on emissions produced at idle, and under start-up conditions after the engine was shut down for varying periods up to 12 hours.

PM emissions at idle from the two locomotives tested were 0.66 and 0.38 grams per minute, respectively; and NOx emissions were 16.7 and 19.8 grams per minute. A significant fraction of the total PM attributable to idle operation (15% in the first case, and 49% in the second) is not emitted at the time, but retained in the exhaust system as “soup”, to be emitted subsequently when the locomotive returns to higher-load operation. The present Federal locomotive test procedure fails to measure these substantially-increased PM emissions during the transient conditions following a period of idle.

The incremental emissions from these locomotives due to engine start-up were small compared to the emissions produced under stabilized idle conditions. In none of the start-up tests conducted did these emissions exceed the equivalent of 8 minutes of idle operation. Based on these data, shutting down the engine and restarting it will result in reduced emissions compared to allowing it to idle, as long as the idle shutdown period is longer than eight minutes. The longer the shutdown period, the greater the emission benefits.

6. REFERENCES

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[3] 40 CFR 86, Subpart N "Emission Regulations for New Otto-Cycle and Diesel Heavy-Duty Engines; Gaseous and Particulate Exhaust Test Procedures"

[4] "California Exhaust Emission Standards and Test Procedures for 1985 and Subsequent Model Heavy-Duty Diesel Engines and Vehicles" as amended on February 26, 1999, California Air Resources Board, available at