

FINAL REPORT

Chassis Dynamometer Emissions Characterization of Buses in Mexico City

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Introduction

The objective of this project was to characterize the vehicle emissions from a variety of buses using both current and advanced engine control and aftertreatment technologies and low emission fuels in Mexico City, Mexico. Emissions were measured from nine vehicles including six utilizing diesel engines, two powered by natural gas and one employing a diesel-hybrid powertrain. For the diesel vehicles, emissions measurements were obtained while using standard pump (350 ppm sulfur), medium sulfur (50 ppm) and low-sulfur (15ppm) diesel fuels (Note: post testing fuel analysis revealed that the 50 ppm sulfur diesel actually contained 150 ppm sulfur).

Prior to initiating the test program, a representative driving cycle termed the "Mexico City Schedule" was developed from data obtained from in-use Mexico City transit buses. The schedule was representative of low-speed, high-speed and corridor transit bus operation. Details on the development of this driving schedule were included in a separate report titled "Development of the Mexico City Schedule for Characterization of Emissions and Performance from Transit Buses".

During testing on five of the vehicles, the "Ride Along" Vehicle Emissions Measurement (RAVEM) system from Engine, Fuel, and Emissions Engineering, Inc. measured emissions in parallel with the West Virginia University laboratory. Data and conclusions from the correlation testing can be found in a separate report titled "Correlation between West Virginia University and Engine, Fuel, and Emissions Engineering, Inc.'s RAVEM Emissions Measurements from Transit Buses."

Laboratory Description

Emissions from the test vehicles were measured by the West Virginia University Transportable Heavy-Duty Vehicle Emissions Laboratory (TransLab). The WVU Transportable Laboratories were constructed to gather emissions data from in-use heavy-duty vehicles. Detailed information pertaining to the design and operation of the laboratories can be found in technical papers [1, 2, 3]. The laboratory was a fully functional heavy-duty chassis dynamometer with constant volume sampling (CVS) capability that can be physically transported to a bus operations site to conduct emissions testing.

Dynamometer

The chassis dynamometer used for this research was mounted on a semi-trailer, with removable wheels, that can be lowered to the ground by hydraulic jacks. The vehicle to be tested was then driven onto the dynamometer rolls via ramps. In most chassis dynamometers the power is taken from a set of rolls upon which the vehicle is secured and driven. Large diameter rolls are not practical for a mobile unit. When small diameter rolls are used, tire slippage proves a problem by corrupting data and overheating tires. The WVU Transportable Chassis Dynamometer withdrew power by coupling directly to the vehicle drive axle via driveshafts connected to hub adapter installed in place of the outer drive wheels (Figure 1). The vehicle was supported on free-spinning rolls which served to link the driven wheels and maintain the same speed on both sides of the vehicle. The dynamometer components, which were largely symmetrical on each side of the vehicle, consisted of power absorbers and sets of selectable flywheels. Different combinations of flywheels in the flywheel set were engaged to allow simulation of inertial loads representative of desired vehicle weight (Figure 2). The vehicle was driven through a speed-time cycle by a driver receiving a prompt on a screen while vehicle speed and load were recorded by encoders and

strain gage torque transducers. The road load applied to the vehicle was determined by performing on-road coast downs for each vehicle. Part of the applied load was dissipated through parasitic losses of the rotating components, and the remaining load was applied by the eddy current absorbers in closed loop control. Parasitic losses were determined using a coast down procedure performed prior to mounting the vehicle to the dynamometer.



Figure 1: Hub adapters connect the vehicle's drive axle to the power absorber unit



Figure 2: Flywheels were used to simulate vehicle inertia

Regulated Emissions Sampling Equipment

Most environmental agencies worldwide have identified particulate matter (PM), oxides of nitrogen, (NO_x) hydrocarbons (HC) and carbon monoxide (CO) as species that must be regulated and quantified. Additionally, in this program, carbon dioxide (CO_2) was sampled since this species is a well-established indicator of engine fuel consumption and is also a major greenhouse gas. The exhaust from the test vehicle was ducted into a total exhaust,

critical flow venturi-constant volume sampler (CFV-CVS) and mixed with HEPA filtered ambient air in the primary dilution tunnel. The primary dilution tunnel measured 18 inches (45cm) in diameter 20 feet (6.1m) in length. The flow rate of diluted exhaust was controlled and measured precisely by a critical flow venturi (CFV) system. Gaseous samples were drawn from the dilution tunnel ten diameters downstream of the exhaust injection zone to allow thorough mixing in the turbulent region of the dilution tunnel. The diluted exhaust was sampled and analyzed in accordance with the procedures outlined in the CFR 40 Part 86 Subpart N [4]. The diluted exhaust was analyzed using non-dispersive infrared (NDIR) detectors for CO and CO₂, and using chemiluminescent detection for NO_x. HC emissions were analyzed using a heated flame ionization detector (HFID). The gaseous data were available as continuous concentrations throughout the test, and the product of concentration and dilution tunnel flow were integrated to yield emissions in units of grams per mile (g/mile). In the case of CO, the laboratory operated two separate analyzers calibrated for different ranges. The lower ranged CO analyzer was set to capture the low-level CO emissions which occur during a majority of testing on diesel vehicles while the higher ranged CO analyzer was set to capture the spikes which occur during transient operation. PM was collected using 70-mm fluorocarbon coated glass fiber filter media and were determined gravimetrically. Fuel efficiencies were determined using a carbon balance, fuel properties and exhaust emissions data. The laboratory is shown in Figure 3.



Figure 3: WVU Transportable Laboratory testing the ALLISON hybrid-electric bus

Non-Regulated Species Sampling

The non-regulated species measured in this program included nitrous oxide (N₂O) and aldehydes. The aldehydes were quantified under a separate agreement by Environment Canada, and so only N₂O emissions are discussed in this report. For each test, an integrated bag sample was collected by a heated sampling system and subsequently analyzed using an Innova 1302 photoacoustic analyzer. The 1302 sample train consisted of a heated stainless steel sample line, a heated head sample pump, a flow controller and a heated enclosure housing a 10-liter Tedlar[®] sample bag. Both the sampling line and bag enclosure were heated to 150° F to prevent condensation. Following collection, a sample was drawn from the Tedlar bag through the 1302 analyzer to determine N₂O and CO₂ levels. CO₂ data measured using the Innova 1302 were compared with the CO₂ data from the emissions laboratory's NDIR analyzer to confirm that the 1302 analyzer was functioning properly and

to check agreement between the 1302 instrument and the laboratory. The Innova 1302 system is shown in Figure 4.



Figure 4: Innova 1302 Photoacoustic analyzer and sampling system.

Vehicles and Fuel

Table 1 shows the matrix of vehicles tested in this program. The original test plan called for ten vehicles to be tested however, one of the subject buses could not be tested due to engine malfunctions that could not be repaired in time for the tests to be accomplished. Engine control system problems were encountered during tests of the Ankaï CNG bus which caused the vehicle to shut down intermittently thus preventing any successful testing on that vehicle. The buses were tested at a weight representing 70% of the full passenger load. In the case of the ALLISON hybrid bus, testing was conducted at two different weights (46,438 lbs., 35,000 lbs.) but only the results from testing at 35,000 lbs. are presented in this report. The reported test weight of 35,000 lbs. represents only 50% passenger loading for the ALLISON. WVU test procedures for determining testing weight require that the vehicle's curb weight and passenger loading be combined to determine an appropriate inertial flywheel setting. The ALLISON hybrid being tested in this program had a chassis that included additional equipment designed for the U.S. market that would not be included on any Mexico City models. The 35,000 lb. test weight was determined by estimating the weight of the additional equipment (wheel chair lifts, etc.) and subtracting it from the curb weight prior to calculating testing weight. State of charge corrections were not required for this vehicle since the control system was load following and net battery state of charge change did not exceed 1% of total energy expended over the test cycles.

Table 1: Vehicles tested in this program

Ref. Name	Vehicle	Transmission	Test Weight (lbs)	Curb Weight (lbs)	Passenger Capacity	Odometer Reading (miles)	Engine	Emissions Controls
ALLISON	2004 ALLISON	Hybrid	35000	29000	113	36846	2002 Cummins ISB-230	CRT Particulate Filter & Catalyst Module
Ankai	2004 Ankai	5 Speed Auto	32150	22700	90	1055	2004 Cummins B5.9-230G	Fleetguard Catalytic Converter Model #3927832
BUSSCAR	2004 BUSSCAR	7 Speed Manual	33025	23425	91	693	2004 Cummins BG-230	Donaldson Catalytic Converter Model #M110857
FAW	2004 Allied Motors	4 Speed Auto	48025	33175	140	553	2004 Cummins CG280	Fleetguard Catalytic Converter Model #3928277
MB10	2004 Marcopolo	5 Speed Manual	26996	17800	87	13749	2004 Mercedes-Benz OM924LA	None
RTP1	2002 Marcopolo	5 Speed Auto	30070	21100	85	100142	2002 Mercedes-Benz OM906LA	Johnson-Matthey
RTP3	2002 Marcopolo	5 Speed Auto	30220	21250	85	89333	2002 Mercedes-Benz OM906LA	None
SCANIA15	2003 SCANIA	4 Speed Auto	50040	35400	139	19819	2003 SCANIA DSC9-260	Oxidation Catalyst
SCANIA18	2004 SCANIA	4 Speed Auto	57025	40075	161	998	2004 SCANIA DC9-300	None
VOLVO12	2004 VOLVO	5 Speed Auto	32050	22500	91	4282	2004 VOLVO VE D7C-300	None

Three different diesel fuels were used during the testing including a pump number 2 diesel designated D2, a low sulfur diesel fuel designated D2S50, and an ultra-low sulfur diesel fuel designated D2S15. In order to test on fuels different than the fuel in the tank when the vehicle was received, the fuel supply and return hoses were routed to fifty-five gallon drums external to the vehicle and a sufficient quantity of fuel was flushed through the vehicle fuel system and into a waste drum to prevent cross-contamination. Fuel properties of each of the diesel fuels are listed in Table 2. These properties were determined from samples analyzed by Saybolt LP (Carson, Ca).

Table 2 - Selected properties of diesel fuels used during testing

	D2S15	D2S50	D2	CNG
Heating Value (BTU/lb)	18576	18577	18302	22745
% Carbon (by weight)	86.97	86.5	86.31	74.04
Cetane Number	41.5	57.3	49.7	n/a
Density (g/ml)	0.8515	0.8454	0.8376	0.7317 kg/m ³
% Aromatics (by volume)	29.4	14.3	25.0	n/a
% Hydrogen Content (by weight)	12.93	13.83	13.44	23.70
Total Sulfur (ppm)	4.3	152.8	355.3	n/a

Analysis of the diesel fuels was not finished until after completion of the testing program when it was discovered that the 50 ppm sulfur diesel actually contained 152.8 ppm sulfur. WVU believes that the fuel may have been contaminated by the drums that the fuel was stored in at STE. The drums had previously contained lubricating oil which typically has high sulfur content. Fractional analysis was performed on the CNG fuel used by the natural gas vehicles and is presented in Table 3. The CNG fuel had a lower heating value of 1037 BTU/scf and a density of 20.7 grams per standard cubic foot.

Table 3 - Fractional analysis of natural gas fuel

Component	% Molar Fraction
Methane	92.633
Ethane	5.568
Propane	0.301
I-Butane	0.052
N-Butane	0.048
I-Pentane	0.021
N-Pentane	0.017
Nitrogen	0.634
Carbon Dioxide	0.629
Oxygen	0.022
Hexanes+	0.074

State of Charge Correction

The research agenda provided for state of charge (SOC) correction, if necessary, on the ALLISON hybrid bus. Guidance for SOC correction is given by SAE J2711 [5]. In the execution of this program, SOC was determined for the ALLISON bus through an amp-hr measurement reported by ALLISON engineers and battery system voltage of 600 volts. It was determined that the highest SOC correction was approximately 0.25% and, therefore, according to SAE J2711, no SOC correction was necessary.

Driving Schedule Development

Three driving cycles representative of transit bus operation in Mexico City were developed for this program. WVU instrumented several buses operating on different bus routes with global positioning system (GPS) data-loggers and gathered speed-time data from over 50 hours of operation. This data was then filtered to produce an array of microtrips which were then randomly combined to form test cycles. WVU selected three cycles, each with a duration of 1000 seconds, which best represented the speed-time characteristics of selected sections of the overall data set. Segment MX1 (Figure 5) represented low-speed operation, MX2 (Figure 6) represented medium-speed operation and MX3 (Figure 7) represented transit bus behavior when utilizing specific “bus only” traffic lanes, associated with Bus Rapid Transit (BRT). The three cycles were combined to form the Mexico City Schedule (MCS - Figure 8). More detailed information about development of the Mexico City Schedule can be found in a separate report to the Mexico City Secretariat of Environment titled “Development of the Mexico City Schedule for Characterization of Emissions and Performance from Transit Buses”.

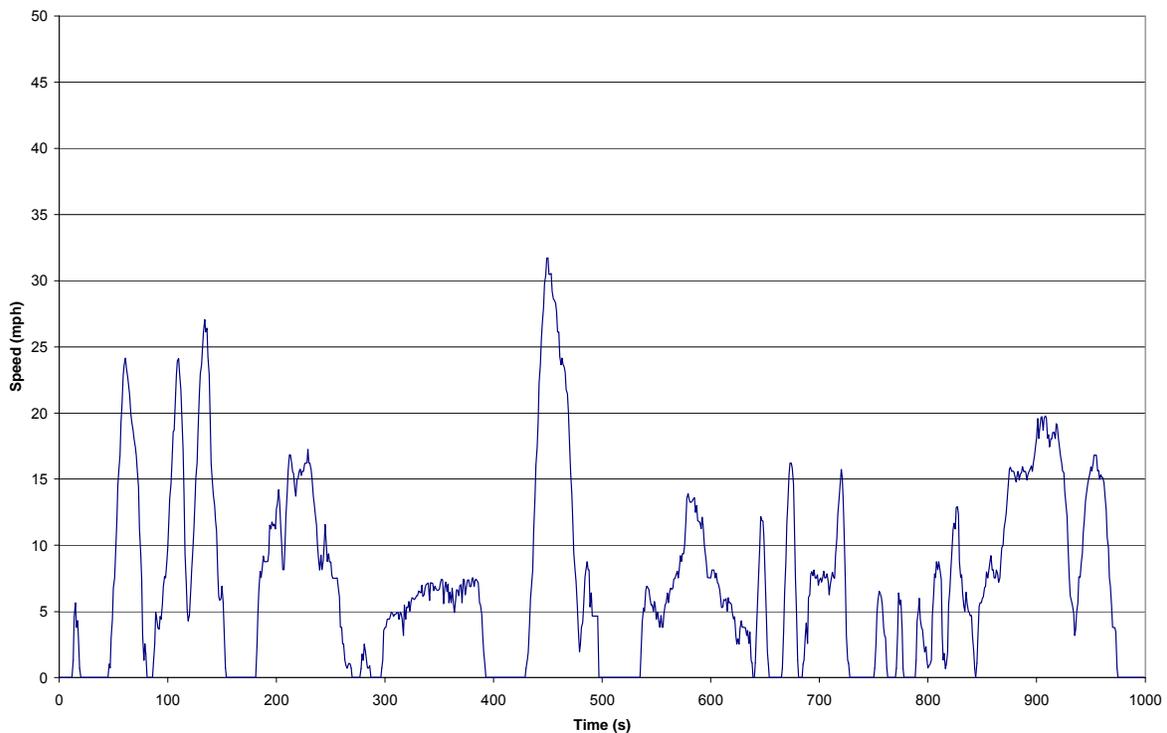


Figure 5: MX1 Segment of the Mexico City Schedule.

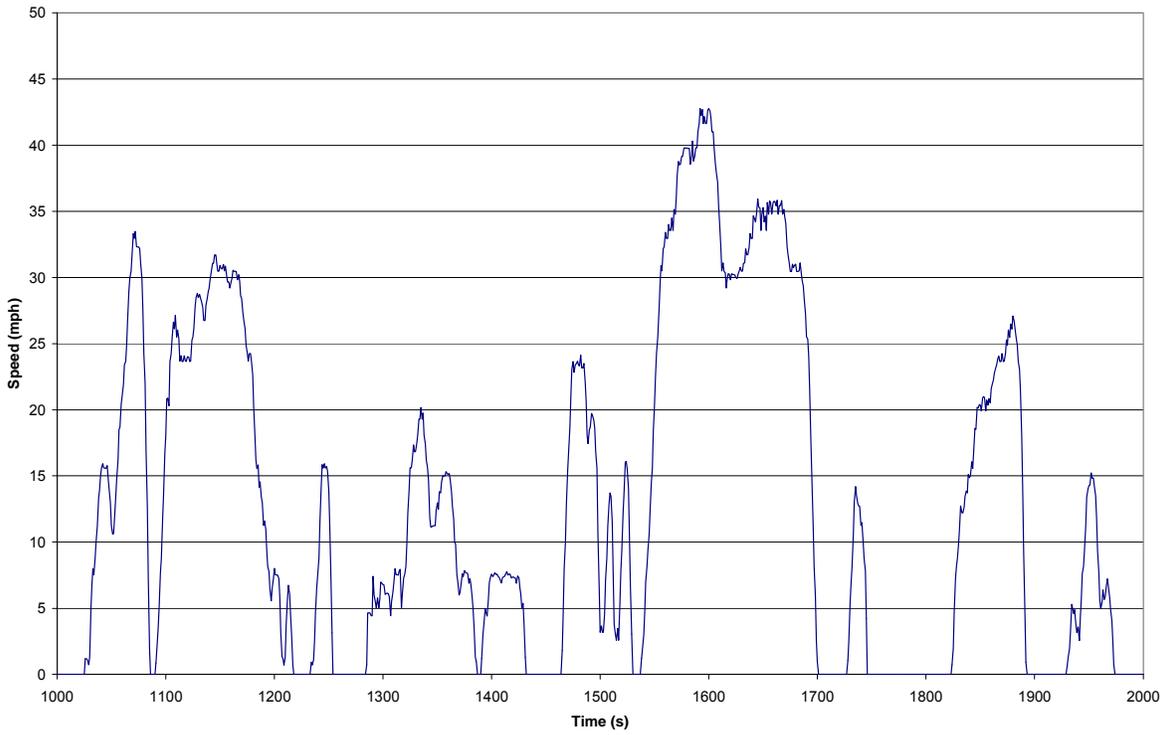


Figure 6: MX2 Segment of the Mexico City Schedule.

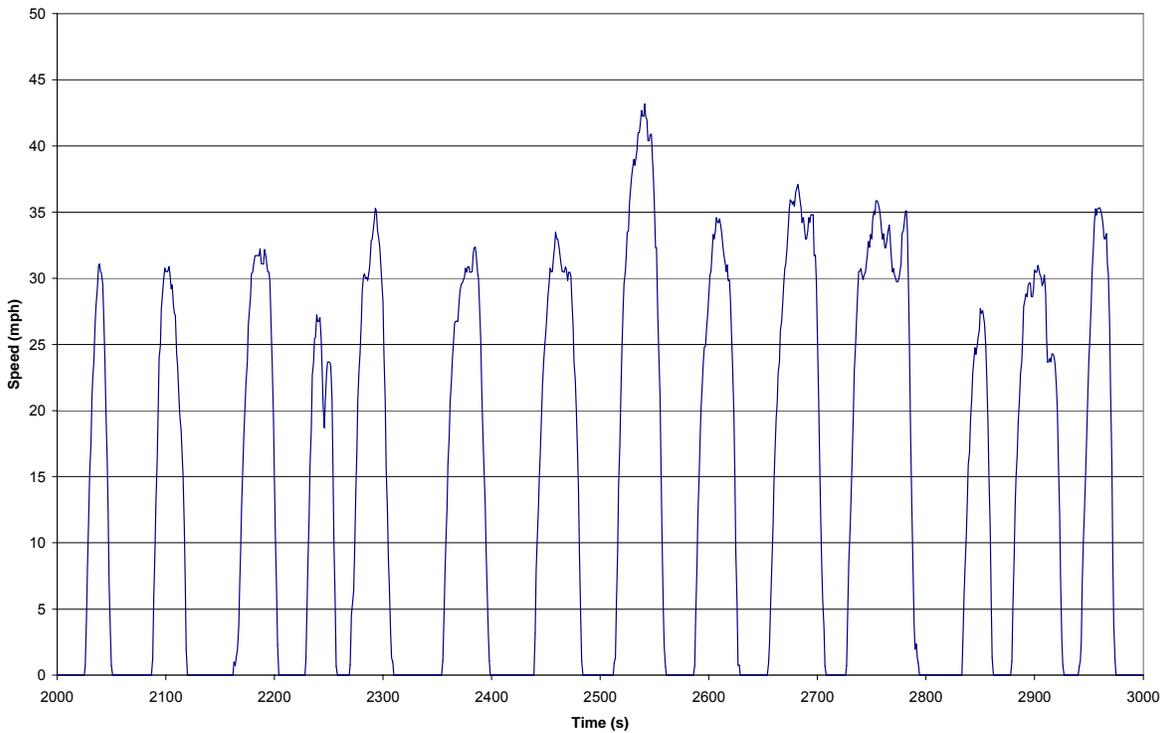


Figure 7: MX3 Segment of the Mexico City Schedule.

