Appendix B - Overview and Results of CNG Emission Testing Programs

A. Background

Two studies have been conducted to evaluate CNG fuel quality effects on light-duty and heavy-duty vehicle driveability, emissions, and fuel economy. These studies are referred to as the Natural Gas Vehicle Technology and Fuel Performance Evaluation Program (PEP).

The PEP studies were supported by a collaborative group that included the Gas Research Institute (GRI), Pacific Gas & Electric (PG&E), Southern California Gas Company (SoCalGas), Atlanta Gas Light Company (AGL), U.S. Environmental Protection Agency (EPA), Air Resources Board (ARB), and auto manufacturers. The Clean Air Vehicle Technology Center (CAVTC) was contracted to conduct the testing and data evaluation. The results from these studies are documented in a light-duty vehicle test report,[1] completed in 1997, and a heavy-duty data presentation,[2] presented in 2000.

B. Light Duty Test Program

1. Test Protocol

The light-duty testing included emissions tests, fuel economy tests, including highway and acceleration, and driveability tests.[1] The emissions tests used the standard 3-phase Federal Test Procedure (FTP) test cycle and the additional acceleration phase (US06) from the proposed supplemental FTP cycle presented by the United States Environmental Protection Agency (U.S. EPA) in 1994. Each test was run twice for each vehicle/fuel combination to determine test repeatability. The measured emissions included total hydrocarbons (THC), methane (CH4), non-methane organic gases (NMOG), nitrogen oxides (NOx), carbon monoxide (CO), and carbon dioxide (CO_2). The vehicles tested included both dedicated NGVs (designed to use only CNG fuel) and bi-fuel vehicles. Some of these NGVs were designed and built by OEMs and others were after-market conversions, as shown in Table B-1 below. The Dodge Dakota vehicle was unique in that it was a bi-fuel prototype designed and built by an OEM. The emissions data for the individual vehicles are provided in Attachment B-1 at the end of this appendix.

Table B-1: Light-Duty Vehicle Testing - Vehicles

Year	Make & Model	Type	OEM	Conversion
1994	Dodge Caravan	Dedicated	X	
1994	Dodge Ram Van	Dedicated	X	
1992	Ford Crown Victoria	Dedicated	X	
1993	Honda Accord	Dedicated	X	
1994	GMC Sierra (Cardinal)	Dedicated		X
1992	GMC Sierra (PAS)	Dedicated		X
1995	Ford F250 (QVM)	Bi-fuel		X
1994	Dodge Dakota	Bi-fuel	X	

The fuels tested, shown in Table B-2, covered Wobbe numbers and methane numbers inclusive of the variation of the gas produced in the South Central Coast and Southern San Joaquin Valley. The current CNG motor vehicle fuel specifications are included in the last column of this table for comparison. Methane numbers of the tested fuels ranged from approximately 63 to 100 and Wobbe numbers from 1425 to 1182. The gas compositions were speciated out to C4+. The C4+ was assumed to be butane for the calculation of the methane number. Only TF-5 had a significant C4+ content. If the C4+ actually included heavier hydrocarbons than butane, the MN of the test fuel would be lower than reported. Methane content for the fuels ranged from 82 percent to 94 percent, ethane content from two percent to eight percent and C3+ from zero percent to 10 percent.

Table B-2: Light-Duty Vehicle Testing - Fuels

Mole %	TF-1	TF-2	TF-3	TF-4	TF-5	Current Spec
Methane	91.44	90.04	84.89	94.97	82.38	88.0 min
Ethane	1.75	4.0	8.44	3.02	4.65	6.0 max
Propane	0.00	C3+ = 2.0	0.00	0.14	6.00	C3+ = 3.0 max
C4+	0.02		0.00	0.06	4.07	
Inerts	6.78	3.5	6.40	1.79	2.89	1.5-4.5
Oxygen	0.01	0.5	0.27	0.02	0.02	1.0 max
MN*	103	89	88	99	63	NA
Wobbe	1245	1182	1284	1341	1425	NA

*ARB staff calculation

2. Test Results

Figure B-1, Figure B-2, and Figure B-3 below show the variation of NOx, CO and NMOG emissions as measured with the FTP cycle for the OEM dedicated light-duty vehicles as a function of fuel methane number. Applicable ARB 50,000 mile ultra low-emissions vehicle (ULEV) standards for the vans and for the passenger cars are shown in these figures for reference. The higher ULEV standards correspond to the two vans, the Caravan and the Ram, while the lower ULEV standards correspond to the two passenger cars, the Accord and Crown Victoria. These standards are only applicable to the FTP test

cycle emissions. The emissions from all the OEM dedicated vehicles were below the applicable ULEV standard with each of the tested fuels. Additionally, the NMOG values in Figure B-3 have not been adjusted by the natural gas reactivity adjustment factor of 0.41. Applying this adjustment factor drops these values an additional 60 percent.[1]

Figure B-1: Measured NOx Emissions from Dedicated Light-Duty Vehicles with the FTP Test Cycle

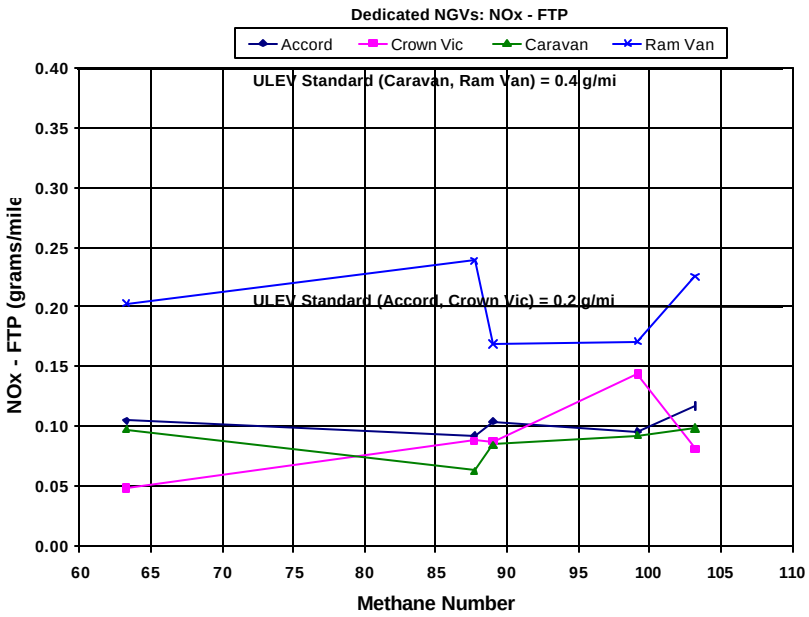


Figure B-2: Measured CO Emissions from Dedicated Light-Duty Vehicles with the FTP Test Cycle

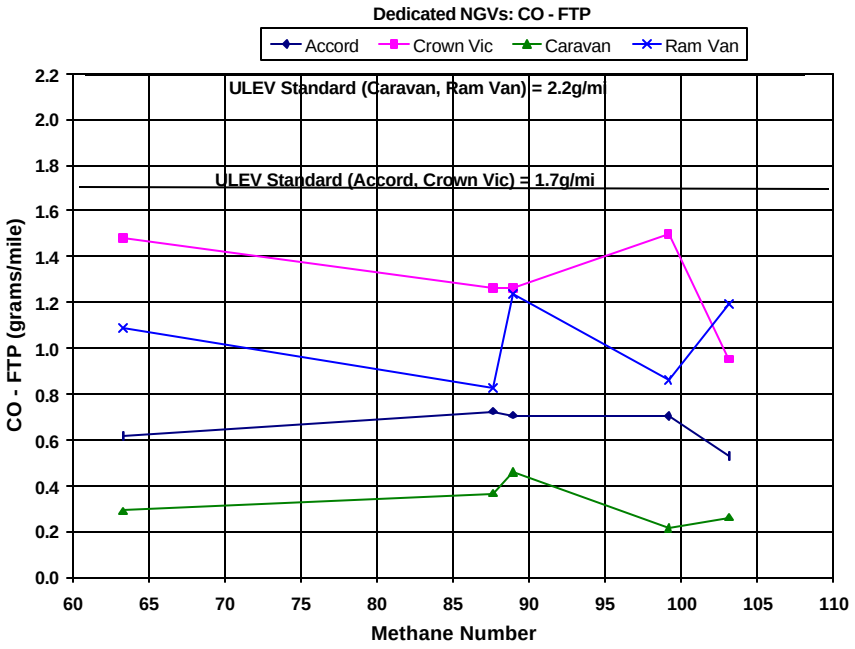


Figure B-3: Measured NMOG Emissions from Dedicated Light-Duty Vehicles with the FTP Test Cycle

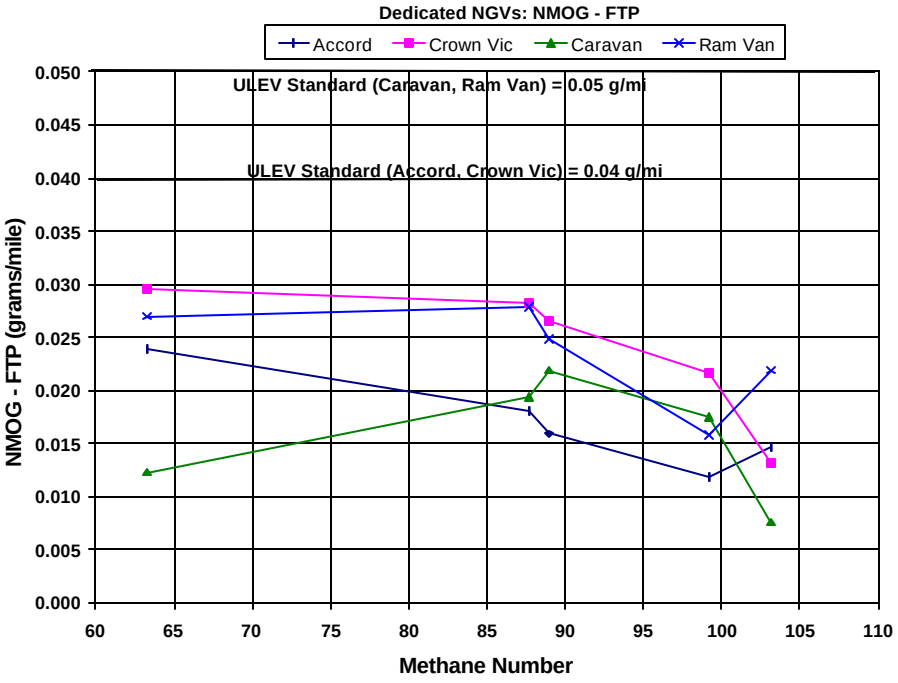


Figure B-4, Figure B-5, and Figure B-6 below show the variation of NOx, CO and NMOG emissions for the after-market conversion dedicated and bi-fuel light-duty vehicles as a function of fuel methane number as measured with the FTP cycle. The OEM prototype bi-fuel Dodge Dakota is included in these figures. The ARB 50,000 mile ultra low-emissions vehicle (ULEV) standard, low emissions vehicle (LEV) standard, and transitional low emission vehicle (TLEV) standard for the this vehicle type (light-duty trucks, 3751-5750 lbs.) are shown in these figures for comparison. Again, these standards are only applicable to the FTP test cycle emissions.

As shown in the figures below, the after-market conversion vehicles and the OEM prototype bi-fuel vehicle had higher emissions and more variation in emissions with fuel quality than the OEM dedicated fuel vehicles. However, all of these vehicles had NMOG emission levels within the LEV standard and NOx levels that were at or near the TLEV standard. Three of the four vehicles also met the TLEV/LEV CO emissions standard. The GMC (PAS), an after-market conversion dedicated vehicle, had CO emissions that were consistently higher than the standard for all tested fuels.

Figure B-4: Measured NOx Emissions from After-market Conversion and OEM Prototype Light-Duty Vehicles with the FTP Test Cycle

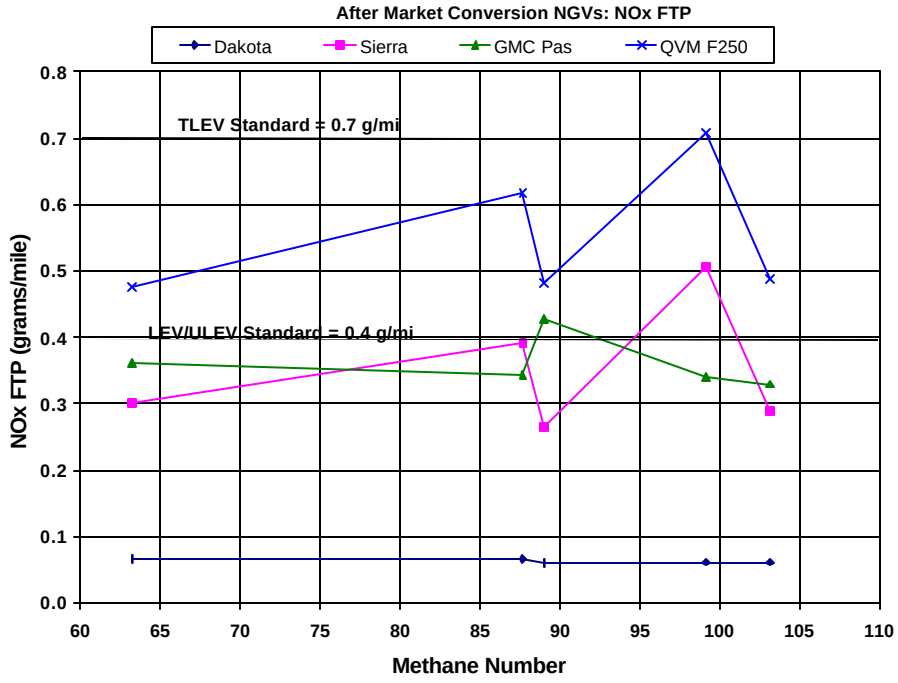


Figure B-5: Measured CO Emissions from After-market Conversion and OEM Prototype Light-Duty Vehicles with the FTP Test Cycle

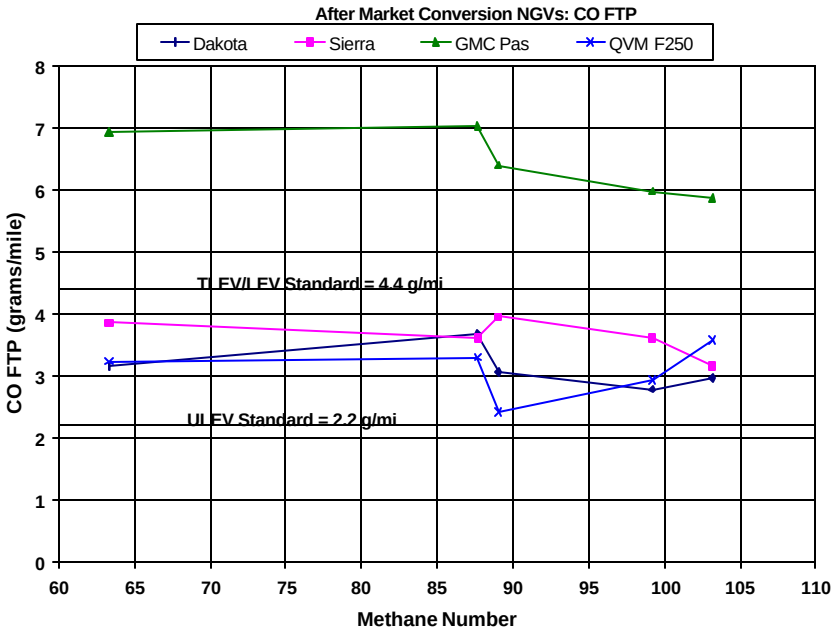


Figure B-6: Measured NMOG Emissions from After-market Conversion and OEM Prototype Light-Duty Vehicles with the FTP Test Cycle

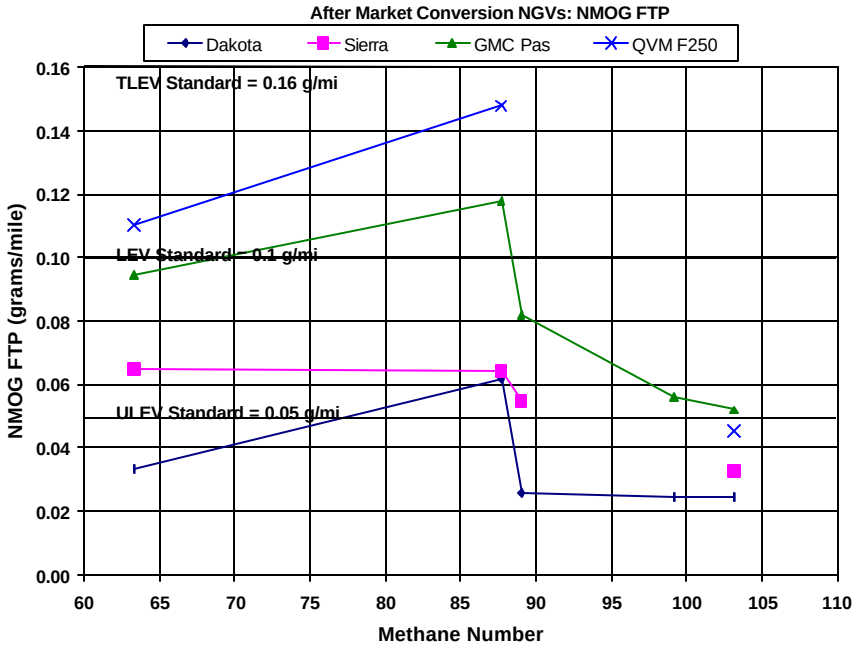
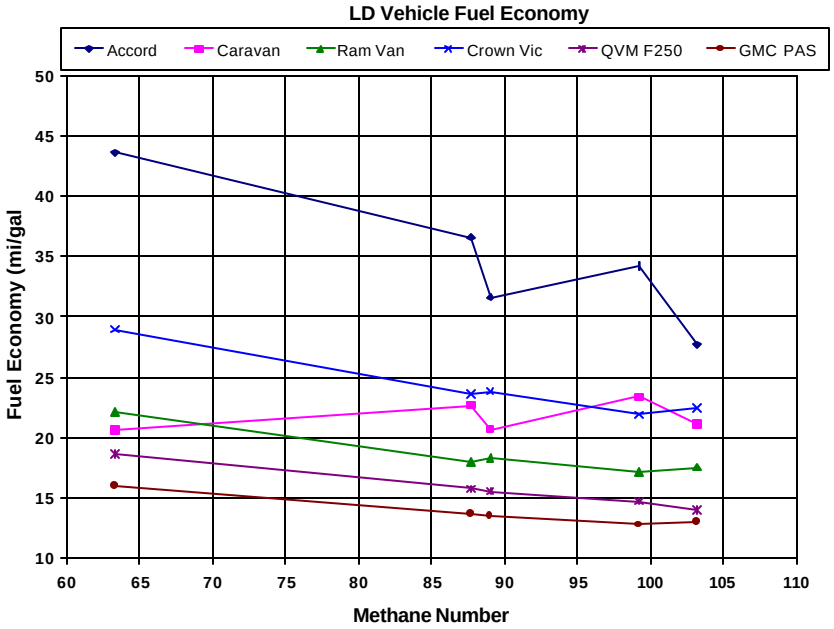


Figure B-7 below shows that fuel economy was either insensitive to fuel quality or increased with the reduced methane number.