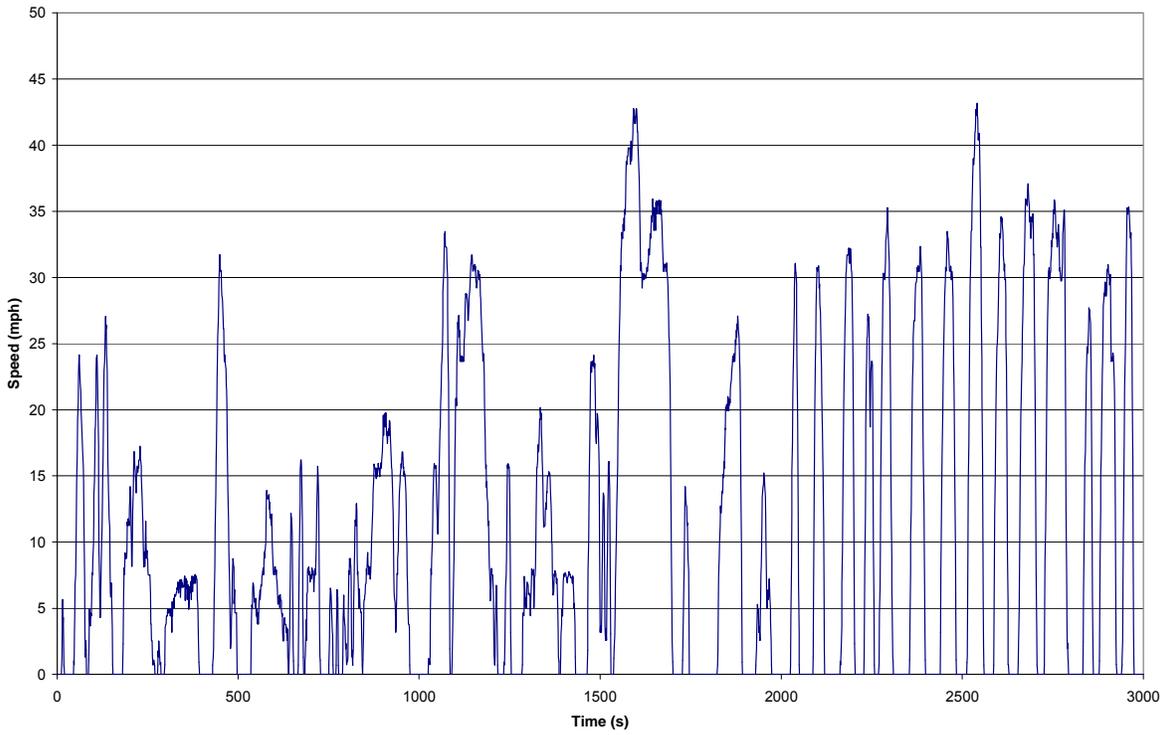


Figure 8: Mexico City Schedule (MCS)

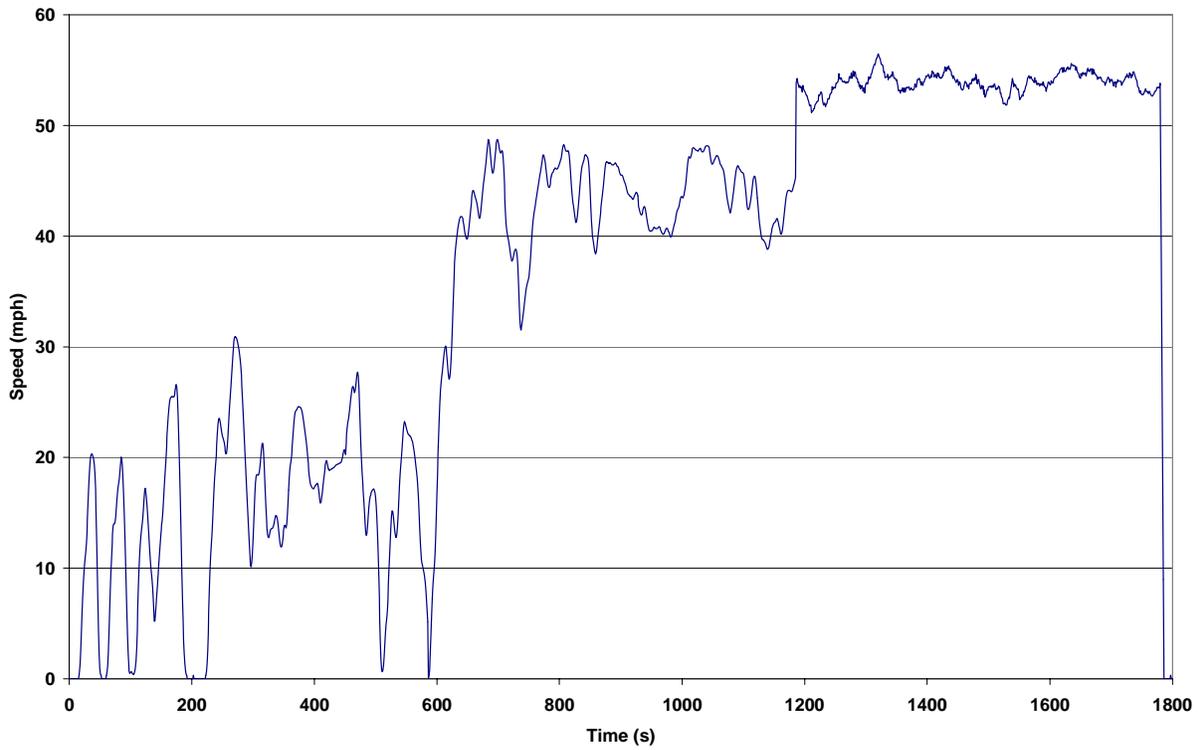


Figure 9: European Transient Cycle (ETC).

Each vehicle was also evaluated using the European Transient Cycle (ETC) which represents urban, rural and highway driving conditions and has a total duration of 1800 seconds (600 seconds for each segment). The urban driving segment has frequent starts and stops and idling and a maximum speed of 31 mph. The rural segment has a steep acceleration with an average speed of 44.6 mph while the highway segment has an average speed of 54.5 mph. The ETC is shown in Figure 9.

Coast Down Procedures

In order to mimic bus operation accurately, those factors that contribute to on-road losses such as wind resistance and tire rolling losses. A vehicle's motion is governed by the following road load equation.

$$\frac{1}{2}mV \frac{dV}{dt} = \frac{1}{2}\rho AC_D V^3 + \mu mgV + mgV \sin \theta$$

Equation 1- Road load equation

Where,

$\frac{1}{2}mV \frac{dV}{dt}$	vehicle inertial power
$\frac{1}{2}\rho AC_D V^3$	power loss to aerodynamic drag
μmgV	power loss to tire rolling resistance
$mgV \sin \theta$	power loss/gain from elevation changes
m = vehicle mass, V = velocity, ρ = air density, A = frontal area, C _D = drag coefficient, μ = tire rolling loss coefficient, g = acceleration due to gravity and θ = road grade	

Since the vehicle's drag coefficient and rolling resistance cannot be determined using static measurements, an empirical method was applied to determine their values. Each vehicle in the test program was driven up to approximately 20 m/s on a near-level road and allowed to coast down to a near stop while data was acquired using global positioning system data loggers. To help eliminate any remaining elevation effects the vehicle was coasted down in both directions. Figure 10 shows actual coast down data for the SCANIA18 bus with the derived coast down curve along the same stretch of roadway.

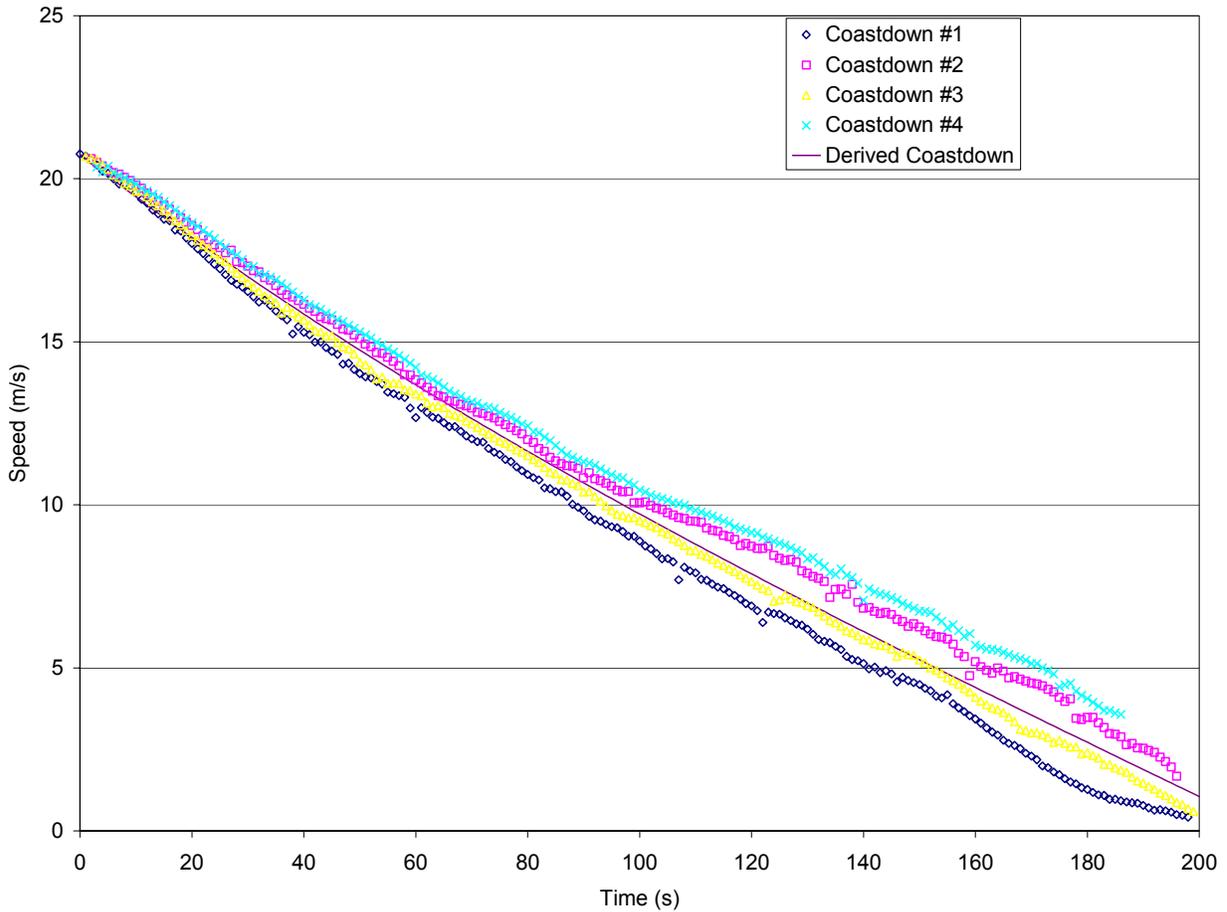


Figure 10: On-road coast down data from the SCANIA18 bus.

The resulting speed-time traces were then manipulated to obtain a plot of acceleration (dV/dt) versus velocity squared (V^2). Equation 1 can be re-written in the following form to determine vehicle acceleration.

$$\frac{dV}{dt} = \frac{\rho A C_D}{2m} V^2 + \mu g$$

Equation 2 - Zero slope road load equation for acceleration

where the terms $\frac{\rho A C_D}{2m}$ and μg are constants C1 and C2.

By performing a least squares error linear regression on the acceleration (dV/dt) versus velocity squared (V^2) data the coefficients C1 and C2 were determined and were used to simulate losses on the dynamometer.

Figure 11 shows actual dV/dt vs. V^2 data for the SCANIA18 bus over four coast downs (2 in each direction). Scatter is due to the high time resolution of the sampling relative to the ability of the global positioning sensor to determine accurate velocity. A value for C_D of 0.686 and μ of 0.0084 were obtained by solving Equation 2 using the empirically derived constants C1 (-0.000119) and C2 (-0.082455). Typical values of C_D and μ for a heavy duty vehicle are 0.79 and 0.009 respectively.

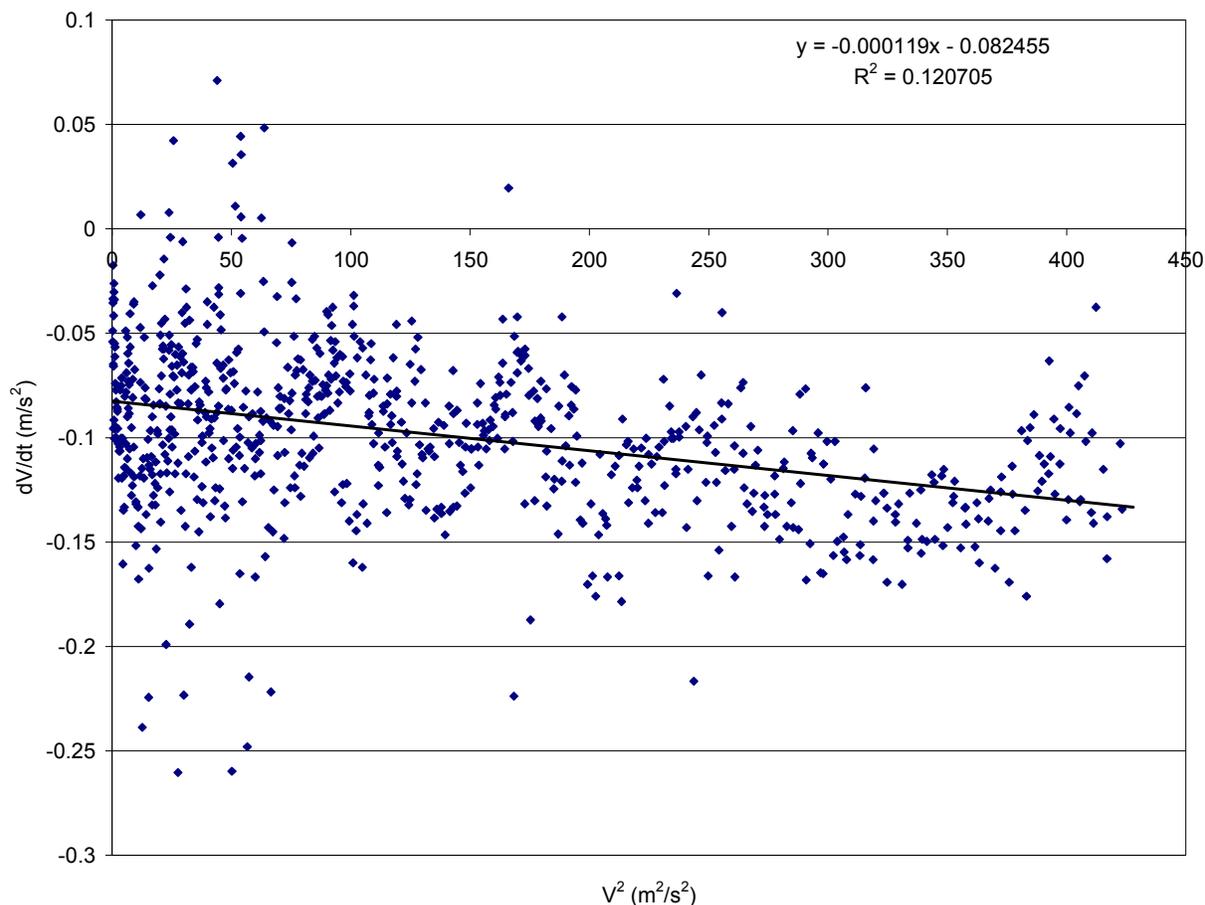


Figure 11: Coast down deceleration data for the SCANIA18 bus (40,075 lb curb weight)

Testing Procedures

Background tests are performed both at the beginning and end of each test day. During these tests, the laboratory sampling system was operated in the same fashion as it would be during a normal test but the vehicle was not operated. This allowed the laboratory to determine background particulate levels for use in correcting particulate samples from the vehicles. For this program, the background tests were 1800 seconds in duration.

Once the initial background sample has been taken, the vehicle is exercised at a steady state speed to warm the dynamometer gear train and allow the flywheel differentials to reach 100°F. After the dynamometer warm-up, emissions were measured while the vehicle was exercised through the MX1 portion of the MCS which allowed technicians to ensure that laboratory instrumentation was operating properly (While this data was recorded, it was not used in comparisons in this report). The vehicle and laboratory were then allowed to soak for 20 minutes prior to initiating reportable testing. After each test, a 20-minute soak period was observed. If the specified soak period was exceeded, another warm up / soak sequence was initiated before performing the next reportable test.

Gaseous samples from the dilution tunnel were continuously analyzed and recorded during the testing process. Additionally, an integrated gas sample was collected in a Tedlar bag for post test analysis. To obtain emissions results from the test, Equation 3 was applied using

$$E_{mass} = \frac{V_{mix} \times \rho_E \times \left[E_{conc} - E_{background} \left[1 - \frac{1}{DF} \right] \right]}{10^6}$$

Equation 3 - Mass emissions calculation

where

E_{mass}	Total mass in grams of emission
V_{mix}	Total volume of dilute exhaust throughout the test
ρ_E	Density of the emission of interest
E_{conc}	Concentration in parts per million (ppm) of the emission in the dilute exhaust stream
$E_{background}$	Concentration in ppm of the emission in the dilution air (background)
DF	Dilution factor

In the case of oxides of nitrogen, the final result is multiplied by a humidity correction factor (KH). The results of these calculations were then divided by the distance traveled to obtain emissions results in grams per mile (g/mile). To present continuous emissions on a grams per second basis as they are in Appendix C, Equation 3 is used to convert each instantaneous concentration from a parts per million concentration to a mass and that mass is integrated over that time period (in this case, one second) to get a grams per second value.

Quality Assurance

As part of the Quality Assurance Program, the WVU researchers performed redundant measurements of NO_x, PM and CO₂. In the case of NO_x, two separate analyzers were used. Figure 12 shows that there was outstanding agreement between these two analyzers. PM was measured using the research grade filter method, as well as using a Tapered Element Oscillating Microbalance (TEOM) for a approximately half of the runs.

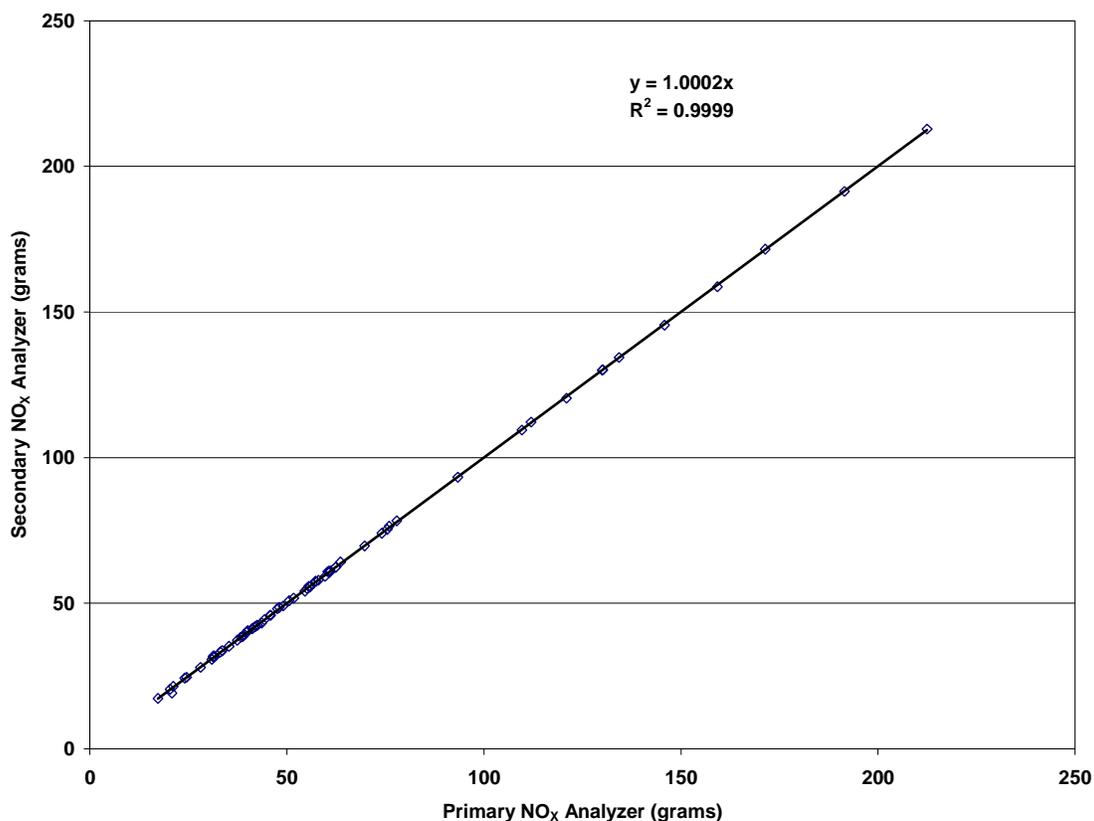


Figure 12: Comparison of Oxides of Nitrogen measurements from parallel analyzers.

TEOM data have been compared with PM filter data in several previous studies. An Australian study found the TEOM to report 16% less mass than a PM filter, on average [5]. Gilbert et al. [7] examined this relationship as the sampling temperature and flow rate of the TEOM were adjusted. Kelley and Morgan [8] found that the TEOM reported 20 to 25% less mass than the filter. Other workers, including Moosmuller et al. [9], have confirmed that the TEOM measures less mass than a filter. Figure 13 shows that the TEOM and filter methods in this survey correlated well, with the TEOM yielded about 76% of the filter mass which compares well to results reported by Kelly and Morgan.

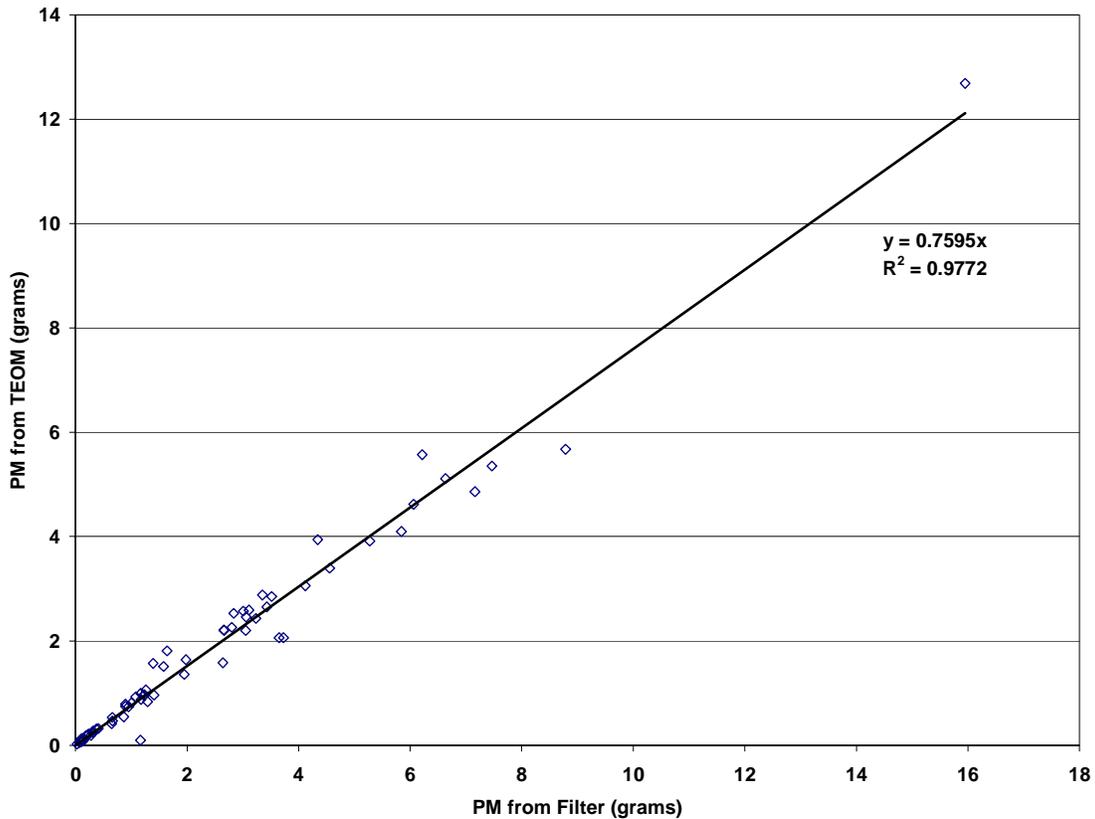


Figure 13: Comparison of particulate matter emissions between filter media and a TEOM device.