Figure B-7: Measured Fuel Economy with Light Duty Vehicles with the FTP Test Cycle



C. Heavy Duty Test Program

1. Test Protocol

The heavy-duty vehicle testing evaluated emissions, fuel economy, and performance of seven different HD vehicles with four different fuels.[2] Testing included three different drive cycles with three tests run for each cycle/fuel/vehicle combination. The three drive cycles used were the EPA Heavy-Duty Urban Dynomometer Driving Schedule (UDDS), the Commuter cycle, and the Modified Central Business District (Mod-CBD) cycle. The measured emissions included total hydrocarbons (THC), methane (CH4), non-methane hydrocarbons (NMHC), nitrogen oxides (NOx), carbon monoxide (CO), and carbon dioxide (CO_2). The seven vehicles tested included both open loop and closed loop technology engines, as shown in Table B-3 below. The closed loop technology engines are designated as either advanced or first generation in Table B-3. The Cummins closed loop technology engine is considered first generation closed loop technology and is not as adaptable to variable fuel quality as the advanced generation closed loop technology engines such as the John Deere.

Table B-3: Heavy-Duty Vehicle Testing - Vehicles

Year	Make & Model	Duty	Control
1997	John Deer 8.1L	School Bus	Closed Loop, Advanced
1999	Cummins 8.3L	School Bus	Closed Loop, First Generation
1996	John Deere 6.8L	School Bus	Closed Loop, Advanced
1999	John Deere 8.1L	Crew Truck	Closed Loop, Advanced
1996	Detroit Diesel 8.5L Series 50	Transit Bus	Open Loop
1996	Cummins 10.0L	Transit Bus	Open Loop
1999/2000	Detroit Diesel 12.7L Series60G(LNG)*	Tractor	Closed Loop, First Generation

* Omitted from the data due to inconsistent data trends

The fuel qualities tested, shown in Table B-4, had methane contents ranging from 82 percent to 95 percent, ethane content from 3 percent to 8 percent and C3+ from 0 percent to 5 percent. The Wobbe numbers for the tested fuels ranged from 1310 to 1360 and methane numbers from 73 to 99. The methane number range included the lowest recommended fuel quality for advanced generation closed loop technology heavy-duty engines, methane number 73. The highest methane number fuel, labeled High Quality, meets the current CNG motor vehicle fuel specifications and exceeds the proposed specification of MN 80. The methane number calculated for the high ethane fuel, MN 81, is in the range of the calculated methane number for gas that meets the current specifications, MN ~ 80 – 82, as shown in Table D-1 in Appendix D. Although this high ethane fuel does not meet the current specifications, due to the slightly low methane content and the high ethane content, the emissions data using this fuel can be equated to a fuel that would meet the proposed MN 80 specification.

Table B-4: Heavy-Duty Vehicle Testing - Fuels

Mole %	High C3+	High Inerts/C3+	High Ethane	High Quality*	Current Spec
Methane	87.25	82.06	87.11	94.97	88.0 min
Ethane	5.84	7.11	8.25	3.02	6.0 max
Propane	3.06	3.83	1.81	0.14	C3+ = 3.0 max
Iso-butane	0.28	0.35	0.09	0.02	
N-butane	0.55	0.17	0.17	0.02	
Iso-pentane	0.08	0.06	0.02	0.01	
N-pentane	0.07	0.04	0.02	0.01	
C6+	0.05	0.0	0.01	0.0	
Inerts	2.82	5.92	2.52	1.81	1.5-4.5
Oxygen	0.0	0.0	0.0	0.03	1.0 max
MN**	77	73	81	99	~80-82***
Wobbe**	1363	1310	1359	1338	

* Meets current specification
** ARB staff calculation
***No current requirement for MN

Three tests were run for each cycle/fuel/vehicle combination for test repeatability. One exception to this was the 1996 8.5L Detroit Diesel Series 50 open loop technology transit bus tested with the UDDS cycle, where only two tests per fuel were completed. The other exception was the absence of particulate emissions data for 1997 8.1L John Deere closed loop technology school bus with the high ethane fuel. Only one measurement was available for this fuel/vehicle combination for the UDDS cycle. No data was available for this fuel/vehicle combination for the other two test cycles.

2. Test Results

The emissions and fuel economy results shown in the following tables and figures are for the UDDS driving schedule. The UDDS driving schedule generally resulted in the highest emissions levels as well as the highest fuel consumption.[3] Figure B-5 through Table B-7 below summarize the emissions data for each technology group. These tables give the range observed for each pollutant with each fuel quality. Table B-6 does not give a range since the first generation closed loop technology group was represented by a single vehicle. The emissions data for the individual vehicles are provided in Attachment B-1 at the end of this appendix. An average value for each cycle/fuel/vehicle combination is given in the attachment.

Table B-5: Advanced Generation Closed Loop Technology Engine Emissions and Fuel Economy Comparison of MN99, MN81, and MN73 CNG

Advanced Generation Closed Loop Technology, Vehicles # 1,3,4 only						
Test Fuel MN	**99**		**81**		**73**	
Tailpipe emissions (grams/mile)	**Minimum**	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**
THC	8.0	8.6	7.5	7.9	7.5	8.2
CO	0.3	3.8	0.2	4.2	0.2	4.2
NOx	6.0	11.4	6.9	12.8	6.1	11.0
CO_2	910	980	944	1020	978	1077
NMHC	0.4	2.0	1.3	2.7	1.5	3.0
PM	0.013	0.032	0.009	0.029	0.008	0.031
(Mi/Gal.)	6.1	7.3	7.6	7.7	8.0	8.3

Table B-6: First Generation Closed Loop Technology Engine Emissions and Fuel Economy Comparison of MN99, MN81, and MN73 CNG

First Generation Closed Loop Technology, Vehicle # 2 only			
Test Fuel MN	**99**	**81**	**73**
Tailpipe emissions (grams/mile)			
THC	9.6	7.2	7.3
CO	0.7	0.7	0.8
NOx	10.3	12.4	12.4
CO_2	1070	1098	1144
NMHC	1.9	1.8	1.9
PM	0.066	0.043	0.039
(Mi/Gal.)	6.1	6.7	7.0

Table B-7: Open Loop Technology Engine Emissions and Fuel Economy Comparison of MN99, MN81, and MN73 CNG

Open Loop Technology, Vehicles # 5 and 6 only						
Test Fuel MN	**99**		**81**		**73**	
Tailpipe emissions (grams/mile)	**Minimum**	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**
THC	5.2	11.0	5.3	9.1	5.2	12.8
CO	0.04	4.6	0.1	5.0	0.1	5.0
NOx	6.4	14.2	16.7	20.8	7.5	18.0
CO_2	1167	1259	1290	1469	1336	1478
NMHC	1.0	2.4	1.3	3.0	1.3	4.7
PM	0.025	0.035	0.033	0.051	0.021	0.055
(Mi/Gal.)	5.1	5.7	5.1	5.7	5.2	6.1

The closed loop technology 12.7L Detroit Diesel LNG tractor was omitted from the data presented because its CO and PM data trends were inconsistent with the other closed loop technology engine data. The LNG tractor PM emissions were over 10 times higher than those for the other engines, independent of fuel quality. Additionally, the LNG tractor CO emissions varied much more significantly with fuel quality than those from the other closed loop technology engines. However, this data can be found in Attachment B-1.

The PM emissions for the open and closed loop technology engines are shown in Figure B-8 and Figure B-9 versus methane number. Both the closed loop and the open loop technology engine PM emissions were 0.07 grams/mile or less with the majority of the data in the 0.02 to 0.04 gram/mile range. The typical PM variation with fuel quality seen in this data, 0.02 grams/mile, was not significantly different from the test to test variations seen within the data sets.

Figure B-8: PM Emissions for Open Loop Technology Engines

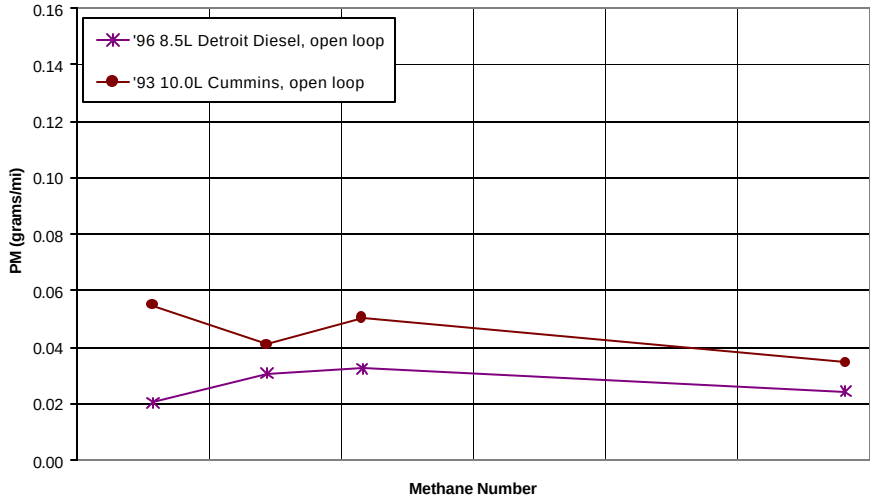
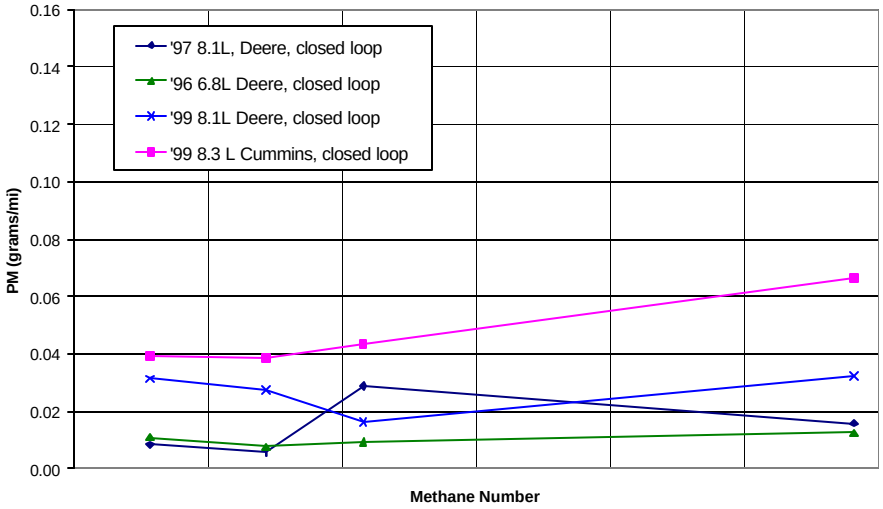


Figure B-9: PM Emissions for Closed Loop Technology Engines



NOx emissions for the open loop technology engines, shown in Figure B-10, were higher and had significantly more variation with fuel quality than those measured with the closed loop technology engines, shown in Figure B-11. The NOx emissions with the high quality MN99 fuel were similar in value between the open loop and closed loop technology engines. However, the open loop technology engines indicated an increase in

NOx emissions with reduced methane number that was not evident with the either the first generation or the advanced generation closed loop technology engines.

Figure B-10: NOx Emissions for Open Loop Technology Engines

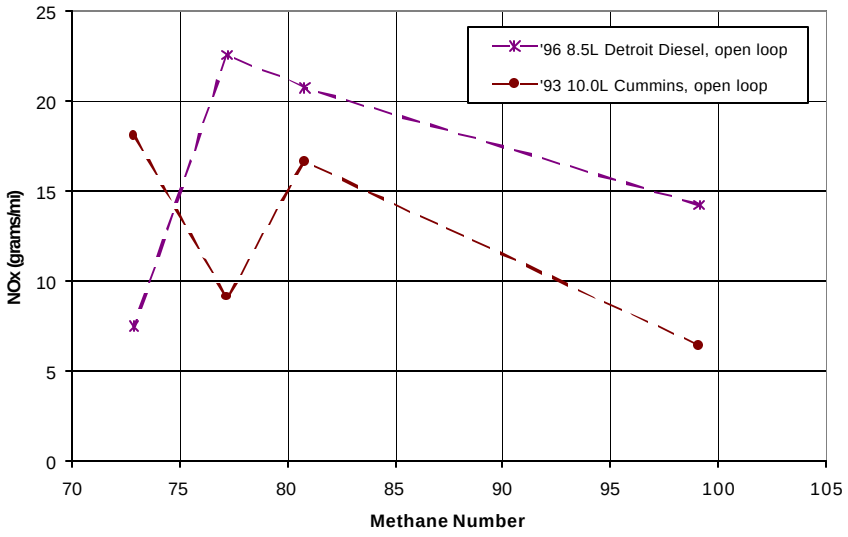
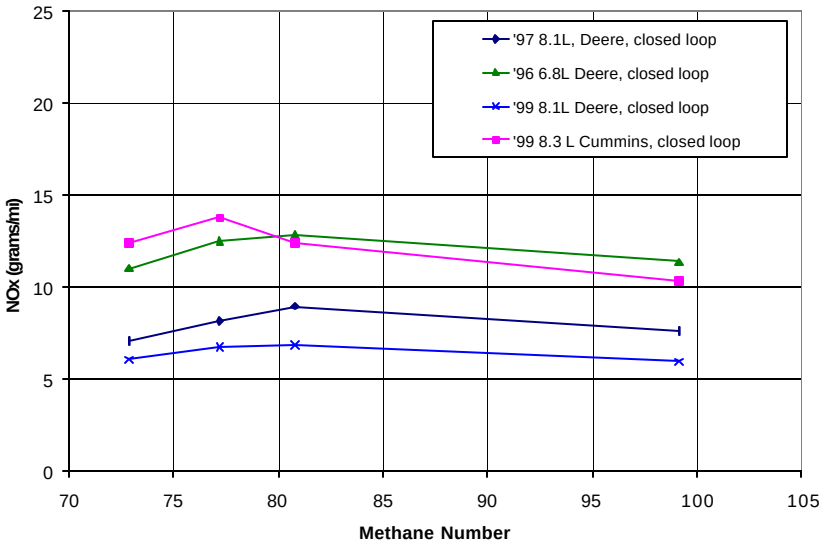


Figure B-11: NOx Emissions for Closed Loop Technology Engines



Non-methane hydrocarbon emissions trends with fuel quality, see Figure B-12 and Figure B-13, were similar for the open loop and closed loop technology engines. Both technologies indicated some increases in emissions with decreasing fuel quality. The Detroit Diesel open loop technology engine exhibited a larger increase in NMHC emissions with the MN73 fuel than any of the other engines. The advanced generation technology engines showed the most consistent trends from vehicle to vehicle with approximately a 10 percent increase from MN81 fuel quality to MN73 fuel quality.

Figure B-12: NMHC Emissions for Open Loop Technology Engines

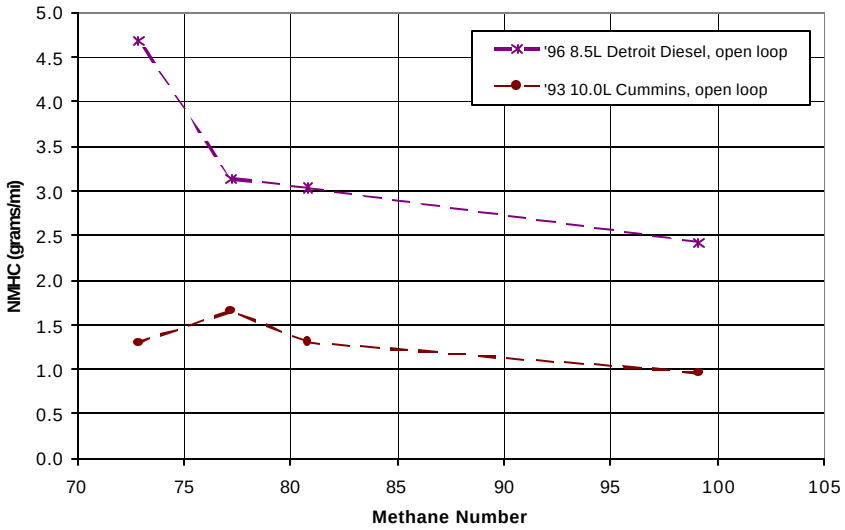
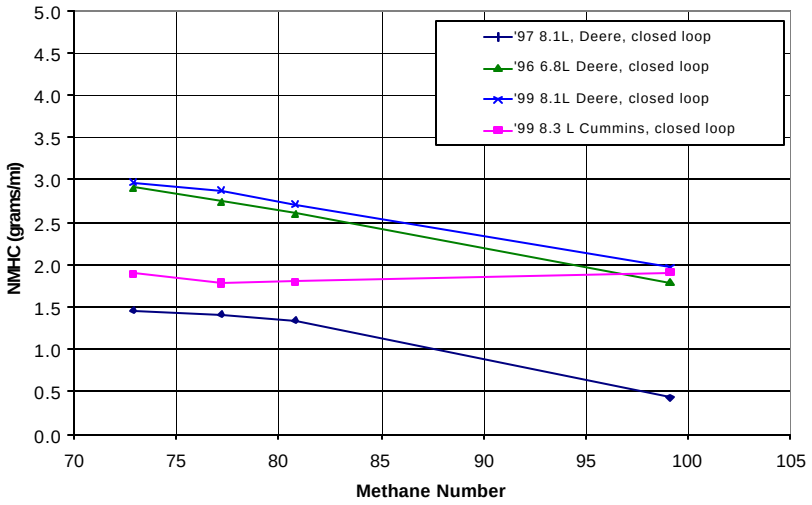


Figure B-13: NMHC Emissions for Closed Loop Technology Engines



THC emissions for both open and closed loop technology engines are shown in Figure B-14 and Figure B-15 below. With the exception of the Detroit Diesel open loop technology vehicle, there was minimal THC emissions variation with fuel quality. The Cummins open loop technology engine actually produced lower THC emissions, 5 to 6 grams/mile, than any of the closed loop technology engines. The THC emissions from all four of the closed loop technology engines were tightly grouped together at approximately 8 grams/mile.