The primary CO₂ measurement method by a research grade infrared analyzer, and could be found both by integration of data recorded continuously during the test by the analysis of batch samples collected in bags. The Innova photoacoustic analyzer used to measure N₂O was also used on a substantial fraction of the runs to measure CO₂. Figure 14 compares photoacoustic and integrated continuous infrared CO₂, and confirms good agreement for the measurements. Good agreements on CO₂ results between the Innova and laboratory gives a measure of confidence in the N₂O data measured using the Innova 1302.

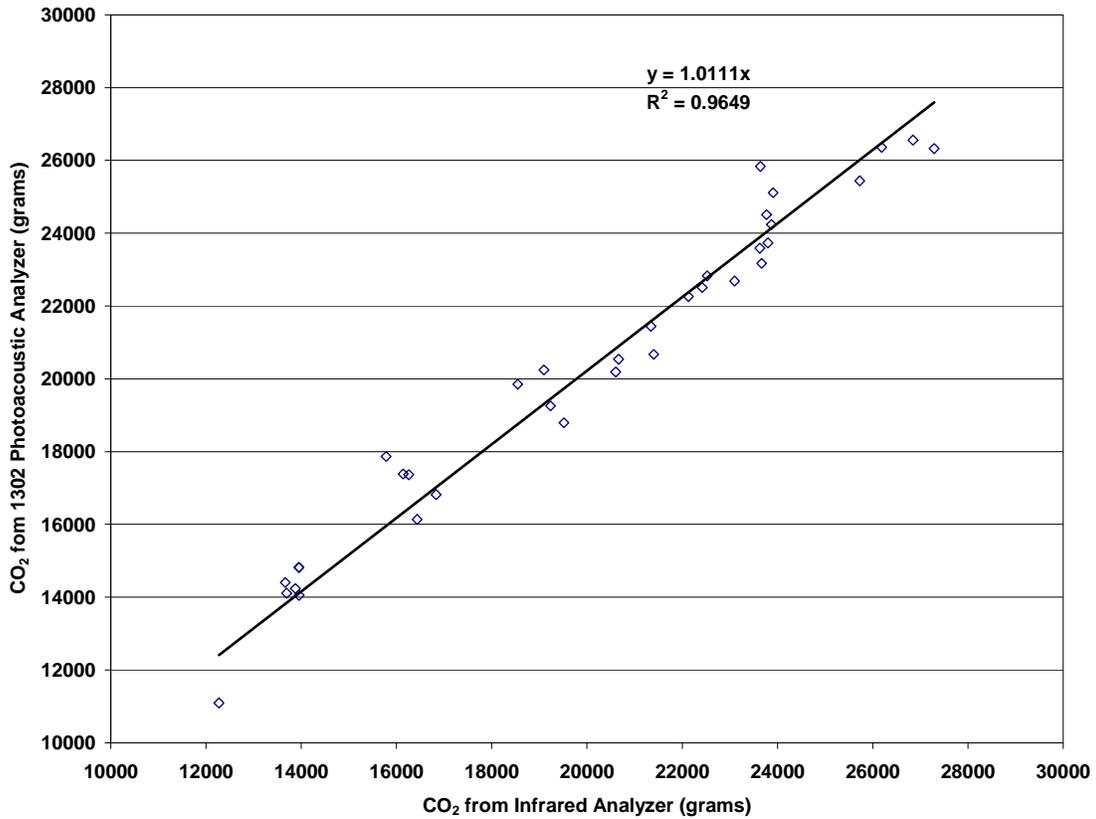


Figure 14: Comparison of carbon dioxide measurements between photoacoustic and infrared analyzers.

Additional confidence checks for the WVU measurements are described in the report titled "Correlation between West Virginia University and Engine, Fuel, and Emissions Engineering, Inc.'s RAVEM Emissions Measurements from Transit Buses."

Results and Discussion

Table 4 presents a summary of the tests performed during this program while Table 5 lists the dates, times, vehicles, weights, test cycles and fuels for those tests. Vehicle and fuel information can be cross referenced to Table 1 and Table 2 presented earlier in the report. Full emissions and fuel economy data are contained in Appendix A. It is recognized that the statistical significance of the results and conclusion could have been strengthened had more repeat tests been conducted; however, funding limitations restricted the number of repeat tests that could be performed.

In reporting emissions data, integrated continuous data is normally used with the integrated bag data being used as a check. In the case of CO, integrated bag data is used for the final CO result for a combination of factors. CO "spikes" during transient operation but a majority of each test, measurement levels are less than 10% that of the spikes. When operating in the lowest 5% of their range, CO analyzers do not perform as accurately. WVU employs two CO analyzers operating in different ranges. The higher ranged analyzer is able to measure all of the transient spikes while the lower range CO analyzer, which goes off scale during continuous measurement, is able to more accurately measure the integrated bag data.

Table 4 - Summary of tests performed during this program

Cycle	Fuel	ALLISON	BUSSCAR	FAW	MB10	RTP1	RTP3	SCANIA15	SCANIA18	VOLVO12	Total
ETC	CNG		2								2
	D2S15	2			2	2	4	2	1	2	15
ETC Total		2	2		2	2	4	2	1	2	17
MX1	CNG		4	3							7
	D2				2		2	3		5	12
	D2S15	3			3	3	4	3	3	3	22
	D2S50				3	2	2		3		10
MX1 Total		3	4	3	8	5	8	6	6	8	51
MX2	CNG		2	2							4
	D2				2		2	2		4	10
	D2S15	2			2	1	1	2	3	2	13
	D2S50				2	2	2		2		8
MX2 Total		2	2	2	6	3	5	4	5	6	35
MX3	CNG		2	2							4
	D2				2		2	2		3	9
	D2S15	2			2	1	2	2	2	2	13
	D2S50				2	2	2		2		8
MX3 Total		2	2	2	6	3	6	4	4	5	34
Grand Total		9	10	7	22	13	23	16	16	21	137

Table 5 - Vehicle tests performed

Date	Time	Vehicle	Test ID	Weight	Cycle	Fuel
10/30	4:30 PM	VOLVO12	4310-1	32050	MX1	D2S15
10/30	5:09 PM	VOLVO12	4311-1	32050	ETC	D2S15
10/30	5:58 PM	VOLVO12	4312-1	32050	MX1	D2S15
10/30	5:58 PM	VOLVO12	4312-2	32050	MX2	D2S15
10/30	5:58 PM	VOLVO12	4312-3	32050	MX3	D2S15
10/30	7:07 PM	VOLVO12	4313-1	32050	ETC	D2S15
10/30	9:10 PM	VOLVO12	4315-1	32050	MX1	D2S15
10/30	9:10 PM	VOLVO12	4315-2	32050	MX2	D2S15
10/30	9:10 PM	VOLVO12	4315-3	32050	MX3	D2S15
10/31	1:07 PM	VOLVO12	4318-1	32050	MX1	D2
10/31	1:45 PM	VOLVO12	4319-1	32050	MX1	D2
10/31	1:45 PM	VOLVO12	4319-2	32050	MX2	D2
10/31	2:56 PM	VOLVO12	4320-1	32050	MX1	D2
10/31	2:56 PM	VOLVO12	4320-2	32050	MX2	D2
10/31	2:56 PM	VOLVO12	4320-3	32050	MX3	D2
10/31	4:10 PM	VOLVO12	4321-1	32050	MX1	D2
10/31	4:10 PM	VOLVO12	4321-2	32050	MX2	D2
10/31	4:10 PM	VOLVO12	4321-3	32050	MX3	D2
10/31	5:20 PM	VOLVO12	4322-1	32050	MX1	D2
10/31	5:20 PM	VOLVO12	4322-2	32050	MX2	D2
10/31	5:20 PM	VOLVO12	4322-3	32050	MX3	D2
11/2	7:10 AM	SCANIA15	4328-1	50040	MX1	D2S15
11/2	7:47 AM	SCANIA15	4329-1	50040	ETC	D2S15
11/2	8:37 AM	SCANIA15	4330-1	50040	MX1	D2S15
11/2	8:37 AM	SCANIA15	4330-2	50040	MX2	D2S15
11/2	8:37 AM	SCANIA15	4330-3	50040	MX3	D2S15
11/2	9:47 AM	SCANIA15	4331-1	50040	ETC	D2S15
11/2	10:37 AM	SCANIA15	4332-1	50040	MX1	D2S15
11/2	10:37 AM	SCANIA15	4332-2	50040	MX2	D2S15
11/2	10:37 AM	SCANIA15	4332-3	50040	MX3	D2S15
11/2	12:18 PM	SCANIA15	4333-1	50040	MX1	D2
11/2	12:55 PM	SCANIA15	4334-1	50040	MX1	D2
11/2	12:55 PM	SCANIA15	4334-2	50040	MX2	D2
11/2	12:55 PM	SCANIA15	4334-3	50040	MX3	D2
11/2	2:05 PM	SCANIA15	4335-1	50040	MX1	D2
11/2	2:05 PM	SCANIA15	4335-2	50040	MX2	D2
11/2	2:05 PM	SCANIA15	4335-3	50040	MX3	D2

Date	Time	Vehicle	Test ID	Weight	Cycle	Fuel
11/5	4:37 PM	RTP3	4352-1	30220	MX1	D2S15
11/5	5:14 PM	RTP3	4353-1	30220	MX1	D2S15
11/5	5:14 PM	RTP3	4353-2	30220	MX2	D2S15
11/5	5:14 PM	RTP3	4353-3	30220	MX3	D2S15
11/5	6:24 PM	RTP3	4354-1	30220	ETC	D2S15
11/5	7:14 PM	RTP3	4355-1	30220	MX1	D2S15
11/5	7:14 PM	RTP3	4355-3	30220	MX3	D2S15
11/5	8:24 PM	RTP3	4356-1	30220	ETC	D2S15
11/6	4:51 PM	RTP3	4359-1	30220	MX1	D2S15
11/6	5:27 PM	RTP3	4360-1	30220	ETC	D2S15
11/6	6:18 PM	RTP3	4361-1	30220	ETC	D2S15
11/6	7:08 PM	RTP3	4362-1	30220	MX1	D2S50
11/6	7:08 PM	RTP3	4362-2	30220	MX2	D2S50
11/6	7:08 PM	RTP3	4362-3	30220	MX3	D2S50
11/6	8:18 PM	RTP3	4363-1	30220	MX1	D2S50
11/6	8:18 PM	RTP3	4363-2	30220	MX2	D2S50
11/6	8:18 PM	RTP3	4363-3	30220	MX3	D2S50
11/6	9:28 PM	RTP3	4364-1	30220	MX1	D2
11/6	9:28 PM	RTP3	4364-2	30220	MX2	D2
11/6	9:28 PM	RTP3	4364-3	30220	MX3	D2
11/6	10:38 PM	RTP3	4365-1	30220	MX1	D2
11/6	10:38 PM	RTP3	4365-2	30220	MX2	D2
11/6	10:38 PM	RTP3	4365-3	30220	MX3	D2
11/7	5:01 PM	MB10	4368-1	26996	MX1	D2S15
11/7	6:14 PM	MB10	4369-1	26996	MX1	D2S15
11/7	6:14 PM	MB10	4369-2	26996	MX2	D2S15
11/7	6:14 PM	MB10	4369-3	26996	MX3	D2S15
11/7	7:25 PM	MB10	4370-1	26996	ETC	D2S15
11/7	8:15 PM	MB10	4371-1	26996	MX1	D2S15
11/7	8:15 PM	MB10	4371-2	26996	MX2	D2S15
11/7	8:15 PM	MB10	4371-3	26996	MX3	D2S15
11/7	9:25 PM	MB10	4372-1	26996	ETC	D2S15
11/8	11:51 AM	MB10	4375-1	26996	MX1	D2S50
11/8	12:28 PM	MB10	4376-1	26996	MX1	D2S50
11/8	12:28 PM	MB10	4376-2	26996	MX2	D2S50
11/8	12:28 PM	MB10	4376-3	26996	MX3	D2S50
11/8	1:38 PM	MB10	4377-1	26995.5	MX1	D2S50
11/8	1:38 PM	MB10	4377-2	26995.5	MX2	D2S50
11/8	1:38 PM	MB10	4377-3	26995.5	MX3	D2S50

Date	Time	Vehicle	Test ID	Weight	Cycle	Fuel
11/8	2:48 PM	MB10	4378-1	26995.5	MX1	D2
11/8	2:48 PM	MB10	4378-2	26995.5	MX2	D2
11/8	2:48 PM	MB10	4378-3	26995.5	MX3	D2
11/8	3:58 PM	MB10	4379-1	26995.5	MX1	D2
11/8	3:58 PM	MB10	4379-2	26995.5	MX2	D2
11/8	3:58 PM	MB10	4379-3	26995.5	MX3	D2
11/9	12:14 PM	BUSSCAR	4382-1	33025	MX1	CNG
11/9	12:50 PM	BUSSCAR	4383-1	33025	MX1	CNG
11/9	12:50 PM	BUSSCAR	4383-2	33025	MX2	CNG
11/9	12:50 PM	BUSSCAR	4383-3	33025	MX3	CNG
11/9	4:00 PM	BUSSCAR	4385-1	33025	MX1	CNG
11/9	4:37 PM	BUSSCAR	4386-1	33025	ETC	CNG
11/9	5:27 PM	BUSSCAR	4387-1	33025	MX1	CNG
11/9	5:27 PM	BUSSCAR	4387-2	33025	MX2	CNG
11/9	5:27 PM	BUSSCAR	4387-3	33025	MX3	CNG
11/9	6:38 PM	BUSSCAR	4388-1	33025	ETC	CNG
11/10	3:18 PM	FAW	4391-1	48025	MX1	CNG
11/10	4:45 PM	FAW	4393-1	48025	MX1	CNG
11/10	4:45 PM	FAW	4393-2	48025	MX2	CNG
11/10	4:45 PM	FAW	4393-3	48025	MX3	CNG
11/10	5:55 PM	FAW	4394-1	48025	MX1	CNG
11/10	5:55 PM	FAW	4394-2	48025	MX2	CNG
11/10	5:55 PM	FAW	4394-3	48025	MX3	CNG
11/11	5:18 PM	ALLISON	4398-1	35000	MX1	D2S15
11/11	6:03 PM	ALLISON	4399-1	35000	ETC	D2S15
11/11	6:53 PM	ALLISON	4400-1	35000	MX1	D2S15
11/11	6:53 PM	ALLISON	4400-2	35000	MX2	D2S15
11/11	6:53 PM	ALLISON	4400-3	35000	MX3	D2S15
11/11	8:03 PM	ALLISON	4401-1	35000	ETC	D2S15
11/11	8:54 PM	ALLISON	4402-1	35000	MX1	D2S15
11/11	8:54 PM	ALLISON	4402-2	35000	MX2	D2S15
11/11	8:54 PM	ALLISON	4402-3	35000	MX3	D2S15
11/12	3:24 PM	RTP1	4405-1	30070	MX1	D2S15
11/12	4:14 PM	RTP1	4406-1	30070	ETC	D2S15
11/12	6:18 PM	RTP1	4407-1	30070	MX1	D2S15
11/12	6:55 PM	RTP1	4408-1	30070	MX1	D2S15
11/12	6:55 PM	RTP1	4408-2	30070	MX2	D2S15
11/12	6:55 PM	RTP1	4408-3	30070	MX3	D2S15
11/12	8:05 PM	RTP1	4409-1	30070	ETC	D2S15

Date	Time	Vehicle	Test ID	Weight	Cycle	Fuel
11/12	8:55 PM	RTP1	4410-1	30070	MX1	D2S50
11/12	8:55 PM	RTP1	4410-2	30070	MX2	D2S50
11/12	8:55 PM	RTP1	4410-3	30070	MX3	D2S50
11/12	10:05 PM	RTP1	4411-1	30070	MX1	D2S50
11/12	10:05 PM	RTP1	4411-2	30070	MX2	D2S50
11/12	10:05 PM	RTP1	4411-3	30070	MX3	D2S50
11/12	11:18 PM	RTP1	4412-1	30070	CBD	D2S50
11/13	12:39 PM	SCANIA18	4415-1	57025	MX1	D2S15
11/13	3:17 PM	SCANIA18	4416-1	57025	MX2	D2S15
11/13	3:53 PM	SCANIA18	4417-1	57025	ETC	D2S15
11/13	4:47 PM	SCANIA18	4418-1	57025	MX1	D2S15
11/13	4:47 PM	SCANIA18	4418-2	57025	MX2	D2S15
11/13	4:47 PM	SCANIA18	4418-3	57025	MX3	D2S15
11/13	5:57 PM	SCANIA18	4419-1	57025	MX1	D2S15
11/13	5:57 PM	SCANIA18	4419-2	57025	MX2	D2S15
11/13	5:57 PM	SCANIA18	4419-3	57025	MX3	D2S15
11/13	7:32 PM	SCANIA18	4420-1	57025	MX1	D2S50
11/13	8:09 PM	SCANIA18	4421-1	57025	MX1	D2S50
11/13	8:09 PM	SCANIA18	4421-2	57025	MX2	D2S50
11/13	8:09 PM	SCANIA18	4421-3	57025	MX3	D2S50
11/13	9:19 PM	SCANIA18	4422-1	57025	MX1	D2S50
11/13	9:19 PM	SCANIA18	4422-2	57025	MX2	D2S50
11/13	9:19 PM	SCANIA18	4422-3	57025	MX3	D2S50

Fuel Economy

Fuel economy was determined by examining the amount of carbon in the exhaust. During combustion, a majority of the carbon from the fuel is converted to carbon dioxide and carbon monoxide. The total mass of fuel used during the test is calculated using the equation

$$M_{fuel} = \frac{\left[\frac{12.011}{12.011 + \alpha(1.008)} \right] HC_{mass} + 0.429CO_{mass} + 0.273CO_{2, mass}}{\frac{12.011}{12.011 + \alpha(1.008)}}$$

Equation 4 - Fuel consumption calculation

where α is the atomic ratio of hydrogen to carbon as determined by fuel analysis. In the case of natural gas fueled vehicles, a diesel equivalent "gallon" of fuel is determined by comparing the lower heating value of the natural gas (1037.7 BTU/scf) to that of the 50 ppm diesel fuel (18577 BTU/lb). Based on these properties, 124.0 scf of CNG had the same energy content as one gallon of the 50 ppm diesel fuel.

The fuel economy, calculated from a carbon balance as described above, is shown for all buses measured over the combined MCS Figure 15. Fuel economy of the natural gas buses is reported on a diesel energy equivalent basis to allow comparison with the diesel-fueled buses. When multiple repeat test runs were conducted, the bars in Figure 15 represent the average result, and the error bars show the maximum and minimum individual test results. Considering the conventional-drive diesel buses tested over the MCS, the MB10 bus achieved the highest fuel economy followed by RTP1 and RTP3, the VOLVO12 and finally the SCANIA15. The ALLISON diesel-hybrid bus demonstrated fuel economy comparable to RTP1 and RTP3. The BUSSCAR CNG bus was comparable to the SCANIA buses and the FAW CNG bus demonstrated the lowest fuel economy on a miles-per-equivalent-diesel-gallon basis. Figure 16 and Figure 17 show the fuel economy over the MCS as a function of vehicle test weight and vehicle power-to-test-weight ratio. Only the 15 ppm sulfur fuel results are shown. There is a strong relationship between test weight and fuel economy as would be expected. There is also an obvious relationship between power-to-weight ratio and fuel economy although the VOLVO12 bus which had the highest power-to-weight ratio would have been expected to get higher fuel economy.

Fuel economy measured over the ETC is shown in Figure 18. Diesel-equivalent fuel economy is presented for the BUSSCAR CNG bus. The FAW bus was not tested over the ETC as it could not attain the high speed operation required by that test cycle. The ETC showed a somewhat different picture for fuel economy. As expected the economy was far higher over the ETC than for any of the MCS modes or the combined MCS (Figure 15) due to the much less transient nature of the ETC compared to the MCS. Over the ETC, the RTP1 bus had the highest fuel economy, followed by the VOLVO12 and ALLISON hybrid, which had similar fuel economy. The MB10 and RTP3 then followed. All of these buses had fuel economies that were close in value. Over the ETC, the BUSSCAR had higher fuel economy than either of the SCANIA buses.

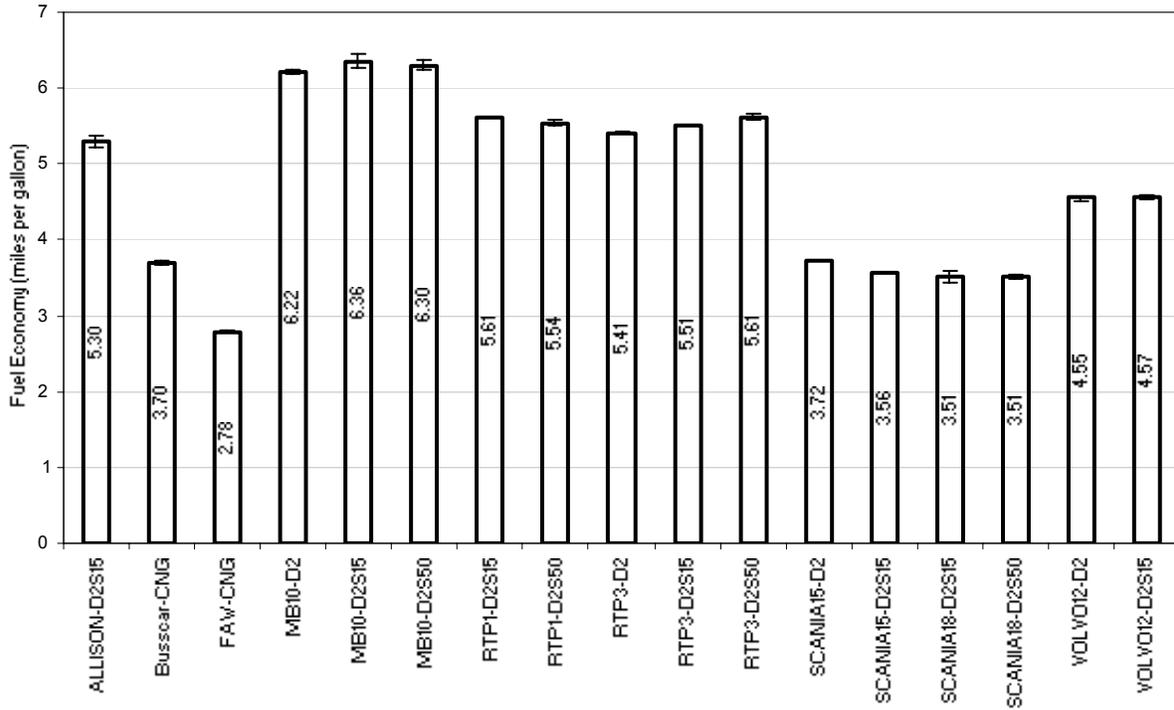


Figure 15: Fuel economy measured over the combined modes of the MCS.