Figure B-14: THC Emissions for Open Loop Technology Engines

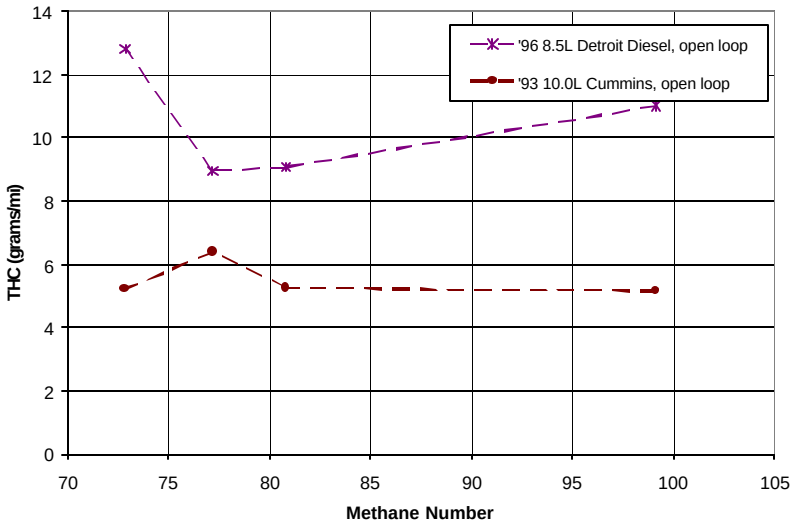
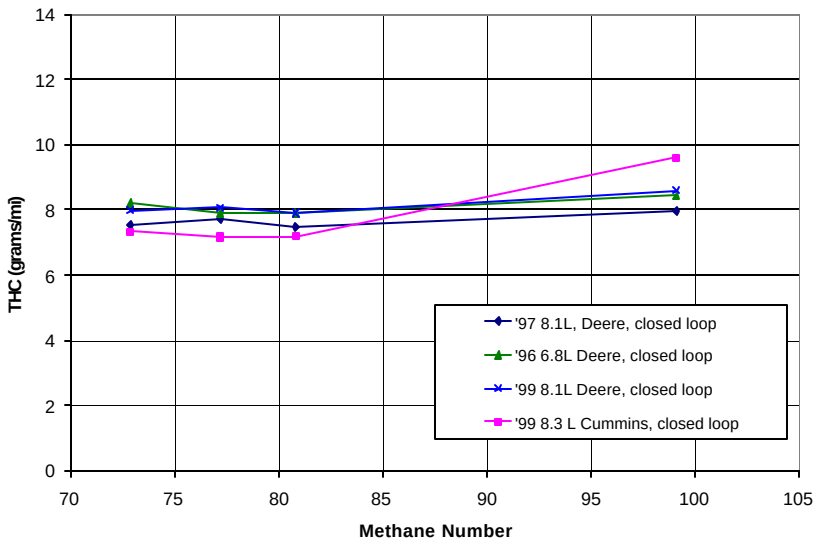


Figure B-15: THC Emissions for Open Loop Technology Engines



CO emissions for both open and closed loop technology engines, shown in Figure B-16 and Figure B-17, did not vary significantly with the variation of fuel quality. However, there was a significant difference between the CO emissions for the different engines. Both the first generation closed loop technology Cummins vehicle and the open loop technology Cummins engine as well as one of the advanced technology closed loop technology engines, the 1997 8.1L John Deere school bus, all had measured CO emissions of less than 1 gram/mile. The other two advanced technology closed loop technology engines had CO emissions of approximately 3 to 4 grams/mile. The Detroit Diesel open loop technology engine produced CO emissions of 4 to 5 grams/mile.

Figure B-16: CO Emissions for Open Loop Technology Engines

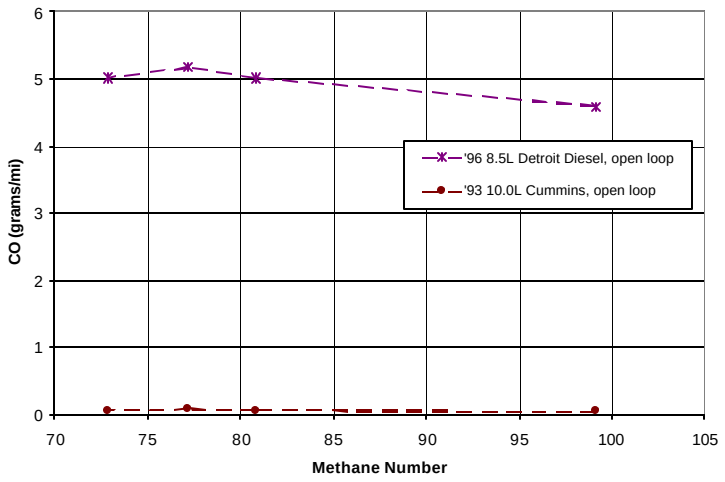
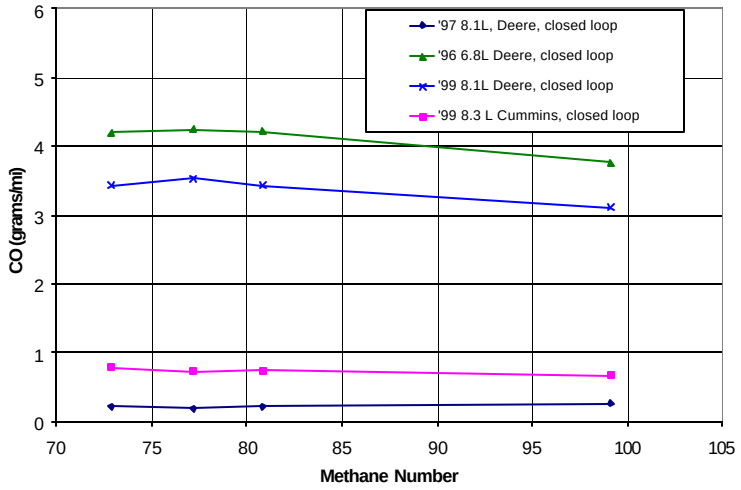


Figure B-17: CO Emissions for Closed Loop Technology Engines



CO_2 emissions for both open and closed loop technology engines are shown in Figure B-18 and Figure B-19 below. The CO_2 emissions for the open loop engines were higher than for the closed loop engines for all fuel qualities. The 1993 Cummins open loop vehicle had significant emissions variation with fuel quality. However the 1996 Detroit Diesel open loop vehicle and all the closed loop vehicles experienced only a six percent increase in emissions from the MN81 to the MN73 fuel quality.

Figure B-18: CO_2 Emissions for Open Loop Technology Engines

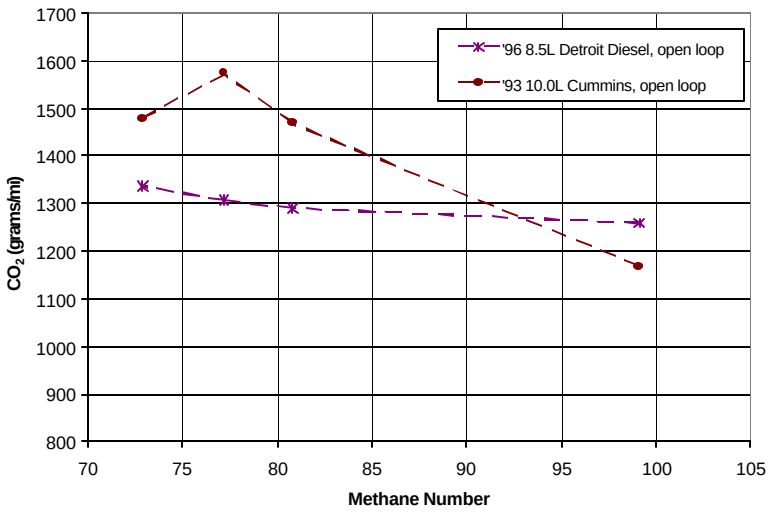


Figure B-19: CO_2 Emissions for Closed Loop Technology Engines

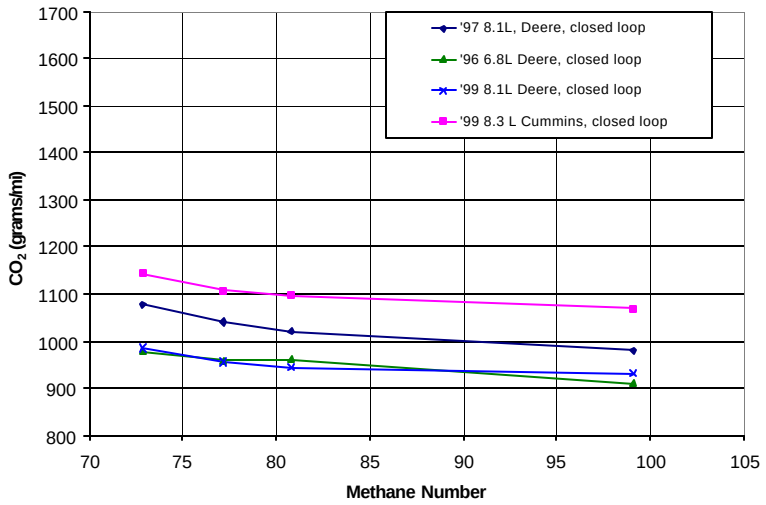


Figure B-20 and Figure B-21, below, show measured fuel economy as a function of fuel grade for the open and closed loop technology engines. The closed loop technology engines produced better fuel economy than the open loop technology engines. All of the closed loop technology engines and one of the open loop technology engines obtained better fuel economy with the lower MN fuels than with the higher MN fuel. The lower MN fuels contain larger fractions of higher molecular weight hydrocarbons, resulting in a higher energy content. The closed loop technology engines were better able to utilize the higher energy content fuels by adjusting the air/fuel ratio accordingly. Consequently, the closed loop technology engines showed a more consistent increase in fuel economy with

fuel variations, an average 20 percent increase from MN99 to MN73 fuel quality, than the open loop technology engines. The open loop technology Detroit Diesel engine also showed a 20 percent increase with decreasing fuel MN. However in contrast, the open loop technology Cummins engine showed a 9 percent decrease in fuel economy with decreasing fuel MN.