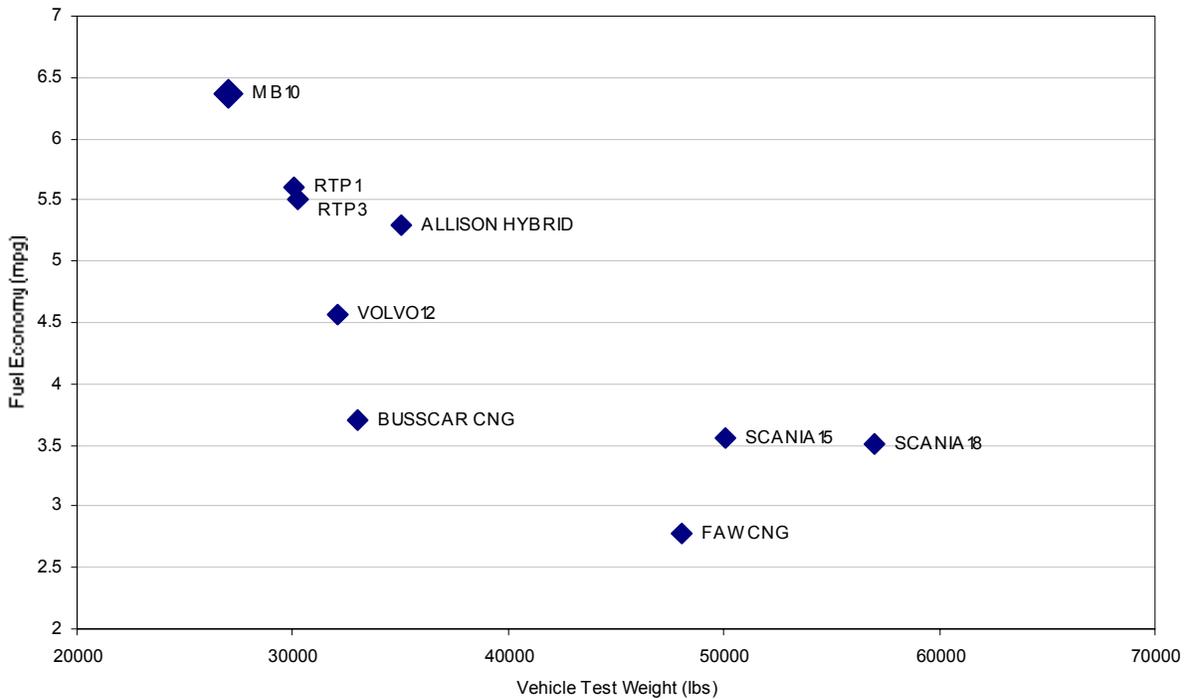


Figure 16: Fuel Economy over the MCS as a function of test weight.

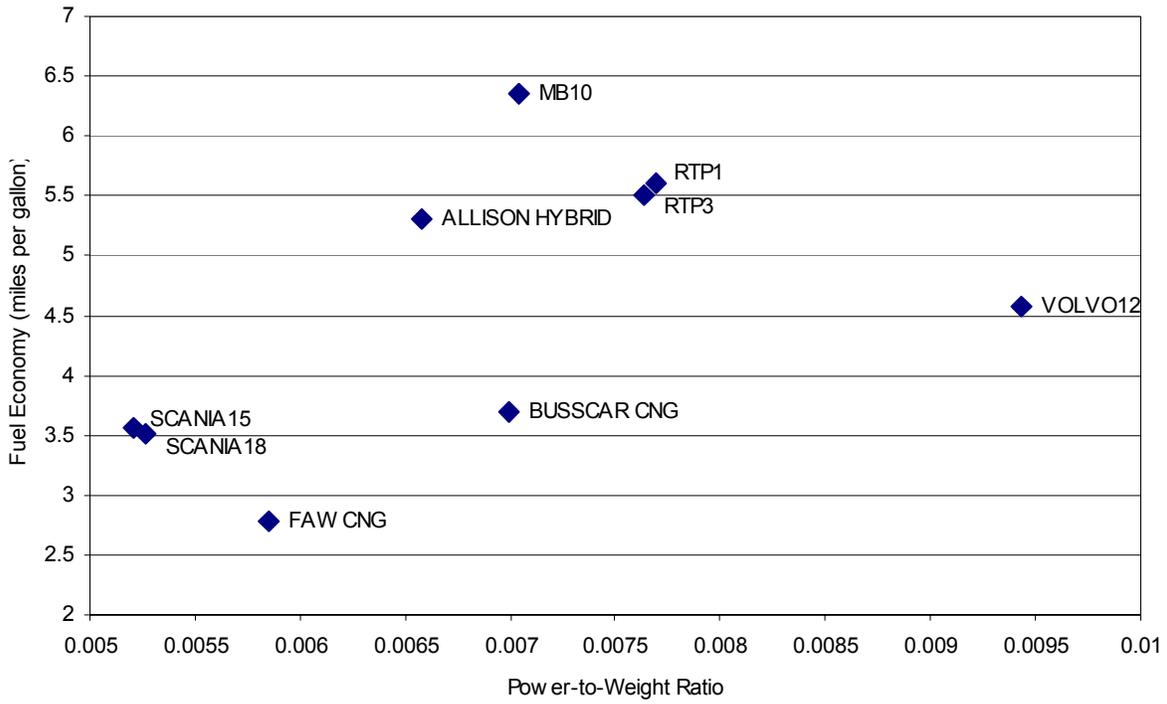


Figure 17: Fuel Economy over the MCS as a function of power-to-weight ratio.

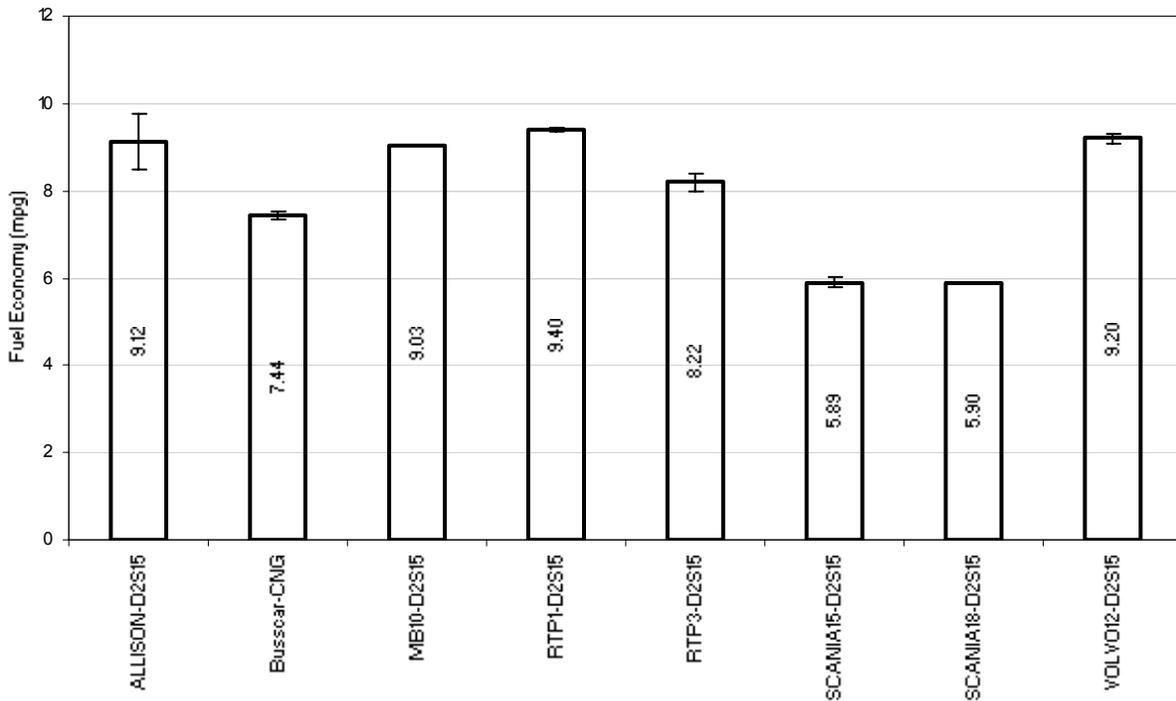


Figure 18: Fuel economy measured over the ETC.

The buses were tested at different weights (representative of real use) and had different passenger loadings associated with those weights. It is also useful to consider fuel economy in units of passenger-miles/gallon shown in Figure 19 for the MCS and Figure 20 for the ETC. On a passenger-miles per gallon basis the ALLISON hybrid bus has the highest fuel economy followed by the SCANIA. Even though the SCANIA buses had comparatively poor fuel economy compared to other buses they may prove to be more economical to operate when passenger capacity is considered. The MB10 bus also exhibited good fuel economy on a passenger-miles per gallon basis. Considering the diesel-fueled buses, the VOLVO12 bus had the lowest fuel economy when passenger capacity is considered and were comparable to the CNG buses. Over the ETC, the ALLISON hybrid bus also exhibited the highest per passenger fuel economy followed by the SCANIA18 bus. The MB10, RTP1, RTP3 and VOLVO12 buses demonstrated average per passenger fuel economy over the ETC and the BUSSCAR CNG bus exhibited the lowest per passenger fuel economy.

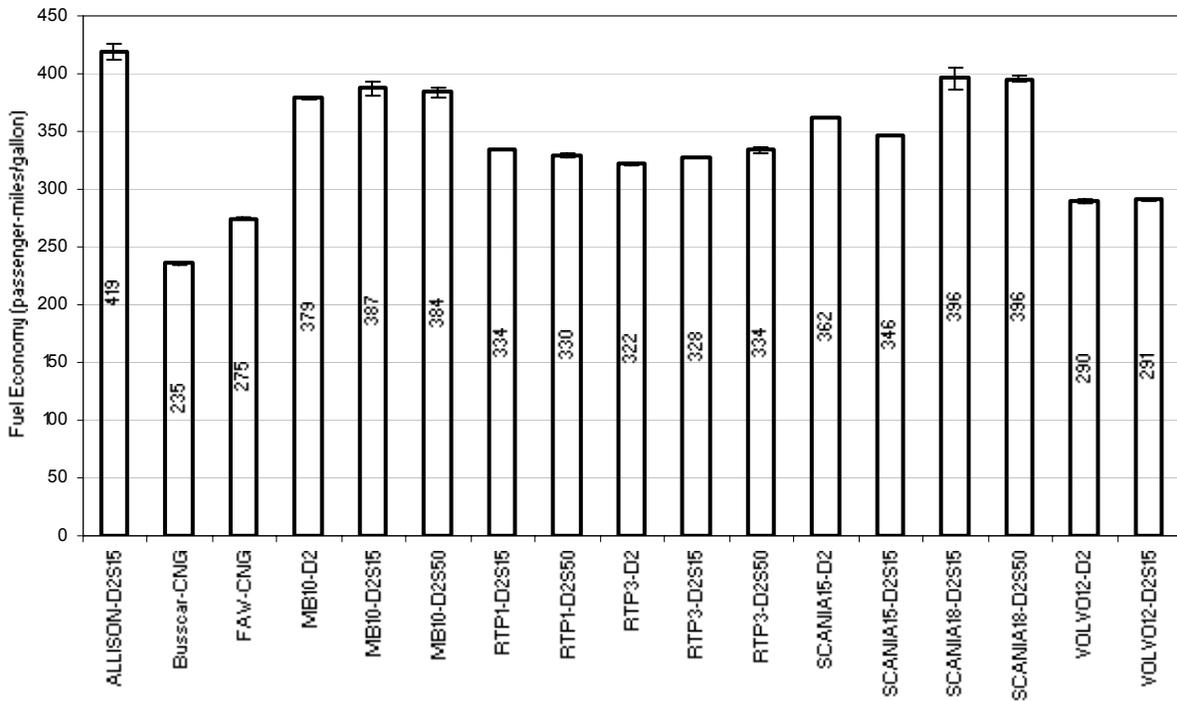


Figure 19: Fuel economy measured over the MCS on a passenger-mile per gallon basis.

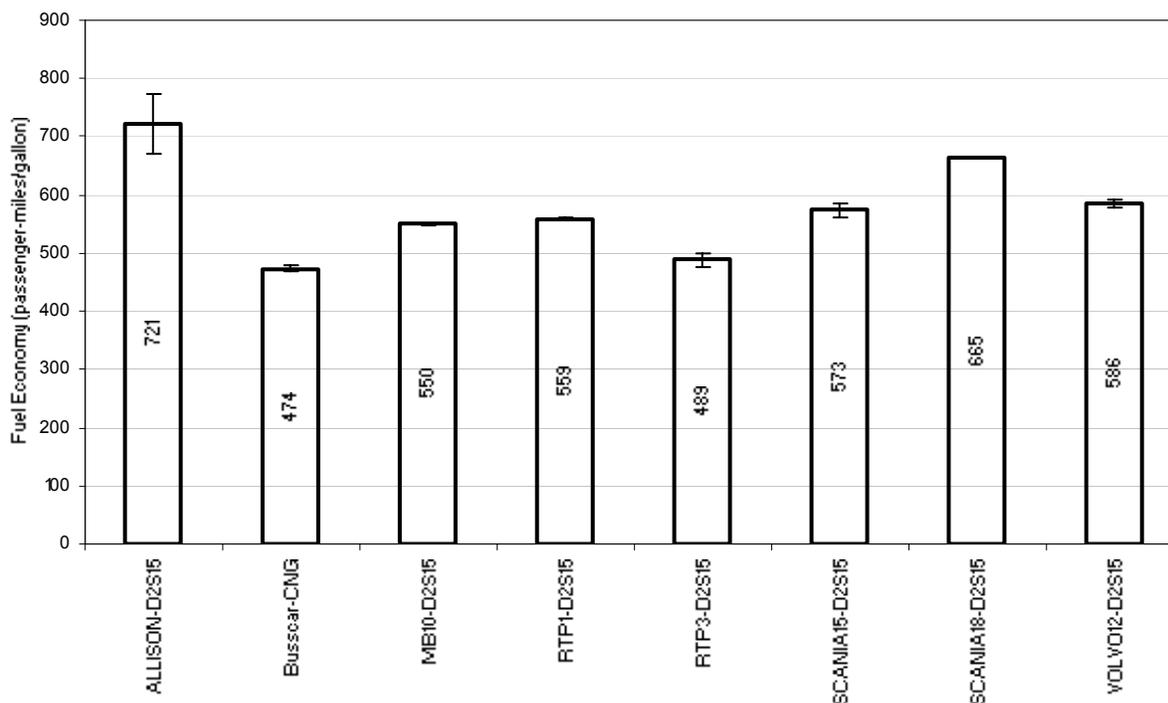


Figure 20: Fuel economy measured over the ETC on a passenger-mile per gallon basis

Fuel economy results measured over the individual MX1, MX2 and MX3 mode are provided in Appendix B. Over the MX1, poor diesel energy-equivalent fuel economy (in distance specific units) was observed from the two natural gas buses. The FAW bus had the lower economy of the two CNG buses and also had the lowest economy of all buses tested. Although CO and HC emissions levels were high for these buses (as shown in the emissions section below), they were not sufficiently high to explain the low fuel economy. The highest fuel economy was returned by the MB10 bus, and there was very little difference in fuel economy between the 15 ppm (sulfur level) fuel, the 150 ppm fuel and the D2 fuel. The ALLISON hybrid bus yielded the best fuel economy after the MB10 bus. The RTP1 and RTP3 buses showed the next best fuel economy and the values for these two buses were similar. Bus RTP3 showed slightly poorer economy on D2 than the two lower sulfur fuels. The VOLVO12 was next best with little influence of fuel type on the economy. The SCANIA15 and SCANIA18 buses had similar fuel economy. Their economy was the lowest of the diesel buses, and was similar (on an energy-equivalent basis) to the BUSSCAR CNG fuel economy. However, the SCANIA buses were both heavy buses, with extended length.

Fuel economy results for the MX2 were similar to those for the MX1, except that the ALLISON bus now had a lower fuel economy than the RTP1 and RTP3 buses. Fuel economy was higher on the MX2 mode than the MX1 mode, which would be expected for the higher speed cycle. The MB10 bus also showed less of an advantage over RTP1 and RTP3 buses that were 2 years older, compared to their fuel economy over the MX1 mode.

The MX3 was the highest speed mode in the MCS. The MX3 showed lower overall fuel economy than both the MX1 and MX2 due to the highly transient nature of the MX3. The MB10 and the older RTP buses now had similar fuel economy and were highest. The ALLISON hybrid was next, followed by the VOLVO12. The two SCANIA buses were similar in fuel economy and were lowest of the diesel buses. The BUSSCAR CNG bus had fuel

economy similar to the SCANIA diesel buses, while the FAW CNG bus had the lowest fuel economy of all. The FAW bus exhibited problems during testing, including engine overheating and inability to adequately follow the driver’s trace.

Figure 21 shows a different picture of fuel economy when the units of ton-miles per gallon are used for comparison (where a ton is a short ton of 2,000lb). Only ETC data are shown in this figure. Highest fuel economy is offered in these units by the SCANIA18 and the ALLISON hybrid buses. There is far lower fuel economy difference between the buses than when units of mile/gallon are used.

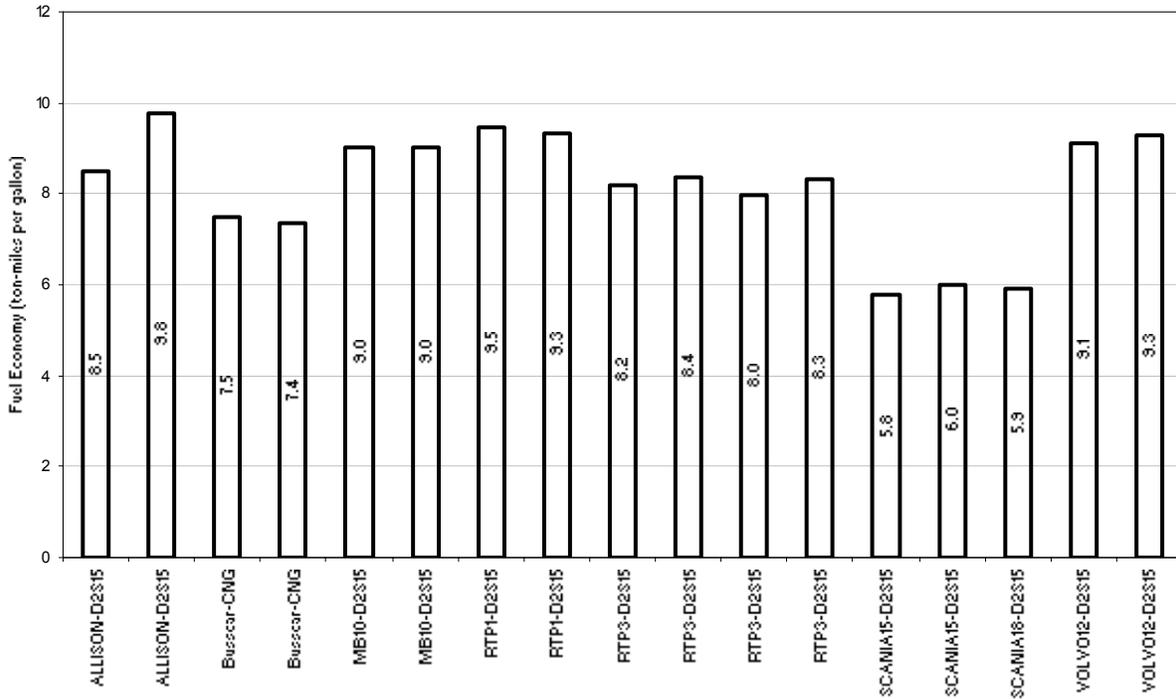


Figure 21: Fuel economy over the ETC on a ton-miles per gallon basis.

NO_x Emissions

Emissions of NO_x are important for both natural gas and diesel fueled buses, because the overall lean burn conditions favor NO_x formation. For at least one run for each vehicle/fuel combination, the primary NO_x analyzer was in "NO_x mode" (where both NO and NO₂ are measured) while the secondary NO_x analyzer was in "NO only mode."

Diesel buses without PM filtration aftertreatment tend to produce far less NO₂ than NO, 3% to 15% as NO₂ depending on engine design and operating conditions and typically 2% to 5% averaged over a transient test cycle. This is evident for most of the diesel buses, including the SCANIA15 bus which was equipped with an oxidation catalyst. The older bus, RTP-1, and the ALLISON hybrid bus, both equipped with catalyzed diesel particulate filters, showed substantial NO₂ content. Passive diesel particulate filters capture and oxidize particulate matter in the exhaust stream. Under idle or low power operation, particulate matter is collected on the wall flow filter and is subsequently burned "oxidized" when the exhaust gas temperatures exceed 250-300°C. Passive particulate filters commonly employ a precious metal catalyst upstream of the filter or a catalyst coating on the filter itself to lower the temperature necessary to oxidize the collected particulate matter. The coating promotes the oxidation of NO in the exhaust stream to produce NO₂. The NO₂ promotes combustion of the collected particulate matter at a significantly lower temperature (>250°C) than in air (>500°C) this allowing for continuous regeneration of the filter system under typical diesel engine exhaust temperatures. NO_x emissions from vehicles equipped with catalyzed particulate filters and other aftertreatment devices may consist of 30% to 40% NO₂.

Figure 22 shows the distance specific NO_x emissions measured over the combined modes of the MCS along with the averaged NO emissions from runs when the second NO_x analyzer was in NO mode. Plots of NO_x emissions measured over the individual MX1, MX2 and MX3 modes are provided in Appendix B. The FAW CNG bus exhibited the highest average NO_x emissions over the MCS at over 30 g/mile. The MB10 bus produced the lowest NO_x emissions, at around 11 g/mile, with the ALLISON bus only slightly higher. NO_x emissions measured over the ETC are shown in Figure 23. The SCANIA buses were the highest emitters of NO_x while the ALLISON and the MB10 buses demonstrated the lowest NO_x emissions. The ALLISON and RTP1 buses emitted over 50% of the NO_x as NO₂ due to the presence of catalyzed particulate filters. The BUSSCAR natural gas bus emitted about one fourth of the NO_x emissions as NO₂, and the levels of NO₂ were a small fraction of the total NO_x for the remaining buses. The FAW bus was unable to complete an emissions test on the ETC.

Plots of NO_x emissions measured over the individual MX1, MX2 and MX3 modes are provided in Appendix B. The FAW CNG bus exhibited the highest distance specific NO_x emissions over the MX1 mode at over 35 g/mile. The SCANIA and VOLVO buses fell between 20 and 30 g/mile. The BUSSCAR produced slightly less than 20 g/mile and the ALLISON and MB10 buses produced the lowest NO_x emissions at approximately 10 g/mile. Over the MX2, the FAW CNG bus was again the highest distance-specific emitter.

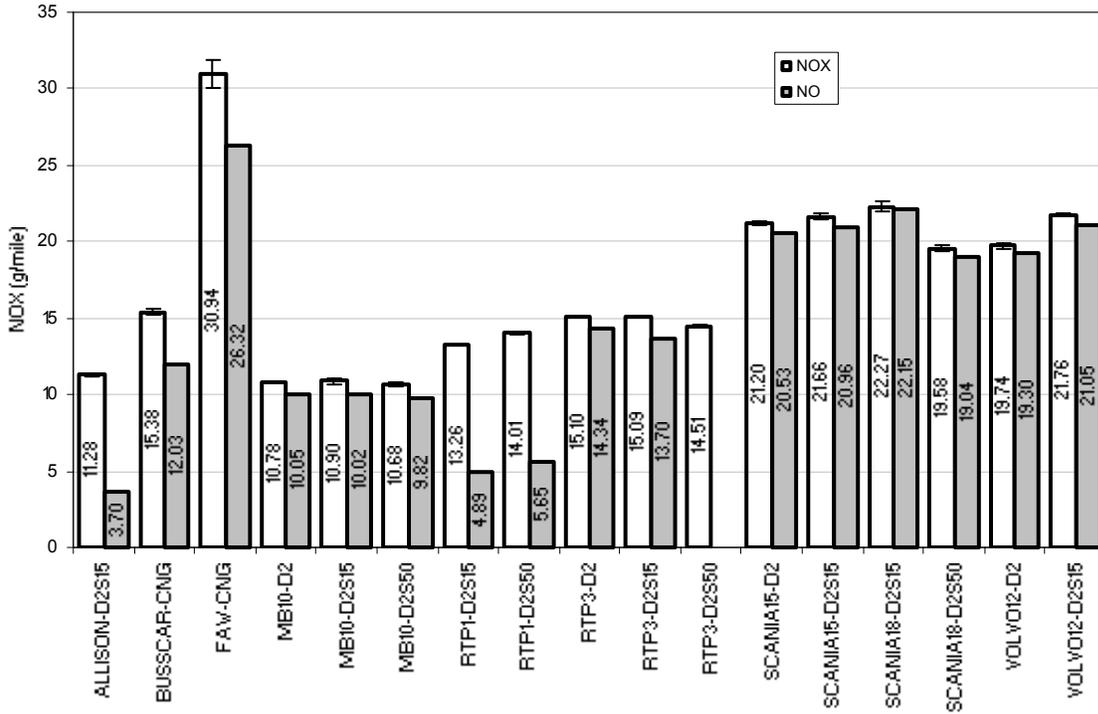


Figure 22: Distance-specific NO_x emissions over the combined modes of the MCS

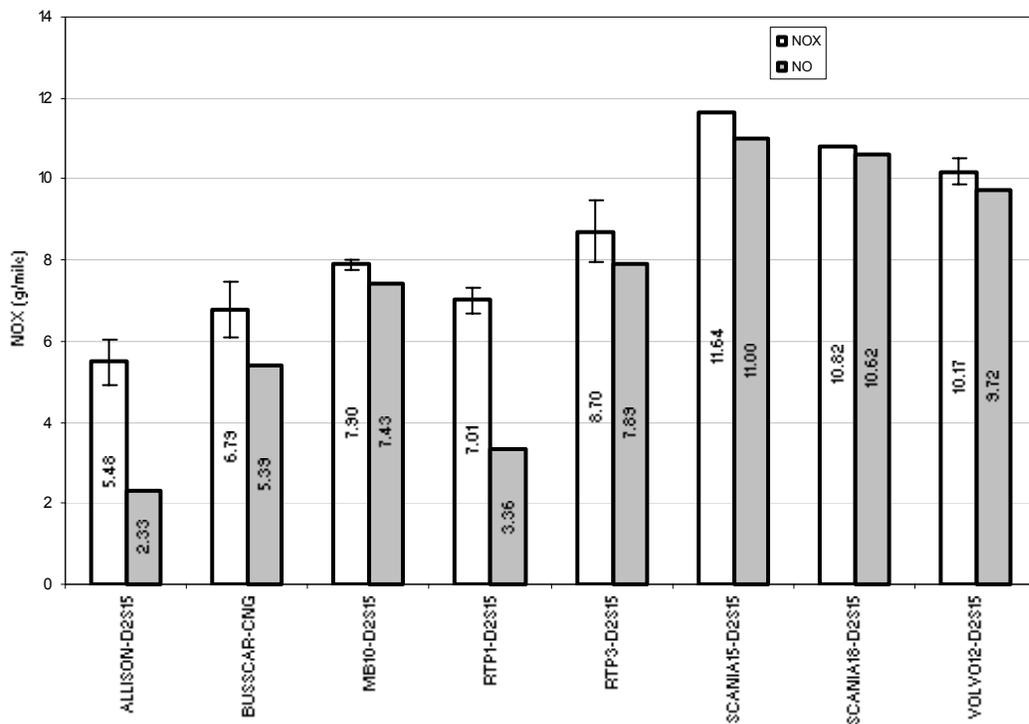


Figure 23: Distance-specific NO_x emissions over the ETC

Figure 24 and Figure 25 show NO_x emissions on a g/passenger-mile basis for the MCS and ETC respectively. Over the MCS, the ALLISON, MB10 and SCANIA18 exhibit the lowest NO_x emissions. The VOLVO12 diesel bus and the FAW CNG bus exhibit the highest NO_x emissions. NO_x emissions from the RTP1, RPT3, SCANIA15 buses and the BUSSCAR CNG bus were similar to one another and composed the middle range of the group. Over the ETC, the ALLISON and SCANIA18 buses exhibited low NO_x emissions while the VOLVO12 once again exhibited the highest emissions. The FAW bus was not tested over the ETC.

Figure 26 and Figure 27 show NO_x data expressed in alternate units of grams/ton-mile over the MCS and ETC. Distance-specific units favor lighter buses, the weight-specific data favors heavier buses. This is because a percentage increase in bus weight does not typically produce the same percentage increase in NO_x, but rather a lower percentage increase. The large SCANIA buses produced lower weight-specific emissions, although the lowest distance-specific emissions came from the ALLISON bus. The MB10, VOLVO and RTP3 buses produced similar NO_x emissions in units of g/ton-mile

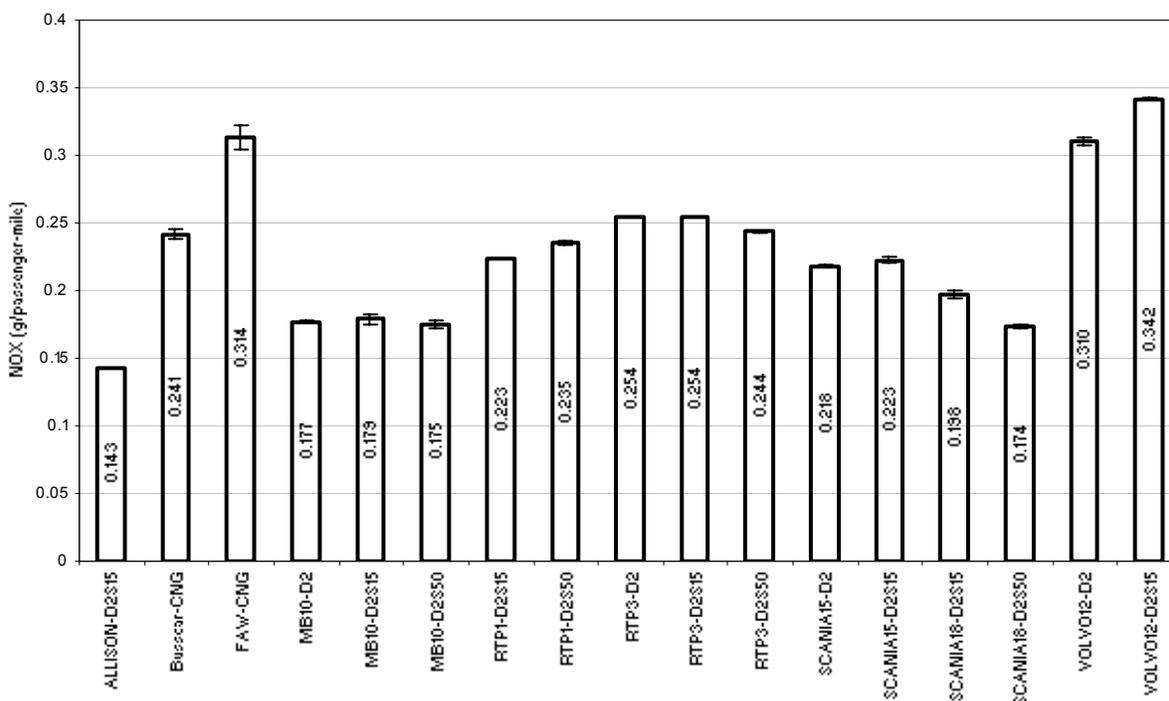


Figure 24: NO_x emissions over the MCS on a mass per passenger-mile basis

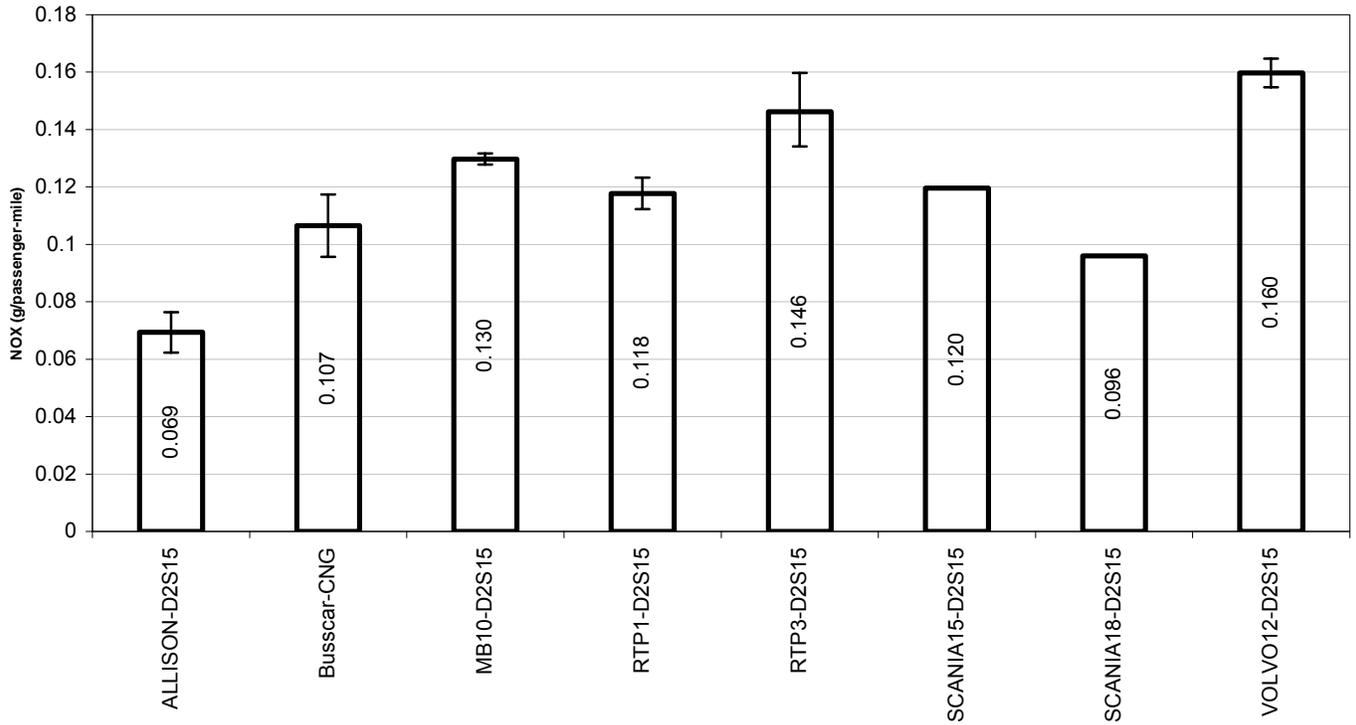


Figure 25: NO_x emissions over the ETC on a mass per passenger-mile basis

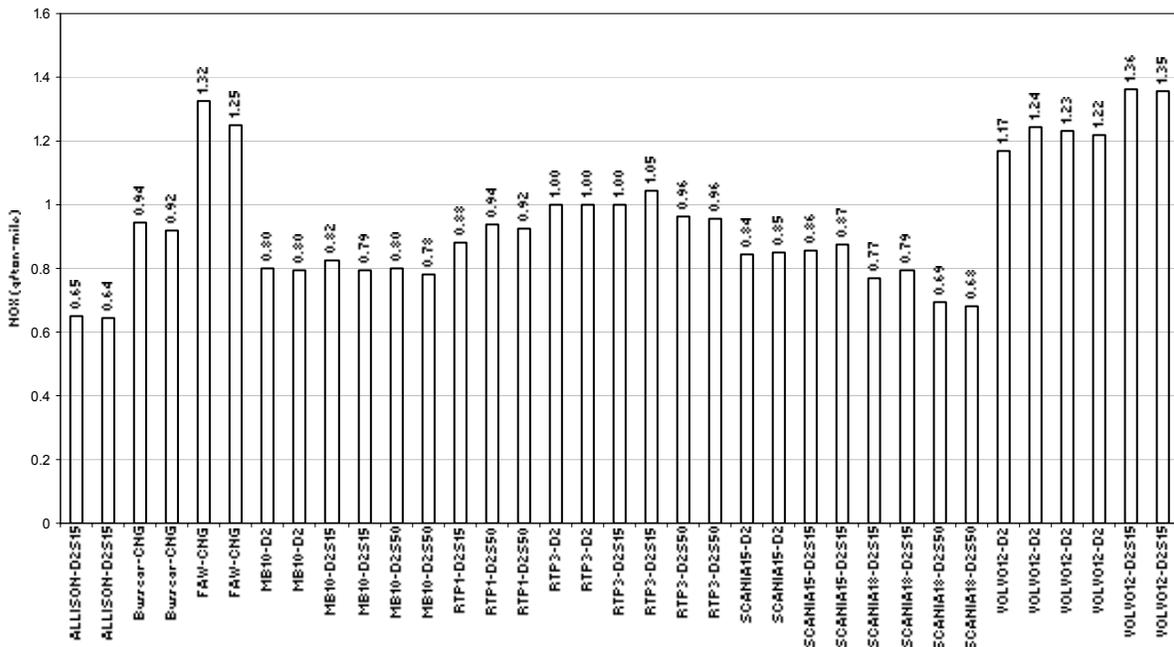


Figure 26: NO_x emissions over the MCS in grams per ton-mile.

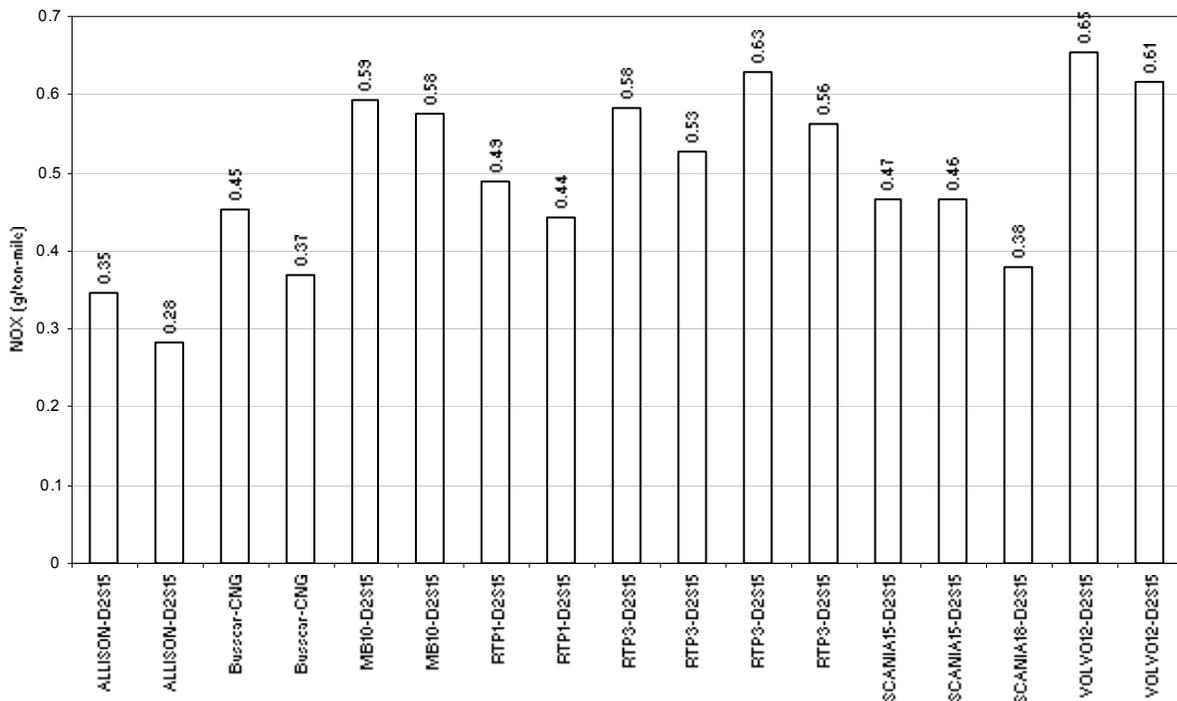


Figure 27: NO_x emissions over the ETC in grams per ton-mile.

Particulate Emissions

Particulate emissions are also of great concern, especially in some geographic regions. Variability in PM measurement is higher than for NO_x measurement because filter weights can be difficult to quantify if the mass of PM on the filter is low and if background PM levels vary. Furthermore, for diesel-fueled vehicles, the PM emissions may be highly sensitive to driving style, which may vary slightly from run to run.

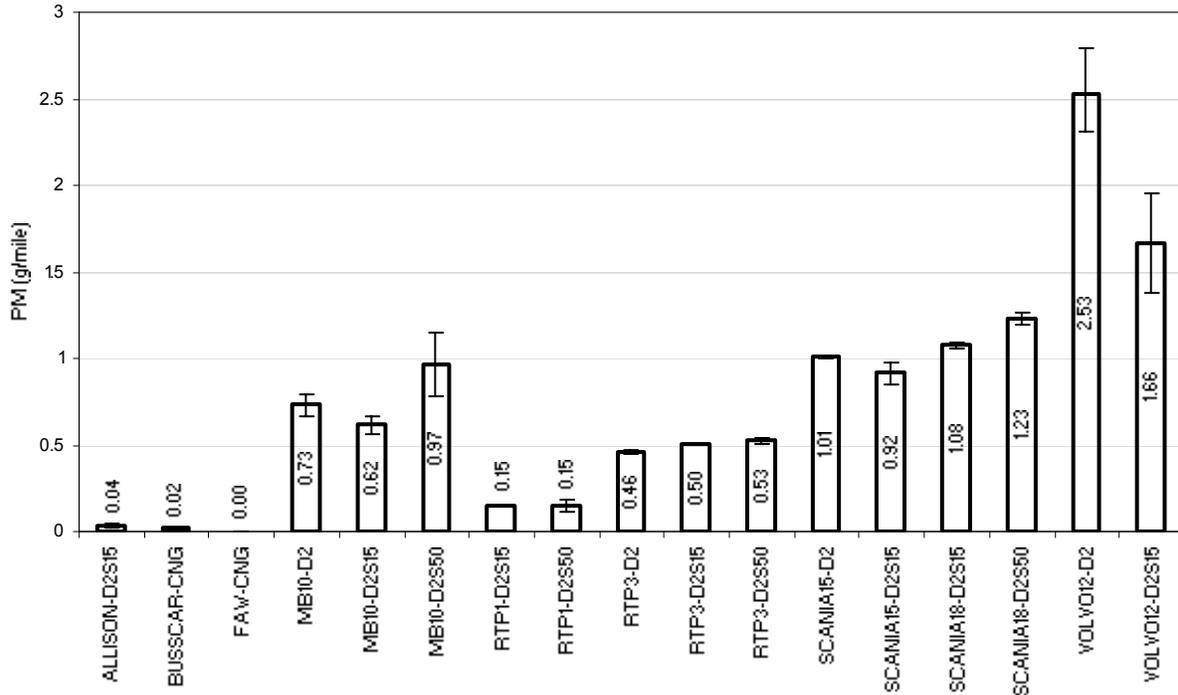


Figure 28: Particulate Emissions measured over the combined modes of the MCS

Figure 28 shows the averaged PM emissions over the MCS on a distance specific basis. As would be expected, the CNG buses had the lowest PM emissions, both less than 0.03 g/mile. The ALLISON hybrid had the next lowest PM emissions while RTP1 and RTP3 had the lowest for the diesel vehicles. It should be noted that the ALLISON Hybrid bus and RTP1 were both equipped with catalyzed diesel particulate filters. None of the other diesel fueled buses were so equipped.

Figure 29 shows the averaged PM emissions over the ETC on a distance specific basis. As with the MCS, the CNG buses and the ALLISON hybrid performed best in this category. The MB10 bus had the best PM emissions performance of the diesel buses while similar to the MCS, the VOLVO bus had the poorest performance. The MB10 bus showed the best performance improvement over the ETC when compared to the MCS with its PM emissions dropping by ~80% while those of the SCANIA18 were 75% lower.