Figure B-20: Fuel Economy for Open Loop Technology Engines

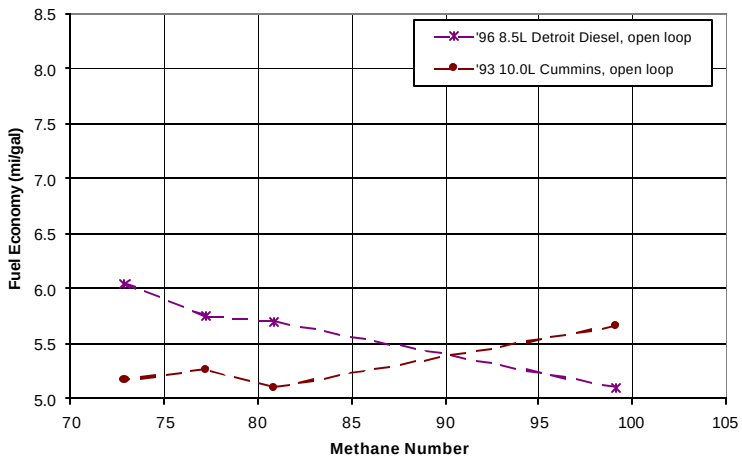
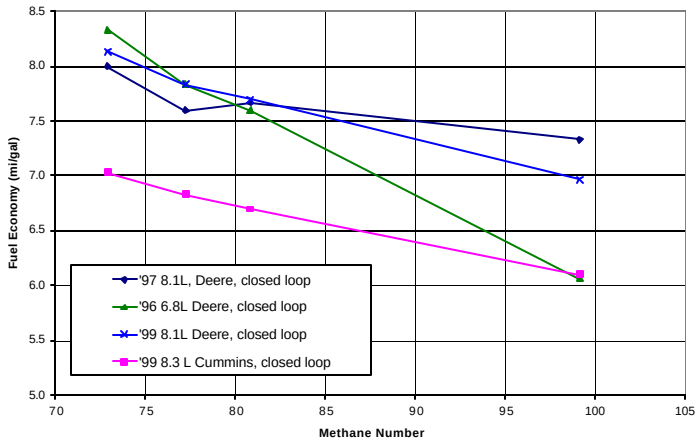


Figure B-21: Fuel Economy for Closed Loop Technology Engines



3. Data Analysis

a) Coefficient of Variance

The coefficient of variance (COV) for the data was maintained at less than 10 percent for the majority of the data, as summarized in Table B-8 for the three technology types.

Table B-8: Coefficient of Variance for Different Technology Groups

Technology Group	Average Coefficient of Variance (%)						
	THC	CO	NOx	CO_2	NMHC	Partic	Fuel Econ
Advanced Generation Closed Loop	2.8%	5.5%	3.5%	1.1%	3.3%	26.2%	3.7%
First Generation Closed Loop	2.6%	4.0%	2.7%	0.5%	3.0%	16.9%	0.6%
Open Loop	1.6%	15.2%	4.5%	0.9%	2.5%	43.1%	1.0%

The COV for the CO emissions exceeded 10 percent for three of the seven vehicles, the 1997 8.1L John Deere advanced generation closed loop technology school bus, the 1993 10.0L Cummins open loop technology transit bus, and the 1999/2000 12.7L Detroit Diesel Series 60G (LNG) closed loop technology tractor. The Detroit Diesel Series 60G (LNG) tractor was excluded from the summary due to inconsistent data trends. The high COVs for the John Deere and the Cummins vehicles were due to the low absolute value of the emissions. The standard deviations of the data were similar to that for the other test vehicles, but the measured CO emissions for these two vehicles were significantly lower, so the standard deviations were a higher percentage of the measured values.

The COVs for the PM emissions were also high due to low emission level. The COV for the PM emissions significantly exceeded 10 percent for at least two of the four fuels for every single vehicle, as evidenced in Table B-8. However, these high COVs were primarily due to the low measured PM emissions values. The PM test to test variations were small relative to more typical diesel PM measurements. However, again, these variations were a large percentage of the measured values for these vehicles. Consequently, while there appears to be a large degree of scatter in the PM emissions measurements, this variation is primarily due to the difficulty of measuring theses low values.

b) Statistical Analysis

A statistical analysis of the NOx and PM emissions data showed minimal statistically significant differences between the different vehicle technology groups and fuels for the UDDS cycle data shown in the preceding figures. The PM emissions data analysis indicated that only the first generation vehicle with the high quality fuel, which appears anomalously high, was statistically different, at a 95 percent confidence level, than any of the other vehicle/fuel combinations. The NOx emissions data analysis indicated that within individual vehicle technology groups, there were no statistically differences from fuel to fuel. However, the NOx emission response of the advanced generation closed loop technology engines showed less variation than either the first generation closed loop technology engine or the open loop technology engines, as shown in Figure B-22. The results of the statistical analysis are summarized in Table B-9 and Table B-10 for PM and NOx respectively.

Figure B-22: NOx Emission Response of the Different Engine Technologies

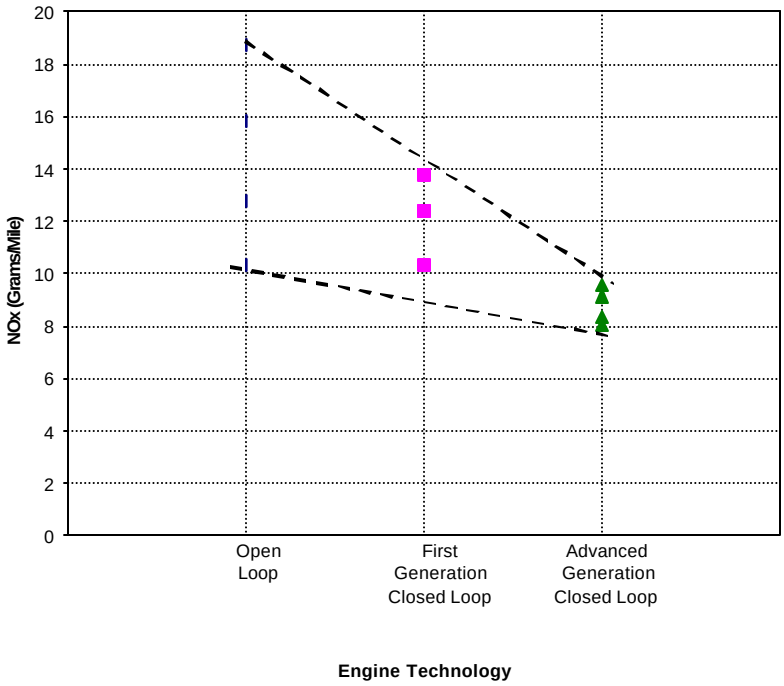


Table B-9: Statistical Mean and Standard Error of the PM Emissions for the Three Technology Groups and Four Fuel Qualities

UDDS Cycle					
Technology Group	**Pollutant**	**Fuel MN**	**Mean**	**Standard Error**	**Group***
Closed Loop Advanced	PM	73	0.017	0.007	A
Closed Loop Advanced	PM	77	0.014	0.007	A
Closed Loop Advanced	PM	81	0.014	0.007	A
Closed Loop Advanced	PM	99	0.020	0.007	A
First Generation Closed Loop	PM	73	0.039	0.012	A
First Generation Closed Loop	PM	77	0.039	0.012	A
First Generation Closed Loop	PM	81	0.043	0.012	A
First Generation Closed Loop	PM	99	0.066	0.012	B
Open Loop	PM	73	0.039	0.009	A B
Open Loop	PM	77	0.035	0.009	A B
Open Loop	PM	81	0.042	0.009	A B
Open Loop	PM	99	0.029	0.009	A

*** Means that share the same letter are not statistically different**

Table B-10: Statistical Mean and Standard Error of the NOx Emissions for the Three Technology Groups and Four Fuel Qualities

UDDS Cycle					
Technology Group	**Pollutant**	**Fuel MN**	**Mean**	**Standard Error**	**Group***
Closed Loop Advanced	NOx	73	8.1	2.6	C
Closed Loop Advanced	NOx	77	9.1	2.6	C
Closed Loop Advanced	NOx	81	9.6	2.6	C
Closed Loop Advanced	NOx	99	8.3	2.6	C
First Generation Closed Loop	NOx	73	12.4	4.6	C D
First Generation Closed Loop	NOx	77	13.8	4.6	C D
First Generation Closed Loop	NOx	81	12.4	4.6	C D
First Generation Closed Loop	NOx	99	10.3	4.6	C D
Open Loop	NOx	73	12.8	3.2	C D
Open Loop	NOx	77	15.9	3.2	C D
Open Loop	NOx	81	18.7	3.2	D
Open Loop	NOx	99	10.3	3.2	C D

*** Means that share the same letter are not statistically different**

D. Estimated Effect on Individual Vehicle Emissions

From the test data presented in the preceding sections, staff concluded that for the advanced generation closed loop technology engines the data show no discernable emissions impact for NOx, PM, THC and CO. However, the data indicate increases of approximately six and 10 percent in CO_2 and NMHC respectively from MN81 to MN73 CNG. For first generation closed loop technology the data show similar emissions trends. However, for open loop technology the data indicate significant increases in NMHC of up to approximately 50 percent.