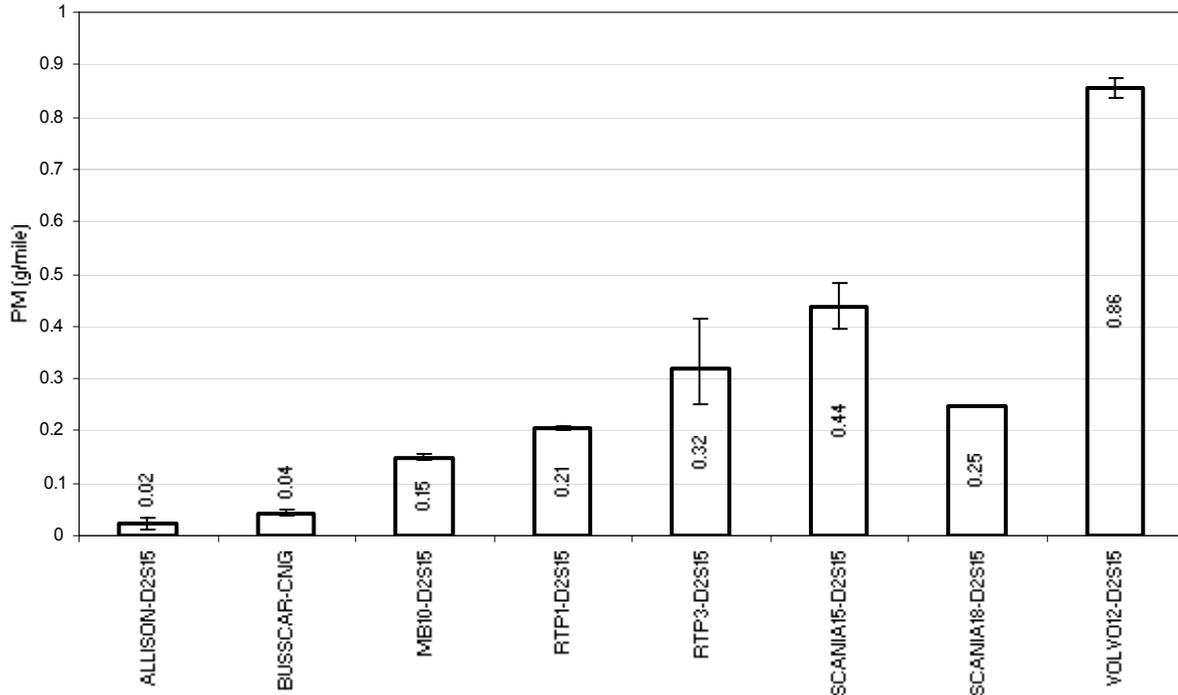


Figure 29: Particulate emissions measured over the ETC

Figure 28 shows no clear trend on the effect of reduced sulfur fuel on PM emissions. This conclusion is consistent with the fact that only a few percent of sulfur in the fuel is converted to sulfate (which is counted as PM mass). Sulfate contribution may become significant for very high sulfur fuels, but the sulfur levels for all three fuels used in this study were low by historical standards. Low sulfur diesel does not reduce PM emissions substantially. It reduces the sulfuric acid / sulfate mass in the PM, but that is a small fraction of overall PM mass. Its benefit is to allow the use of catalyzed PM filters on the exhaust. This is important, because these catalyzed filters will generally not function well without the low sulfur diesel.

Particulate results are plotted for the MX1, MX2 and MX3 modes of the MCS in Appendix B. Conclusions on PM production are substantially similar for the MX2 mode and the MX3 mode. Interestingly, the RTP1 bus produced substantially higher distance specific PM emissions on the MX3 mode than on the MX1 and MX2 modes, although these emissions were still below the level of all the buses except the ALLISON hybrid and the natural gas fueled buses. Interestingly the RTP 1 bus produced substantially higher PM emissions on the MX3 mode than on MX1 and MX2 modes (RPT 1 bus with CRT showed changes in emission of approximately 90% from the RTP3 bus without CRT for the MX1 and MX2 cycles, these change decreases by approximately 1/2 for the MX3 and ETC cycles.

Figure 30 and Figure 31 show PM emissions on a per passenger-mile basis. As with performance on a distance-specific basis, the CNG and ALLISON hybrid buses had the best performance while the VOLVO again performed the worst of all the buses. The SCANIA buses, when examined on a per passenger-mile basis, compare more favorably to the other diesel buses than on a distance-specific emissions due to their larger passenger capacity.

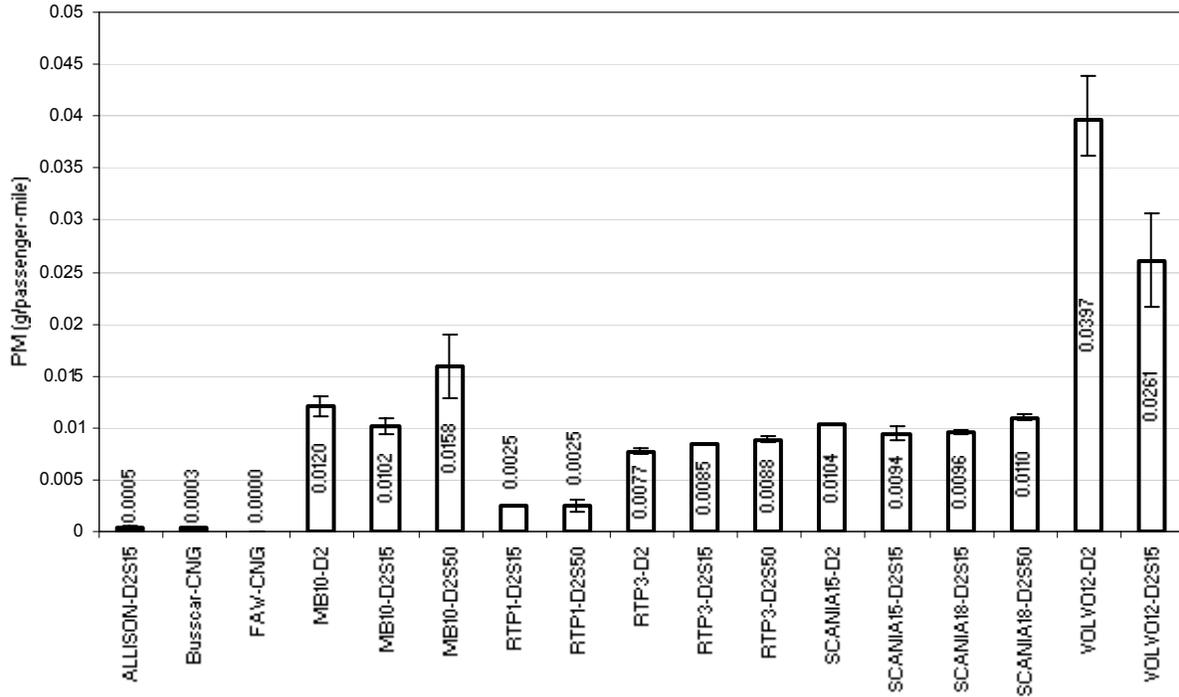


Figure 30: PM emissions over the MCS on a mass per passenger-mile basis

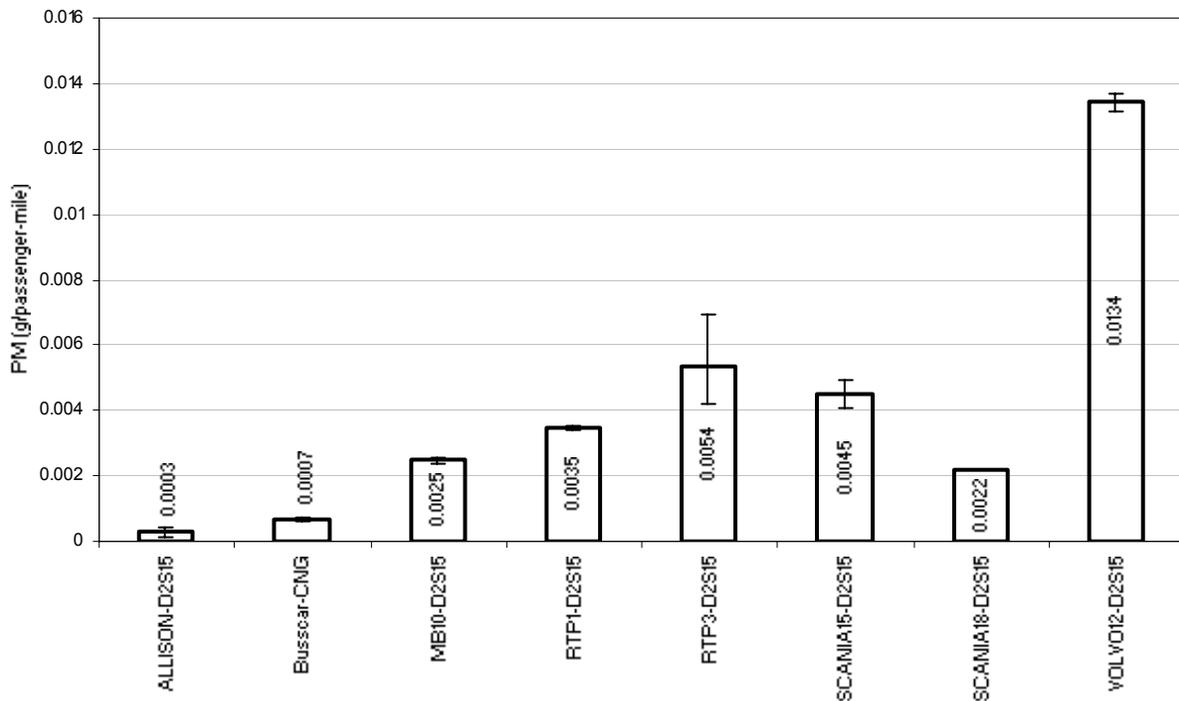


Figure 31: PM emissions over the ETC on a mass per passenger-mile basis

Another comparative method is to examine PM emissions on a per ton-mile basis (Figure 32 and Figure 33). Comparing emissions in this fashion favors the heavier buses (SCANIA18, SCANIA15, FAW) since they were tested at a substantially (~50%) heavier weight than the other buses.

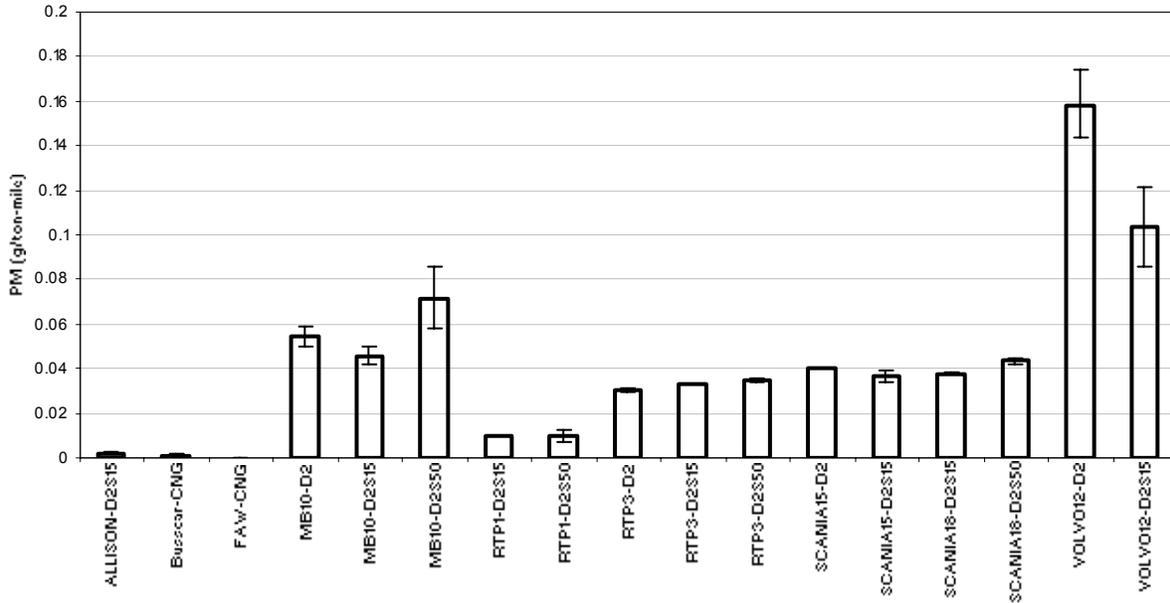


Figure 32: PM emissions over the MCS in grams per ton-mile.

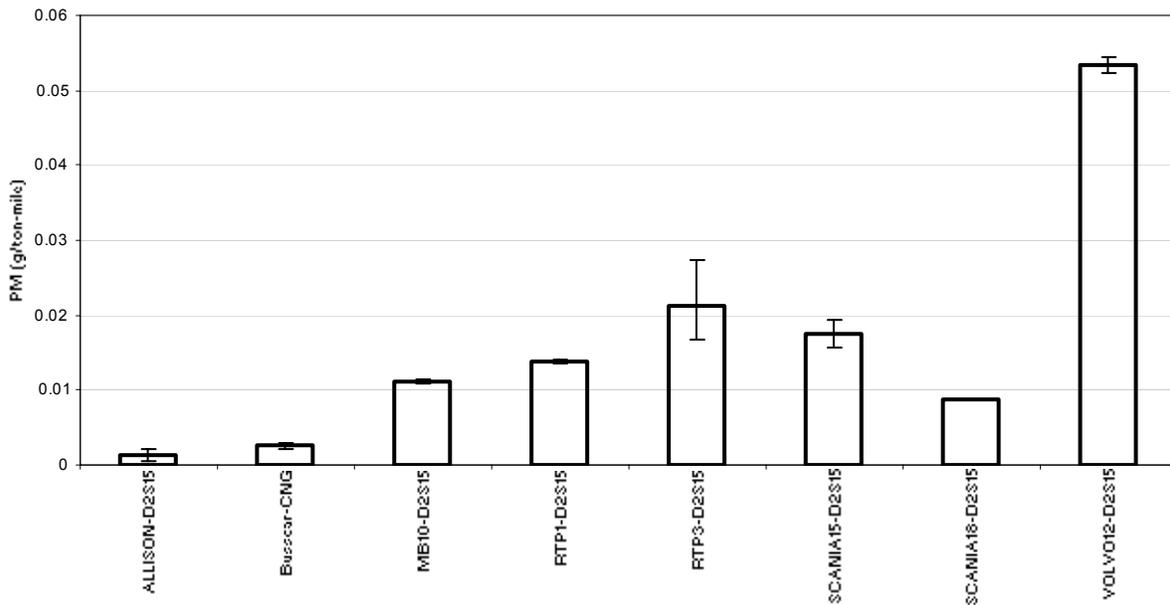


Figure 33: PM emissions over the ETC in grams per ton-mile.

Carbon Monoxide Emissions

CO emissions from diesel buses are generally low. Figure 34 shows the CO emissions from the buses tested in this program over the MCS schedule while Figure 34 shows CO emissions over the ETC. These data clearly show the benefits of the PM reduction aftertreatment in reducing CO for the ALLISON and RTP1 buses where oxidizing CO was evident. The VOLVO bus had the highest CO emissions of all of the buses over both the MCS and ETC.

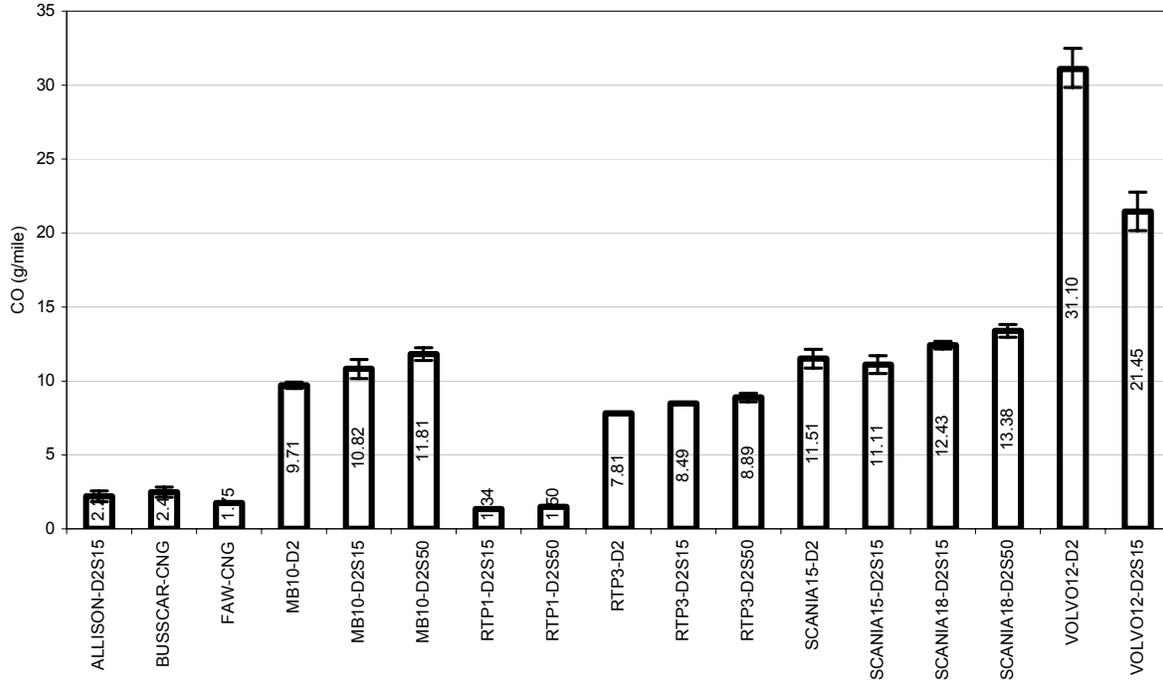


Figure 34: Carbon monoxide emissions measured over the combined modes of the MCS

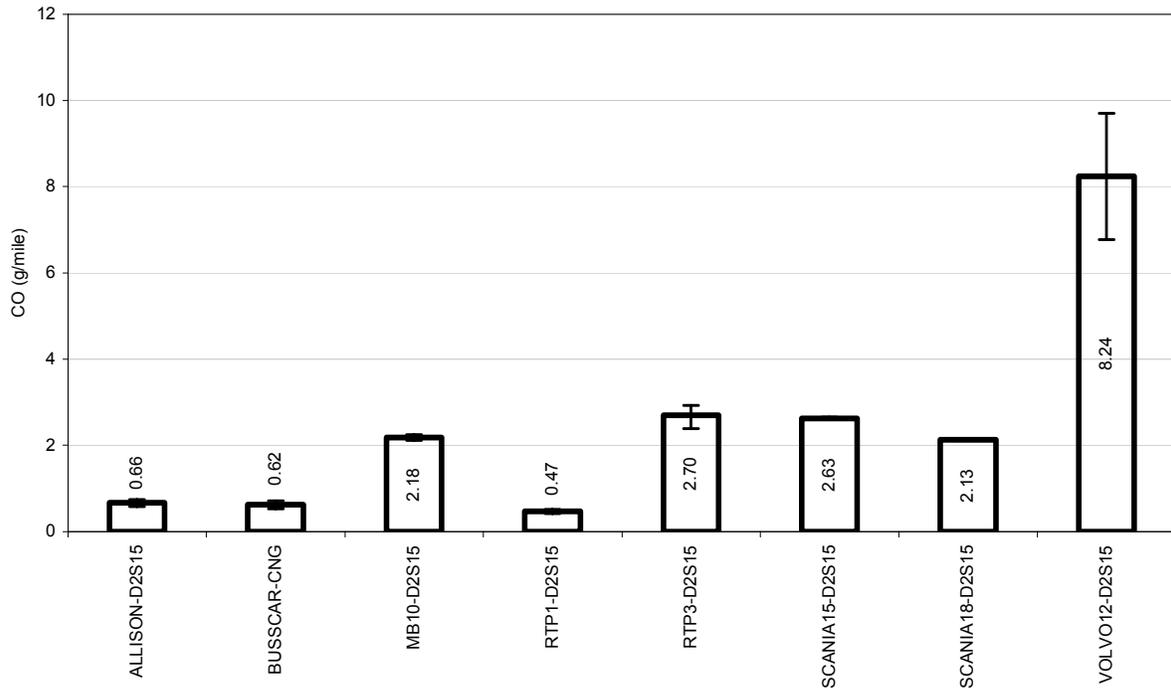


Figure 35: Carbon monoxide emissions over the ETC

Figure 36 and Figure 37 show CO emissions on a per passenger-mile basis. In similar fashion to particulate matter emissions, the CNG buses and the ALLISON hybrid had the lowest CO emissions while the RTP1 performed best among the diesel buses while the SCANIA18 and SCANIA15 buses compared more favorably due to their higher passenger capacity.