Attachment B-1: Data Tables

Table A: Measured Emissions From Light-Duty Dedicated Fuel OEM Vehicles[1]

Vehicle Emissions (grams/mile) - Dedicated OEMs

NOx - FTP

Fuel	Wobbe	Accord	Crown Vic	Caravan	Ram Van	MN*
TF-1	1245	0.1175	0.0815	0.0988	0.2255	103
TF-2	1182	0.1045	0.0880	0.0850	0.1695	89
TF-3	1284	0.0930	0.0885	0.0630	0.2387	88
TF-4	1341	0.0963	0.1442	0.0930	0.1715	99
TF-5	1425	0.1050	0.0490	0.0980	0.2030	63

NOx - US06

Fuel	Wobbe	Accord	Crown Vic	Caravan	Ram Van	MN*
TF-1	1245	0.3840	0.3625	0.1645	0.2987	103
TF-2	1182	0.1570	0.2705	0.1340	0.2345	89
TF-3	1284	0.1865	0.1970	0.1040	0.2700	88
TF-4	1341	0.1203	0.3534	0.1680	0.2210	99
TF-5	1425	0.1360	0.0935	0.1503	0.2700	63

NMOG - FTP

Fuel	Wobbe	Accord	Crown Vic	Caravan	Ram Van	MN*
TF-1	1245	0.0146	0.0132	0.0076	0.0219	103
TF-2	1182	0.0159	0.0266	0.0219	0.0249	89
TF-3	1284	0.0181	0.0282	0.0194	0.0279	88
TF-4	1341	0.0119	0.0216	0.0175	0.0158	99
TF-5	1425	0.0239	0.0296	0.0123	0.0270	63

NMOG - US06

Fuel	Wobbe	Accord	Crown Vic	Caravan	Ram Van	MN*
TF-1	1245	0.0040	0.0038	0.0037	0.0040	103
TF-2	1182	0.0056	0.0049	0.0045	0.0021	89
TF-3	1284	0.0037	0.0042	0.0049	0.0044	88
TF-4	1341	0.0017	0.0055	0.0029	0.0035	99
TF-5	1425	0.0040	0.0041	0.0023	0.0046	63

CO - FTP

Fuel	Wobbe	Accord	Crown Vic	Caravan	Ram Van	MN*
TF-1	1245	0.5315	0.9525	0.2623	1.1925	103
TF-2	1182	0.7080	1.2640	0.4605	1.2365	89
TF-3	1284	0.7260	1.2615	0.3665	0.8283	88
TF-4	1341	0.7063	1.4974	0.2145	0.8590	99
TF-5	1425	0.6187	1.4815	0.2907	1.0870	63

CO - US06

Fuel	Wobbe	Accord	Crown Vic	Caravan	Ram Van	MN*
TF-1	1245	0.5970	1.1550	0.4813	1.6343	103
TF-2	1182	0.7545	1.4770	0.6545	1.2610	89
TF-3	1284	0.7010	1.3395	0.6110	0.9615	88
TF-4	1341	0.7527	1.8116	0.2435	1.0160	99
TF-5	1425.00	0.6760	1.6680	0.3423	1.1090	63

* ARB Staff Calculation

Table B: Measured Emissions From Light-Duty Bi-fuel and After-Market Conversion Vehicles[1]

Vehicle Emissions (grams/mile) - Bi-Fuel After Market Conversions and Prototype

NOx - FTP

Fuel	Wobbe	Dakota	Sierra	GMC Pas	QVM F250	MN*
TF-1	1245	0.0613	0.2893	0.3295	0.4890	103
TF-2	1182	0.0600	0.2650	0.4275	0.4820	89
TF-3	1284	0.0673	0.3910	0.3420	0.6170	88
TF-4	1341	0.0615	0.5070	0.3405	0.7075	99
TF-5	1425	0.0670	0.3015	0.3610	0.4765	63

NOx - US06

Fuel	Wobbe	Dakota	Sierra	GMC Pas	QVM F250	MN*
TF-1	1245	0.2280	0.4877	0.7375	0.6285	103
TF-2	1182	0.2940	0.4235	0.8120	0.6740	89
TF-3	1284	0.2935	0.5805	0.7325	0.7315	88
TF-4	1341	0.2370	0.7130	0.7700	0.7300	99
TF-5	1425	0.3170	0.5175	0.8080	0.5745	63

NMOG - FTP

Fuel	Wobbe	Dakota	Sierra	GMC Pas	QVM F250	MN*
TF-1	1245	0.0246	0.0327	0.0520	0.0452	103
TF-2	1182	0.0256	0.0550	0.0820	n/a	89
TF-3	1284	0.0616	0.0645	0.1179	0.1479	88
TF-4	1341	0.0245	n/a	0.0562	n/a	99
TF-5	1425	0.0334	0.0648	0.0946	0.1105	63

NMOG - US06

Fuel	Wobbe	Dakota	Sierra	GMC Pas	QVM F250	MN*
TF-1	1245	0.0023	0.0068	0.0262	0.0213	103
TF-2	1182	0.0033	0.0184	0.0717	n/a	89
TF-3	1284	0.0044	0.0135	0.0764	0.0488	88
TF-4	1341	0.0034	n/a	0.0427	n/a	99
TF-5	1425	0.0041	0.0154	0.0771	0.0418	63

CO - FTP

Fuel	Wobbe	Dakota	Sierra	GMC Pas	QVM F250	MN*
TF-1	1245	2.9727	3.1593	5.8705	3.5800	103
TF-2	1182	3.0585	3.9595	6.4060	2.4220	89
TF-3	1284	3.6863	3.6100	7.0400	3.3060	88
TF-4	1341	2.7850	3.6160	5.9830	2.9340	99
TF-5	1425	3.1605	3.8565	6.9345	3.2380	63

CO - US06

Fuel	Wobbe	Dakota	Sierra	GMC Pas	QVM F250	MN*
TF-1	1245	3.6005	3.4223	7.3355	4.7420	103
TF-2	1182	3.9195	4.6905	7.8355	3.6990	89
TF-3	1284	4.3705	4.1320	8.2180	4.4495	88
TF-4	1341	3.9160	3.9233	7.5235	4.3950	99
TF-5	1425	4.1515	4.2080	8.2880	4.5340	63

* ARB Staff Calculation

Table C: Light-Duty Dedicated OEM Vehicle Fuel Economy Data[1]

Dedicated NGVs (OEMs)

Average Fuel Economy (mpg)

Fuel	Wobbe	CH4/THC Vol. %	Lower Heating Value (LHV)	Specific Gravity X LHV	Accord	Caravan	MN*
TF-1	1245	0.981	864	512	27.69	21.15	103
TF-2	1182	0.938	839	519	31.66	20.67	89
TF-3	1284	0.910	913	566	36.62	22.68	88
TF-4	1341	0.967	922	536	34.22	23.38	99
TF-5	1425	0.848	1101	799	43.65	20.64	63

Fuel	Wobbe	CH4/THC Vol. %	Lower Heating Value (LHV)	Specific Gravity X LHV	Ram Van	Crown Vic	MN*
TF-1	1245	0.981	864	512	17.54	22.47	103
TF-2	1182	0.938	839	519	18.31	23.82	89
TF-3	1284	0.910	913	566	17.93	23.62	88
TF-4	1341	0.967	922	536	17.16	21.88	99
TF-5	1425	0.848	1101	799	22.08	28.97	63

*** ARB Staff Calculation**

Table D: Light-Duty Bifuel and After-Market Conversion Vehicles Fuel Economy Data[1]

Bi-Fuel After Market Conversion and Prototype

Average Fuel Economy (mpg)

Fuel I	Wobbe	CH4/THC Vol. %	Lower Heating Value (LHV)	Specific Gravity X LHV	QVM F250	GMC PAS	MN*
TF-1	1245	0.981	864	512	13.94	12.95	103
TF-2	1182	0.938	839	519	15.52	13.47	89
TF-3	1284	0.910	913	566	15.74	13.62	88
TF-4	1341	0.967	922	536	14.70	12.74	99
TF-5	1425	0.848	1101	799	18.65	15.97	63

*** ARB Staff Calculation**

Table E: Summarized HD Data for UDDS Cycle[2]

TEST CYCLE: UDDS

'97 8.1L, Deere, closed loop							
#1	Tailpipe Emissions (GRAMS/MI.)						Fuel Econ
MN*	THC	CO	NOx	CO2	NMHC	Partic	(Mi/Gal.)
99.1	7.97	0.26	7.62	980.1	0.43	0.016	7.33
80.8	7.47	0.22	8.98	1020.3	1.34	0.029	7.67
77.2	7.71	0.19	8.16	1040.7	1.41	0.006	7.60
72.9	7.52	0.22	7.10	1077.1	1.466	0.008	8.00

'99 8.3 L Cummins, closed loop							
#2	Tailpipe Emissions (GRAMS/MI.)						Fuel Econ
MN*	THC	CO	NOx	CO2	NMHC	Partic	(Mi/Gal.)
99.1	9.59	0.68	10.34	1069.9	1.90	0.07	6.10
80.8	7.18	0.75	12.40	1097.7	1.80	0.043	6.70
77.2	7.16	0.72	13.79	1106.2	1.78	0.039	6.83
72.9	7.33	0.78	12.42	1143.7	1.89	0.039	7.03

'96 6.8L Deere, closed loop							
#3	Tailpipe Emissions (GRAMS/MI.)						Fuel Econ
MN*	THC	CO	NOx	CO2	NMHC	Partic	(Mi/Gal.)
99.1	8.43	3.77	11.39	910.3	1.79	0.013	6.07
80.8	7.90	4.22	12.84	961.2	2.60	0.009	7.60
77.2	7.90	4.24	12.51	959.2	2.74	0.008	7.83
72.9	8.22	4.20	11.03	978.1	2.91	0.011	8.33

'99 8.1L Deere, closed loop							
#4	Tailpipe Emissions (GRAMS/MI.)						Fuel Econ
MN*	THC	CO	NOx	CO2	NMHC	Partic	(Mi/Gal.)
99.1	8.59	3.12	5.96	931.6	1.97	0.032	6.97
80.8	7.91	3.43	6.86	944.1	2.71	0.016	7.70
77.2	8.06	3.54	6.76	956.2	2.87	0.027	7.83
72.9	7.99	3.44	6.07	985.3	2.97	0.031	8.13

'96 8.5L Detroit Diesel, open loop							
#5	Tailpipe Emissions (GRAMS/MI.)						Fuel Econ
MN*	THC	CO	NOx	CO2	NMHC	Partic	(Mi/Gal.)
99.1	11.01	4.59	14.24	1258.9	2.42	0.02	5.10
80.8	9.07	5.01	20.76	1290.1	3.03	0.033	5.70
77.2	8.96	5.18	22.57	1306.7	3.14	0.031	5.75
72.9	12.79	5.02	7.52	1336.3	4.67	0.021	6.05

'93 10.0L Cummins, open loop							
#6	Tailpipe Emissions (GRAMS/MI.)						Fuel Econ
MN*	THC	CO	NOx	CO2	NMHC	Partic	(Mi/Gal.)
99.1	5.16	0.04	6.39	1167.1	0.96	0.03	5.66
80.8	5.25	0.06	16.66	1468.7	1.30	0.051	5.10
77.2	6.40	0.08	9.15	1573.2	1.65	0.041	5.27
72.9	5.22	0.06	18.04	1478.5	1.30	0.055	5.17

'99/'00 12.7L DD (LNG), closed loop							
#7	Tailpipe Emissions (GRAMS/MI.)						Fuel Econ
MN*	THC	CO	NOx	CO2	NMHC	Partic	(Mi/Gal.)
99.1	15.00	6.45	4.53	1101.1	0.85	0.52	8.80
80.8	13.53	10.88	6.10	1084.3	2.71	0.482	8.90
77.2	14.64	13.48	6.46	1083.8	3.24	0.512	8.83
72.9	14.19	7.53	4.47	1139.8	3.34	0.500	8.50

*ARB staff calculation

Table F: Summarized HD Data for Mod-CBD Cycle[2]

TEST CYCLE: MCBD

'97 8.1L, Deere, closed loop							
#1	Tailpipe Emissions (GRAMS/MI.)						Fuel Econ
MN*	THC	CO	NOx	CO2	NMHC	Partic	(Mi/Gal.)
99.1	5.06	0.16	3.88	767.1	0.329	0.008	9.43
80.8	4.64	0.14	4.56	788.2	0.78	n.a.	9.97
77.2	4.90	0.18	4.60	811.1	0.86	0.004	9.80
72.9	4.53	0.14	4.09	825.2	0.82	0.008	10.47

'99 8.3 L Cummins, closed loop							
#2	Tailpipe Emissions (GRAMS/MI.)						Fuel Econ
MN*	THC	CO	NOx	CO2	NMHC	Partic	(Mi/Gal.)
99.1	5.01	0.53	7.28	831.9	1.01	0.028	7.87
80.8	3.87	0.57	9.28	853.0	0.95	0.03	8.67
77.2	3.82	0.59	9.04	845.7	0.93	0.026	9.00
72.9	3.91	0.59	8.59	872.6	0.99	0.028	9.30

'96 6.8L Deere, closed loop							
#3	Tailpipe Emissions (GRAMS/MI.)						Fuel Econ
MN*	THC	CO	NOx	CO2	NMHC	Partic	(Mi/Gal.)
99.1	6.29	3.38	8.38	766.4	1.40	0.006	8.43
80.8	5.81	3.89	9.12	805.1	1.97	0.004	9.10
77.2	5.87	4.01	10.70	822.0	2.06	0.006	9.17
72.9	6.36	3.90	7.02	838.4	2.24	0.006	9.73

'99 8.1L Deere, closed loop							
#4	Tailpipe Emissions (GRAMS/MI.)						Fuel Econ
MN*	THC	CO	NOx	CO2	NMHC	Partic	(Mi/Gal.)
99.1	5.50	2.58	3.82	759.6	1.29	0.033	8.57
80.8	4.78	2.94	4.32	755.1	1.65	0.019	9.67
77.2	5.14	2.99	4.15	781.2	1.87	0.019	9.60
72.9	5.31	2.97	3.79	813.4	2.00	0.025	9.87

'96 8.5L Detroit Diesel, open loop							
#5	Tailpipe Emissions (GRAMS/MI.)						Fuel Econ
MN*	THC	CO	NOx	CO2	NMHC	Partic	(Mi/Gal.)
99.1	7.69	3.49	8.04	1013.5	1.68	0.025	6.40
80.8	6.70	3.78	11.15	1039.8	2.25	0.04	7.07
77.2	6.48	3.97	12.32	1039.1	2.25	0.022	7.23
72.9	8.43	3.91	4.44	1099.8	2.98	0.021	7.43

'93 10.0L Cummins, open loop							
#6	Tailpipe Emissions (GRAMS/MI.)						Fuel Econ
MN*	THC	CO	NOx	CO2	NMHC	Partic	(Mi/Gal.)
99.1	6.90	0.07	9.96	1454.0	1.26	0.090	4.50
80.8	4.14	0.04	9.70	1193.1	1.02	0.03	6.23
77.2	4.96	0.05	4.36	1242.0	1.30	0.030	6.67
72.9	3.87	0.06	11.24	1180.2	0.94	0.037	6.47

'99/'00 12.7L DD (LNG), closed loop							
#7	Tailpipe Emissions (GRAMS/MI.)						Fuel Econ
MN*	THC	CO	NOx	CO2	NMHC	Partic	(Mi/Gal.)
99.1	10.08	5.33	2.26	1051.7	0.82	0.175	9.33
80.8	8.50	7.43	2.95	1034.9	1.97	0.18	9.47
77.2	8.43	7.70	3.13	1050.6	2.14	0.177	9.33
72.9	10.35	6.19	2.20	1126.4	2.70	0.196	8.70

*ARB staff calculation

Table G: Summarized HD Data for Commuter Cycle[2]

TEST CYCLE: Commuter

'97 8.1L, Deere, closed loop							
#1	Tailpipe Emissions (GRAMS/MI.)						Fuel Econ
MN*	THC	CO	NOx	CO2	NMHC	Partic	(Mi/Gal.)
99.1	4.69	0.08	3.58	674.9	0.208	0.005	10.67
80.8	4.17	0.03	4.59	718.5	0.60	n.a.	10.97
77.2	3.97	0.08	4.33	690.1	0.62	0.007	11.57
72.9	3.77	0.04	4.47	711.3	0.57	0.009	12.13

'99 8.3 L Cummins, closed loop							
#2	Tailpipe Emissions (GRAMS/MI.)						Fuel Econ
MN*	THC	CO	NOx	CO2	NMHC	Partic	(Mi/Gal.)
99.1	4.69	0.30	3.99	723.8	0.96	0.075	9.07
80.8	3.47	0.34	5.46	712.4	0.81	0.02	10.33
77.2	3.58	0.35	5.05	715.7	0.83	0.035	10.63
72.9	3.53	0.34	4.92	737.4	0.85	0.031	10.97

'96 6.8L Deere, closed loop							
#3	Tailpipe Emissions (GRAMS/MI.)						Fuel Econ
MN*	THC	CO	NOx	CO2	NMHC	Partic	(Mi/Gal.)
99.1	4.66	2.64	10.22	627.1	0.99	0.009	10.30
80.8	4.35	2.90	11.63	662.0	1.46	0.006	11.10
77.2	4.52	3.01	11.49	676.9	1.58	0.021	11.13
72.9	4.47	2.93	9.80	681.7	1.55	0.004	12.00

'99 8.1L Deere, closed loop							
#4	Tailpipe Emissions (GRAMS/MI.)						Fuel Econ
MN*	THC	CO	NOx	CO2	NMHC	Partic	(Mi/Gal.)
99.1	4.55	1.95	4.40	614.2	0.99	0.033	10.60
80.8	5.08	2.40	4.56	714.3	1.74	0.030	10.20
77.2	5.14	2.45	4.32	717.4	1.83	0.027	10.47
72.9	5.17	2.45	4.20	740.8	1.92	0.013	10.83

'96 8.5L Detroit Diesel, open loop							
#5	Tailpipe Emissions (GRAMS/MI.)						Fuel Econ
MN*	THC	CO	NOx	CO2	NMHC	Partic	(Mi/Gal.)
99.1	5.27	3.05	7.81	894.7	1.24	0.020	7.27
80.8	4.32	3.43	10.65	926.4	1.43	0.03	8.00
77.2	4.02	3.53	11.91	914.5	1.39	0.018	8.27
72.9	5.95	3.45	4.20	983.9	2.19	0.024	8.37

'93 10.0L Cummins, open loop							
#6	Tailpipe Emissions (GRAMS/MI.)						Fuel Econ
MN*	THC	CO	NOx	CO2	NMHC	Partic	(Mi/Gal.)
99.1	4.08	0.04	8.32	1070.5	0.70	0.029	6.13
80.8	2.80	0.02	12.91	1075.0	0.61	0.02	6.97
77.2	2.44	0.02	16.34	1068.2	0.53	0.044	7.17
72.9	3.54	0.03	6.36	1137.5	0.82	0.020	7.30

'99/'00 12.7L DD (LNG), closed loop							
#7	Tailpipe Emissions (GRAMS/MI.)						Fuel Econ
MN*	THC	CO	NOx	CO2	NMHC	Partic	(Mi/Gal.)
99.1	5.02	2.54	3.02	660.8	0.31	0.116	14.93
80.8	4.15	3.22	5.39	657.4	0.89	0.10	15.07
77.2	4.33	3.83	4.33	667.2	1.00	0.113	14.80
72.9	4.77	3.13	3.26	706.8	1.15	0.117	14.03

*ARB staff calculation

[1] Bevilacqua, Oreste M., Ph.D. "Natural Gas Vehicle Technology and Fuel Performance Evaluation Program", Clean Air Vehicle Technology Center, File No. Z-19-2-013-96, April 1, 1997.

[2] Bevilacqua, Oreste M., Ph.D., "Impacts of Natural Gas Fuel Composition on Tailpipe Emissions and Fuel Economy", ARB Public Workshop on the Alternative Fuels Regulations, Sacramento, CA, June 21, 2000.

[3] Bevilacqua, Oreste M., "Natural Gas Vehicle Technology and Fuel Performance Evaluation Program (PEP), Phase II: Medium- and Heavy-Duty Vehicle Testing, Technical Proposal", Clean Air Vehicle Technology Center, December 18, 1998.