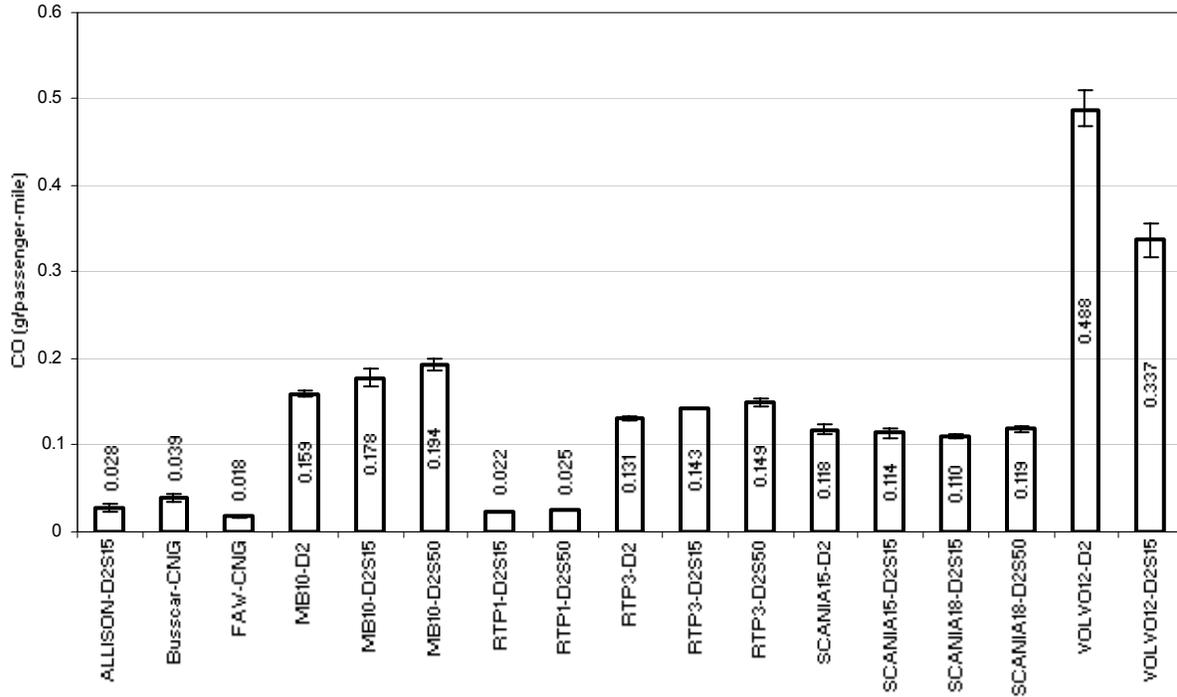


Figure 36: Carbon monoxide emissions over the MCS on a mass per passenger-mile basis

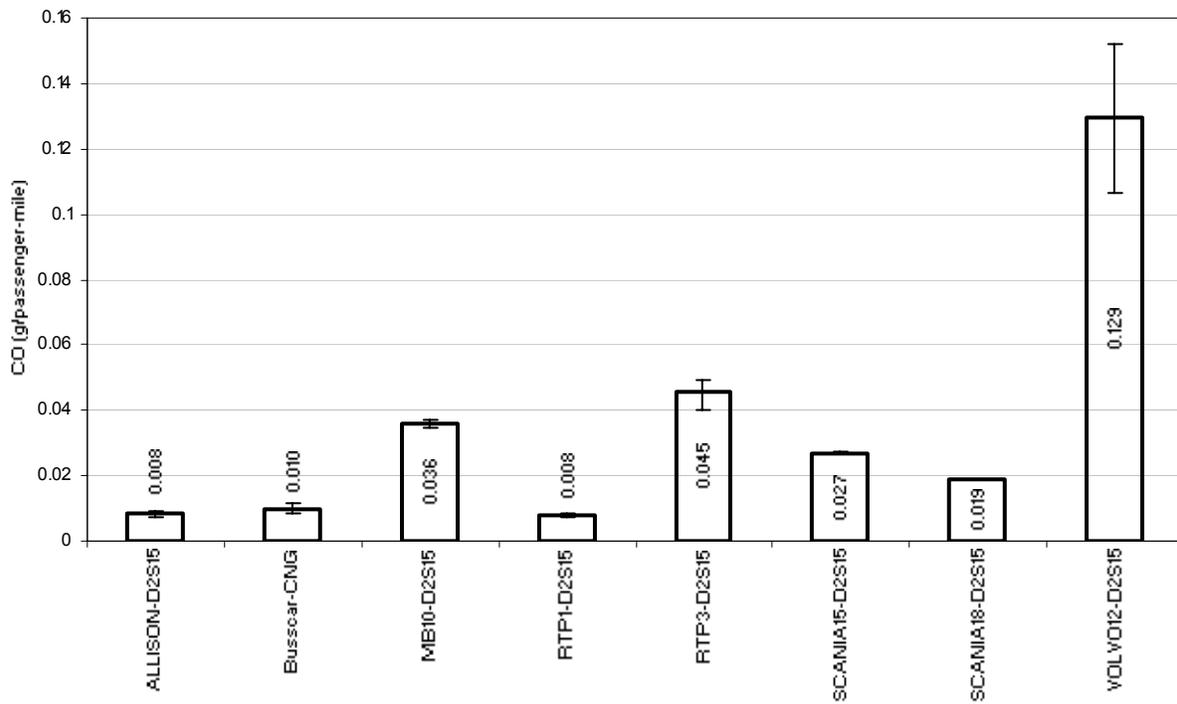


Figure 37: Carbon monoxide emissions over the ETC on a mass per passenger-mile basis

Hydrocarbon Emissions

Diesel engines have very high combustion efficiency, and as such produce very low hydrocarbon levels. This is evident in Figure 38 and Figure 39, where only the natural gas buses produced high HC levels. Most of these hydrocarbons from the natural gas buses consist of unburned fuel, particularly methane. Figure 42 shows that the field hydrocarbon emissions matched well with subsequent gas chromatograph analyses of sample bags, and that most of the sample HC was methane. The non-methane hydrocarbons (NMHC) were low in value, of the order of 1 g/mile, but were still, on average, higher than for the diesel vehicles. The data in Figure 38 and Figure 39 also show that the PM reduction aftertreatment (ALLISON hybrid, RTP1) eliminated diesel HC.

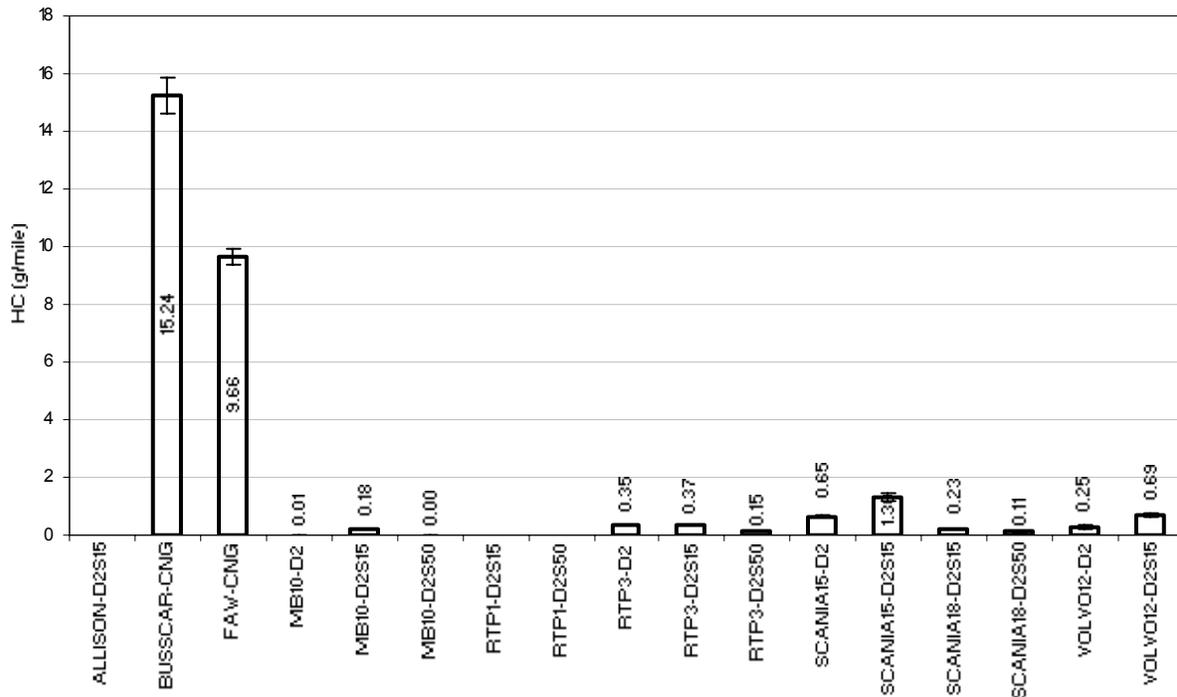


Figure 38: Hydrocarbon emissions measured over the combined modes of the MCS

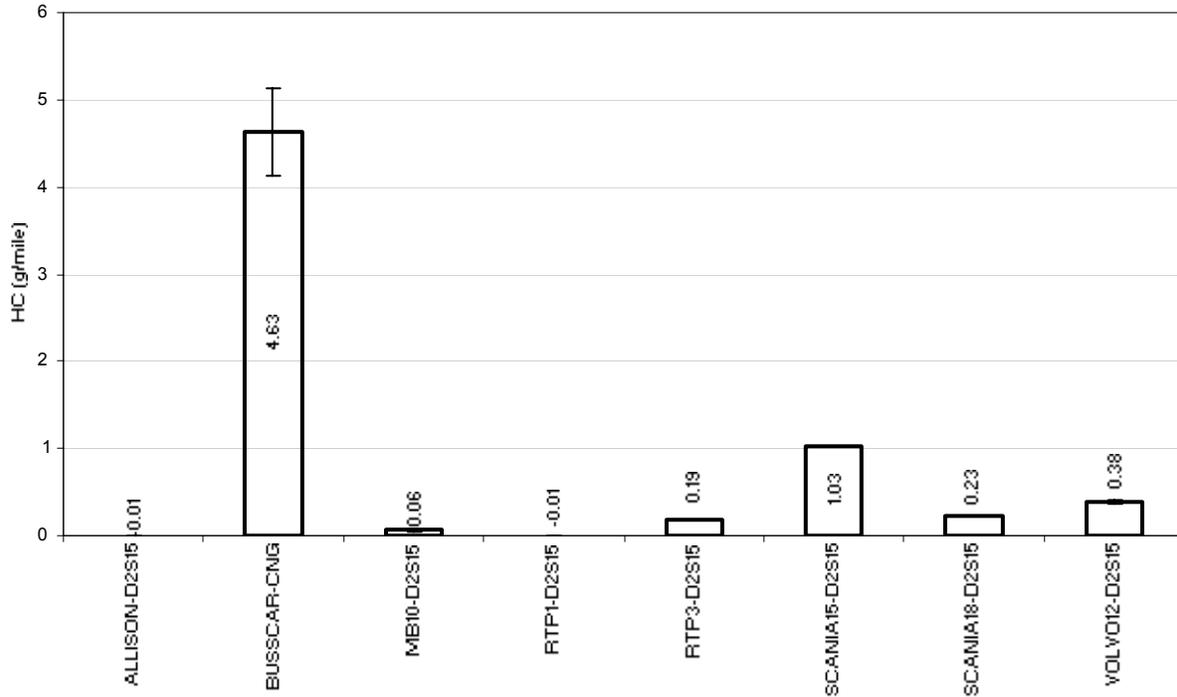


Figure 39 : Hydrocarbon emissions over the ETC.

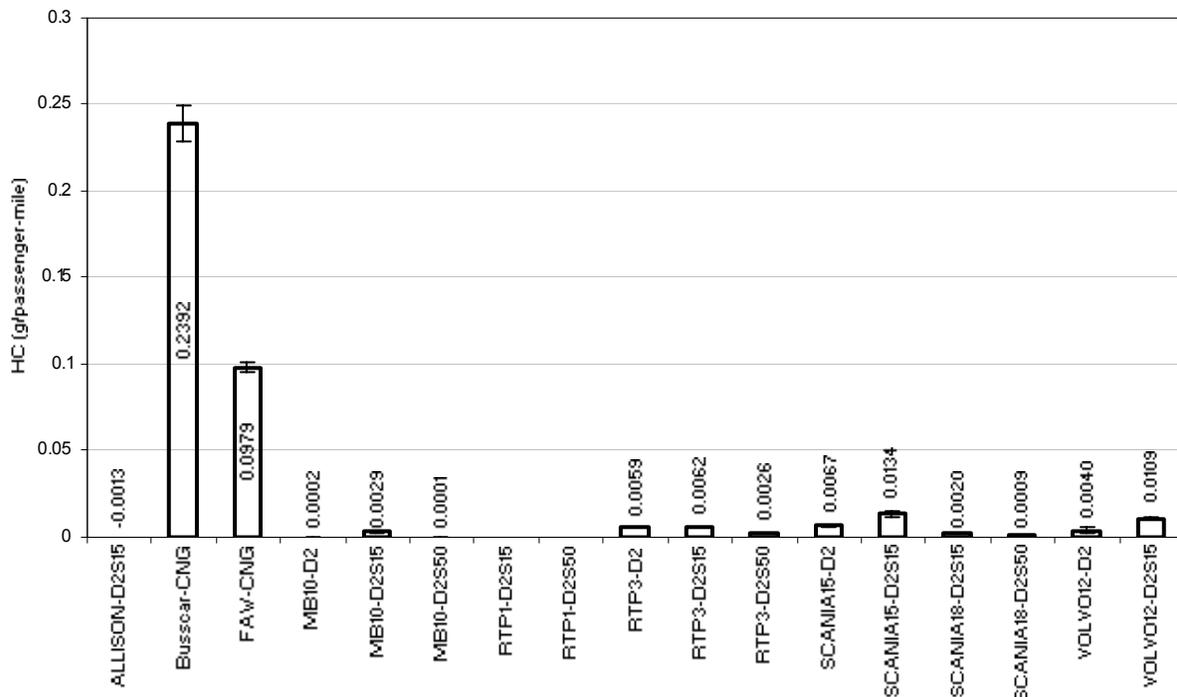


Figure 40: Hydrocarbon emissions over the MCS on a mass per passenger-mile basis

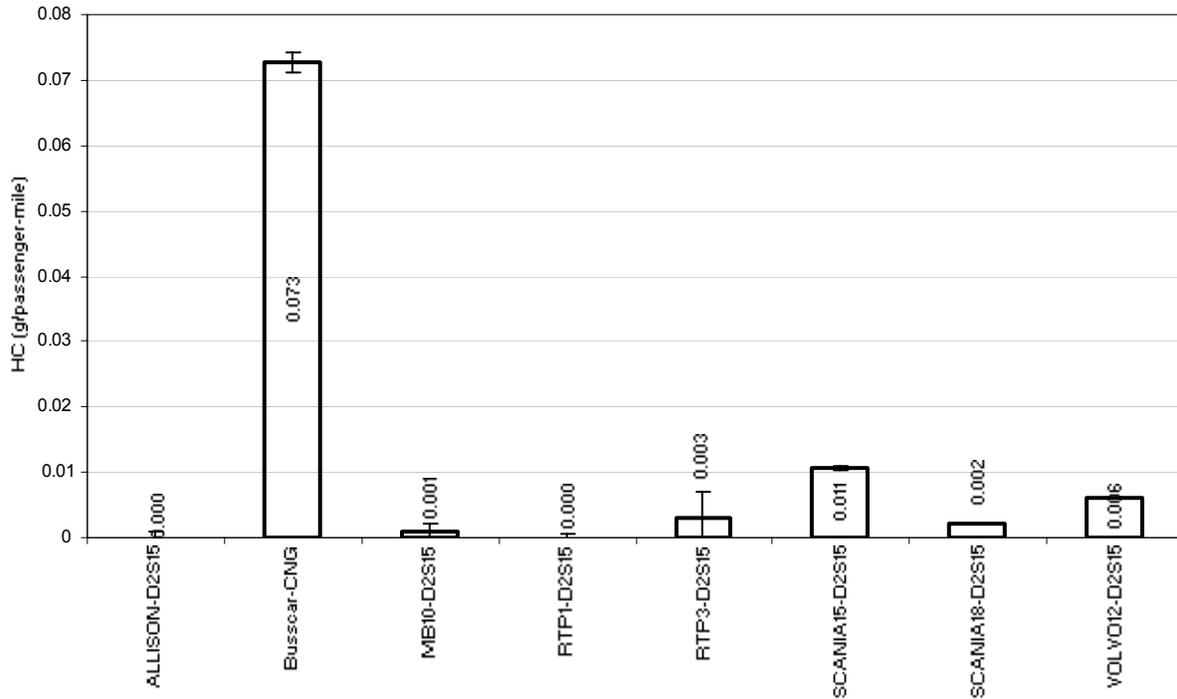


Figure 41: Hydrocarbon emissions over the ETC on a mass per passenger-mile basis

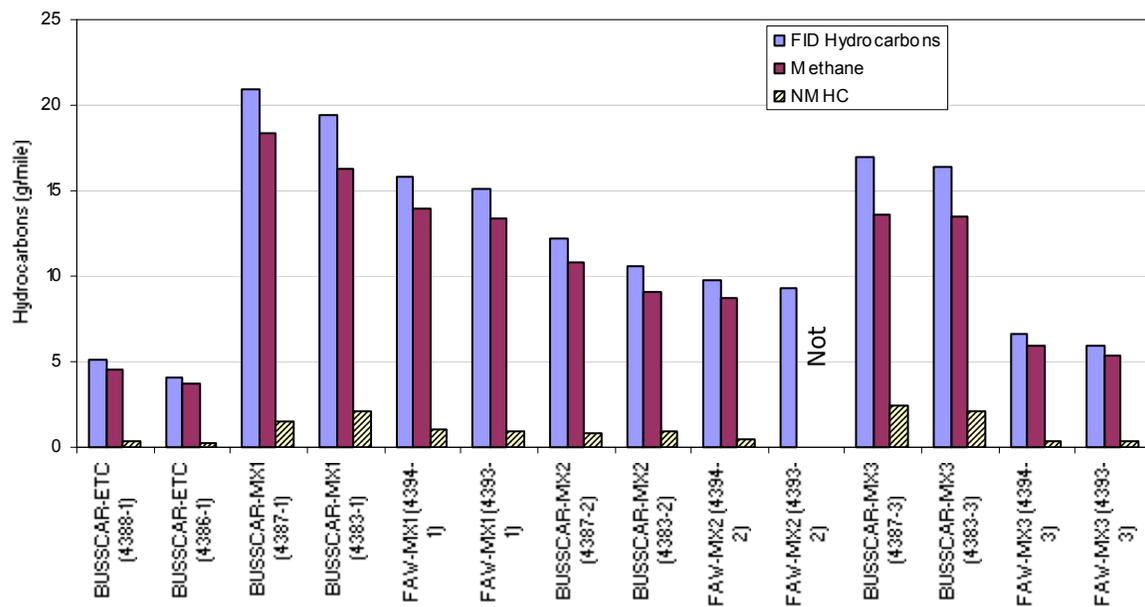


Figure 42 - Comparison of FID and gas chromatograph hydrocarbon measurements.

Nitrous Oxide (N₂O) emissions

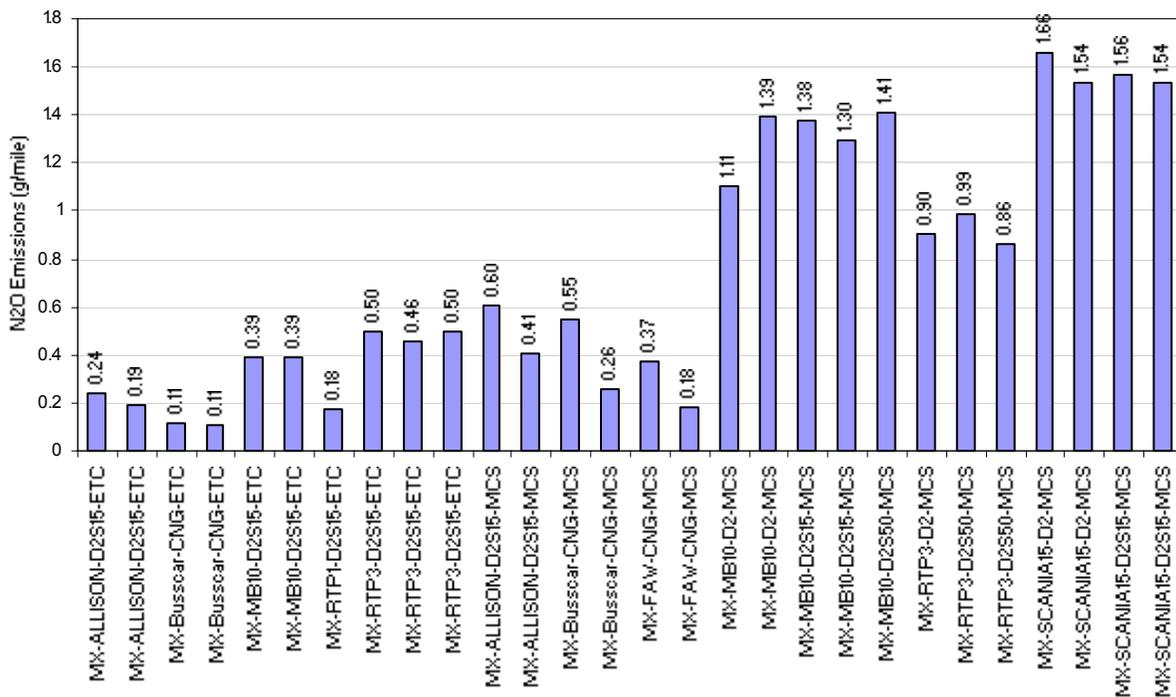


Figure 43: N₂O emissions over both the ETC and MCS

Figure 43 presents the emissions of nitrous oxide (N₂O) from the tested fleet. Data were available for limited number of runs because the INNOVA analyzer, which is not normally used during WVU emissions measurements, malfunctioned. From the available data, the SCANIA15 bus produced the highest emissions while the average N₂O emissions from all of the vehicles were more than an order of magnitude lower than the total NO_x emissions.

Carbon Dioxide Emissions

Emissions of CO₂, a non-regulated species, are presented in Figure 44 through Figure 47, and closely reflect the fuel economy data presented above.

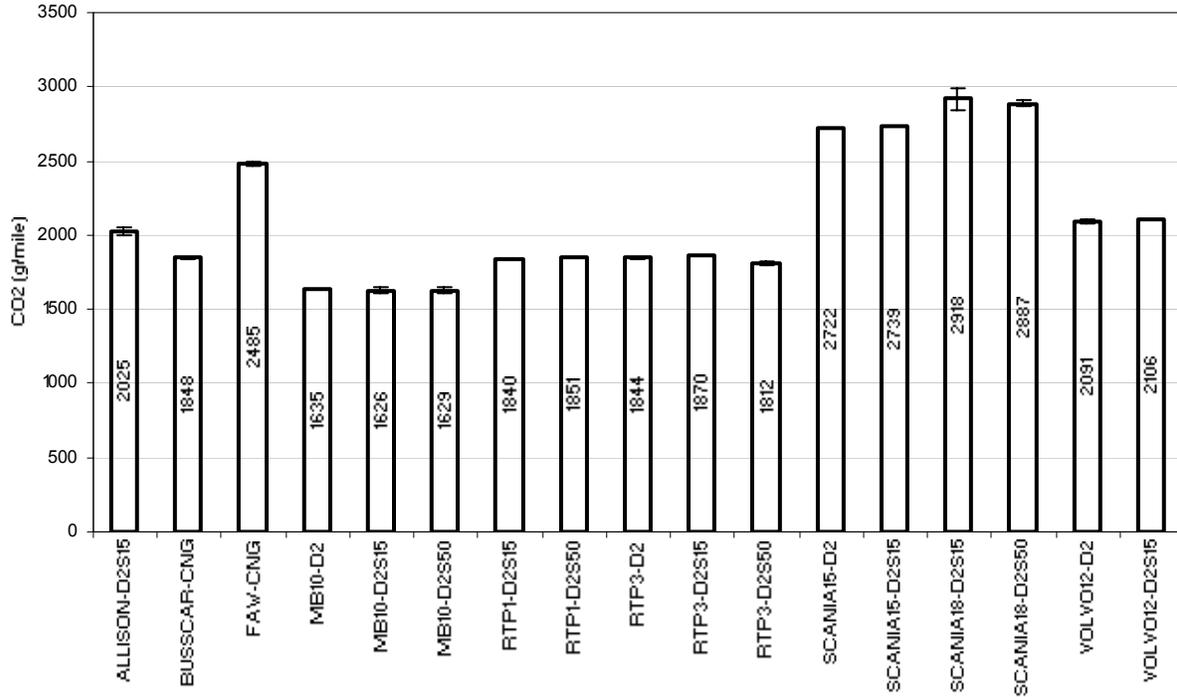


Figure 44: Carbon dioxide Emissions measured over the combined modes of the MCS

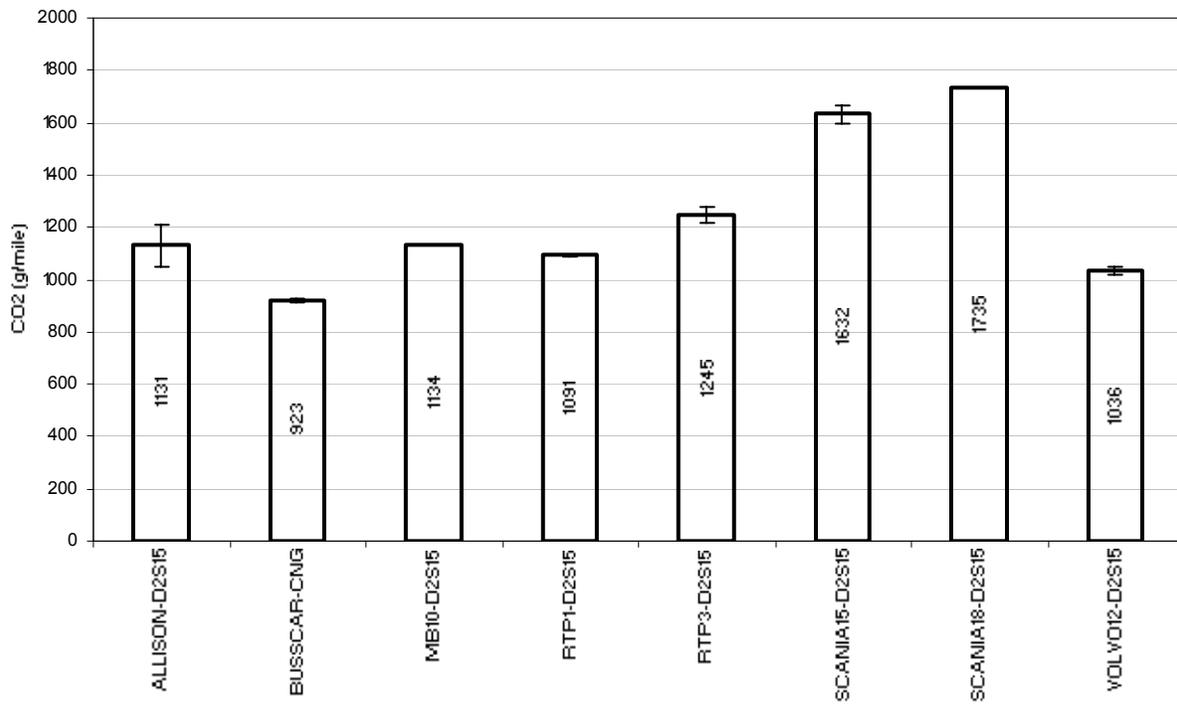


Figure 45: Carbon dioxide emissions measured over ETC

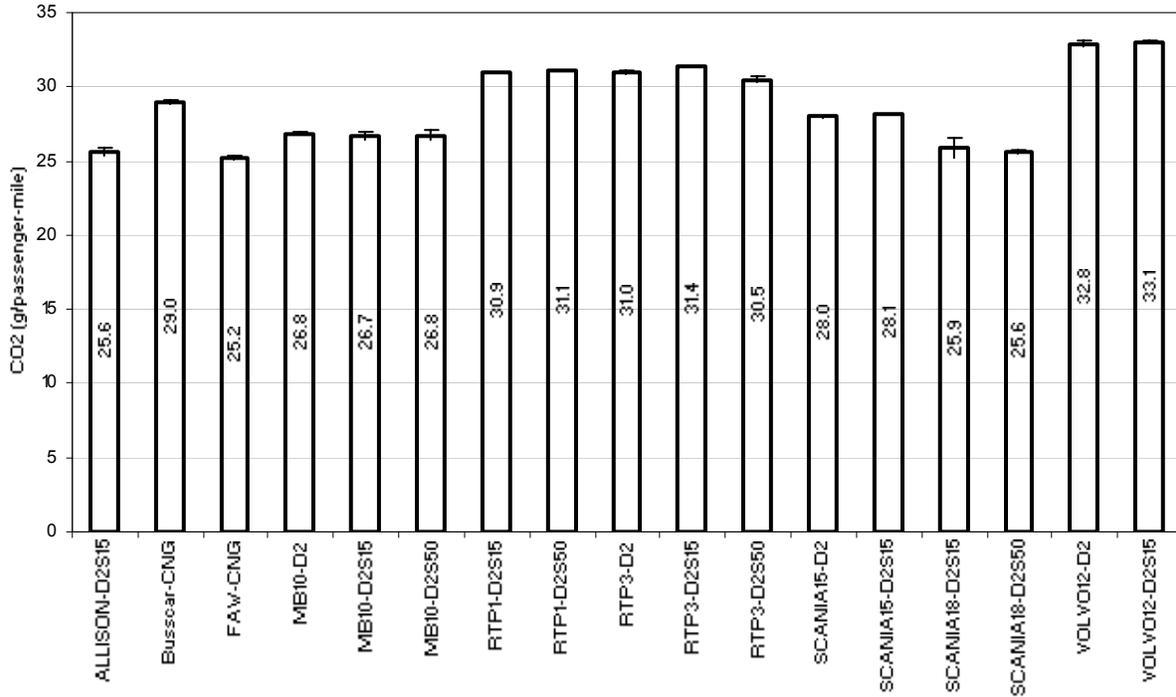


Figure 46: Carbon dioxide emissions over the MCS on a mass per passenger-mile basis

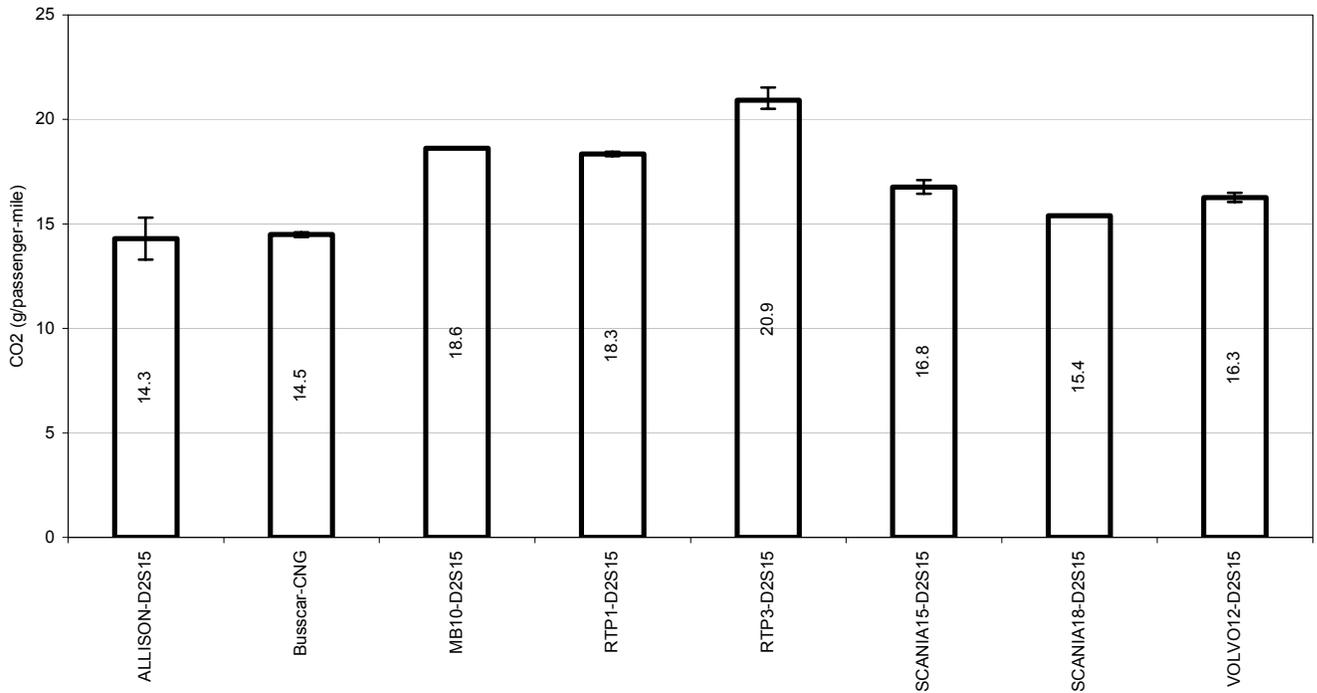


Figure 47: Carbon dioxide emissions over the ETC on a mass per passenger-mile basis

Findings and Conclusions

The CNG vehicles, as expected, produced lower particulate matter emissions than the diesel buses. However, the exhibited poorer when compared on fuel economy. Also, the results indicated a large difference in the emission between the two CNG vehicles. Emissions from CNG buses are highly dependent on the exact control strategy of the engine. In many cases this represents a tradeoff between high NO_x or high methane emissions, as the air/fuel ratio is varied. It is not possible to select CNG technology based on the fuel alone – the technology must be considered. In this case, the basic engine technology was similar, but clearly the two engines were operating at different air/fuel ratios. While we have no information on the actual control strategy used, it may be that the altitude (low atmospheric pressure) of Mexico City affected one of the buses.

Emissions from the VOLVO bus were higher than those from the other buses in almost all cases. We cannot say why emissions are higher on one vehicle than another, without separate study of the engine technology employed. PM and NO_x can vary widely in engines that are quite similar due to injection timing and maximum fueling rate and, since it is common that if PM is high, CO will be high since both of these emissions arise from zones in the cylinder that are “too rich in fuel”.

The ALLISON hybrid bus performed well on fuel economy and emissions. However, the ALLISON bus (tested at 50% passenger loading) and MB10 exhibited test weight to passenger capacity ratios that were ~10% lower than the other vehicles examined in this program. Since bus weight is a major influence on fuel economy and emissions, lighter buses with similar passenger capacities will generally exhibit improved performance.

Ref. Name	Tested Weight (lbs)	Curb Weight (lbs)	Passenger Capacity	Tested Weight to Passenger Ratio (lbs/passenger)
ALLISON	35000	29000	113	310
Ankai	32150	22700	90	357
BUSSCAR	33025	23425	91	363
FAW	48025	33175	140	343
MB10	26996	17800	87	310
RTP1	30070	21100	85	354
RTP3	30220	21250	85	356
SCANIA15	50040	35400	139	360
SCANIA18	57025	40075	161	354
VOLVO12	32050	22500	91	352

Low sulfur diesel did not reduce PM emissions substantially. Low sulfur diesel reduces the sulfuric acid / sulfate mass in the PM, but that is a small fraction of overall PM mass. Its benefit is to allow the use of “PM traps” on the exhaust since these traps will generally not function well without the low sulfur diesel.

Examination of emissions on a per passenger-mile basis provides valuable analytical insight. Traditionally, vehicle emissions have been reported on a distance specific basis which tends to favor vehicles with higher power to weight/passenger capacity. Using this analysis, the comparison of the SCANIA and ALLISON buses became more favorable since they had a higher passenger loading capacity than the other buses tested in the program. Conversely, the smaller capacity buses will show less favorable performance. However, it must be cautioned that applying only the per passenger mile basis performance without considering normal passenger loading would result in poorly informed decisions.

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7. Gilbert, M.,S. and Clark, N., N., "Measurement of Particulate Matter from Diesel Engine Exhaust Using a Tapered Element Oscillating Microbalance," *Int J Engine Research*, 2001, Vol.2, No. 4, 277-287.
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Appendix A: Tabulated Emissions and Fuel Economy Data

Table A- 1: Emissions and fuel economy from tests over the MX1 segment of the MCS

Vehicle	Test ID	Testing Weight (lbf)	CO g/mile	CO ₂ g/mile	NO _x g/mile	NO _{x2} g/mile	FIDHC ⁽¹⁾ g/mile	PM g/mile	TEOM g/mile	Fuel Economy (mile/gal)
MX-VOLVO12-D2S15-MCS	4312-1	32050	37.6	2286.1	26.6	26.7	0.71	3.06		4.11
MX-VOLVO12-D2S15-MCS	4315-1	32050	33.2	2271.0	26.1	25.0	0.88	1.82	1.41	4.15
MX-VOLVO12-D2-MCS	4319-1	32050	48.2	2399.6	23.7	23.8	0.44	3.44	2.65	3.90
MX-VOLVO12-D2-MCS	4320-1	32050	48.9	2262.6	23.2	23.3	0.31	3.26	2.92	4.13
MX-VOLVO12-D2-MCS	4321-1	32050	47.3	2266.9	23.2	22.5	0.18	3.21	2.44	4.12
MX-VOLVO12-D2-MCS	4322-1	32050	50.9	2321.9	23.1	22.4	0.08	3.52		4.02
MX-SCANIA15-D2S15-MCS	4330-1	50040	20.1	2884.2	24.7	25.0	3.04	1.58	1.14	3.30
MX-SCANIA15-D2S15-MCS	4332-1	50040	18.5	2820.8	24.7	23.5	1.77	1.39	1.15	3.38
MX-SCANIA15-D2-MCS	4334-1	50040	22.1	2828.1	23.7	23.7	0.70	1.61	1.34	3.50
MX-SCANIA15-D2-MCS	4335-1	50040	19.9	2806.2	23.6	22.7	0.63	1.58	1.35	3.53
MX-RTP3-D2S15-MCS	4353-1	30220	11.9	2011.0	17.4	17.5	0.58	0.50	0.39	5.05
MX-RTP3-D2S15-MCS	4355-1	30220	12.0	1971.1	16.5	15.5	0.50	0.61	0.05	5.16
MX-RTP3-D2S50-MCS	4362-1	30220	12.0	1936.3	16.2	16.4	0.18	0.65	0.55	5.18
MX-RTP3-D2S50-MCS	4363-1	30220	12.5	1928.2	16.3	15.4	0.17	0.62	0.52	5.20
MX-RTP3-D2-MCS	4364-1	30220	10.4	2069.2	17.8	17.9	0.57	0.47	0.42	4.80
MX-RTP3-D2-MCS	4365-1	30220	11.9	2099.4	18.6	17.4	0.54	0.65	0.54	4.73
MX-MB10-D2S15-MCS	4369-1	26996	15.3	1682.4	12.9	13.0	0.35	0.65	0.50	6.01
MX-MB10-D2S15-MCS	4371-1	26996	14.4	1601.9	11.9	11.1	0.37	0.57	0.49	6.32
MX-MB10-D2S50-MCS	4376-1	26996	15.7	1601.5	11.2	11.3	0.12	0.87	0.96	6.23
MX-MB10-D2S50-MCS	4377-1	26996	14.1	1572.2	10.8	9.9		0.82	0.78	6.36
MX-MB10-D2-MCS	4378-1	26996	12.0	1636.1	11.2	11.1	0.09	1.37	1.54	6.06
MX-MB10-D2-MCS	4379-1	26996	12.1	1588.4	10.9	10.0		0.73	0.50	6.24
MX-BUSSCAR-CNG-MCS	4383-1	33025	3.7	1972.2	19.8	19.7	16.29/2.15	0.01		3.43
MX-BUSSCAR-CNG-MCS	4387-1	33025	2.9	1954.9	19.0	12.8	18.32/1.56	0.01	0.01	3.45
MX-FAW-CNG-MCS	4393-1	48025	2.4	2678.7	36.1	36.1	13.39/0.94	0.01		2.56
MX-FAW-CNG-MCS	4394-1	48025	2.4	2682.6	35.1	28.2	13.90/1.07	0.02		2.55
MX-ALLISON-D2S15-MCS	4400-1	35000	6.7	1773.4	8.6	8.6		0.10	0.09	5.76
MX-ALLISON-D2S15-MCS	4402-1	35000	3.6	1843.7	11.5	1.9		0.04	0.03	5.55
MX-RTP1-D2S15-MCS	4408-1	30070	2.0	2005.5	15.4	5.3		0.08	0.05	5.11
MX-RTP1-D2S50-MCS	4410-1	30070	2.3	1889.7	14.9	14.8		0.15		5.36
MX-RTP1-D2S50-MCS	4411-1	30070	2.3	1927.4	14.8	5.2		0.05	0.04	5.25
MX-SCANIA18-D2S15-MCS	4418-1	57025	21.5	2963.7	28.3	28.3	0.24	1.68	1.35	3.42
MX-SCANIA18-D2S15-MCS	4419-1	57025	21.0	3075.3	28.9	28.2	0.21	1.54	1.37	3.30
MX-SCANIA18-D2S50-MCS	4421-1	57025	24.3	2968.7	23.6	23.4	0.17	1.91	1.55	3.37
MX-SCANIA18-D2S50-MCS	4422-1	57025	23.0	2973.7	23.5	22.9	0.05	1.81	1.55	3.37

Table A- 2: Emissions and fuel economy from tests over the MX2 segment of the MCS

WVU Ref Num	Test ID	CO g/mile	CO ₂ g/mile	NO _x g/mile	NO _x 2 g/mile	FIDHC ⁽¹⁾ g/mile	PM g/mile	Fuel Economy (mile/gal)
MX-VOLVO12-D2S15-MCS	4312-2	19.9	1659.0	17.3	17.4	0.55	1.69	5.71
MX-VOLVO12-D2S15-MCS	4315-2	17.9	1647.7	17.2	16.7	0.63	1.26	5.76
MX-VOLVO12-D2-MCS	4319-2	30.2	1718.1	16.0	16.1	0.32	2.36	5.47
MX-VOLVO12-D2-MCS	4320-2	29.1	1667.3	15.9	15.8	0.33	2.24	5.63
MX-VOLVO12-D2-MCS	4321-2	27.7	1653.2	15.7	15.3	0.25	2.11	5.69
MX-VOLVO12-D2-MCS	4322-2	30.7	1652.9	15.3	15.0	0.17	2.42	5.67
MX-SCANIA15-D2S15-MCS	4330-2	9.6	2180.3	18.3	18.5	1.04	0.85	4.39
MX-SCANIA15-D2S15-MCS	4332-2	8.5	2178.6	18.3	17.5	0.98	0.69	4.40
MX-SCANIA15-D2-MCS	4334-2	9.5	2199.9	18.1	18.1	0.63	0.83	4.52
MX-SCANIA15-D2-MCS	4335-2	8.3	2176.6	17.8	17.1	0.57	0.81	4.57
MX-RTP3-D2S15-MCS	4353-2	7.6	1508.6	12.1	12.1	0.35	0.42	6.75
MX-RTP3-D2S50-MCS	4362-2	8.4	1490.4	11.5	11.7	0.19	0.47	6.74
MX-RTP3-D2S50-MCS	4363-2	7.7	1452.5	11.3	10.7	0.16	0.45	6.92
MX-RTP3-D2-MCS	4364-2	7.1	1480.3	11.8	11.9	0.35	0.41	6.72
MX-RTP3-D2-MCS	4365-2	7.3	1480.6	11.8	11.2	0.38	0.41	6.71
MX-MB10-D2S15-MCS	4369-2	8.9	1338.0	9.0	9.0	0.16	0.57	7.59
MX-MB10-D2S15-MCS	4371-2	7.8	1294.3	8.7	8.2	0.15	0.45	7.86
MX-MB10-D2S50-MCS	4376-2	9.5	1335.6	9.0	9.1	0.13	0.62	7.51
MX-MB10-D2S50-MCS	4377-2	9.2	1306.8	8.7	8.2		0.61	7.68
MX-MB10-D2-MCS	4378-2	7.7	1311.1	9.0	8.9	0.01	0.64	7.58
MX-MB10-D2-MCS	4379-2	8.5	1320.7	8.8	8.2	0.01	0.58	7.52
MX-BUSSCAR-CNG-MCS	4383-2	2.2	1479.8	13.0	13.0	9.06/0.94	0.02	4.61
MX-BUSSCAR-CNG-MCS	4387-2	1.7	1466.4	12.8	10.6	10.82/0.80	0.01	4.64
MX-FAW-CNG-MCS	4393-2	1.9	2054.9	26.9	26.8	n/a	0.01	3.34
MX-FAW-CNG-MCS	4394-2	1.3	2017.8	25.6	23.0	8.71/0.52	0.00	3.40
MX-ALLISON-D2S15-MCS	4400-2	1.3	1801.7	10.9	10.9		0.04	5.69
MX-ALLISON-D2S15-MCS	4402-2	1.4	1597.0	9.6	2.7		0.02	6.42
MX-RTP1-D2S15-MCS	4408-2	1.1	1482.9	10.4	3.6		0.06	6.92
MX-RTP1-D2S50-MCS	4410-2	1.3	1512.2	10.9	10.9		0.07	6.70
MX-RTP1-D2S50-MCS	4411-2	1.2	1547.2	11.2	4.3		0.05	6.55
MX-SCANIA18-D2S15-MCS	4418-2	9.2	2391.4	18.5	18.5	0.19	0.90	4.27
MX-SCANIA18-D2S15-MCS	4419-2	10.2	2478.8	18.5	18.2	0.20	0.92	4.11
MX-SCANIA18-D2S50-MCS	4421-2	10.4	2370.6	16.3	16.2	0.09	1.11	4.25
MX-SCANIA18-D2S50-MCS	4422-2	9.0	2410.1	16.1	15.8	0.09	0.98	4.18

Table A- 3: Emissions and fuel economy from tests over the MX3 segment of the MCS.

WVU Ref Num	Test ID	CO g/mile	CO ₂ g/mile	NO _x g/mile	NO _{x2} g/mile	FIDHC ⁽¹⁾ g/mile	PM g/mile	Fuel Economy (mile/gal)
MX-VOLVO12-D2S15-MCS	4312-3	17.1	2495.3	23.9	24.0	0.72	1.58	3.82
MX-VOLVO12-D2S15-MCS	4315-3	15.0	2484.6	23.9	23.4	0.77	1.24	3.85
MX-VOLVO12-D2-MCS	4320-3	22.8	2408.9	22.3	22.2	0.35	1.83	3.95
MX-VOLVO12-D2-MCS	4321-3	22.0	2436.5	22.1	21.7	0.28	3.27	3.91
MX-VOLVO12-D2-MCS	4322-3	23.7	2462.8	21.9	21.4	0.24	1.94	3.86
MX-SCANIA15-D2S15-MCS	4330-3	9.0	3234.8	22.9	23.0	0.91	0.76	2.97
MX-SCANIA15-D2S15-MCS	4332-3	8.0	3285.2	24.0	23.1	1.02	0.72	2.93
MX-SCANIA15-D2-MCS	4334-3	9.1	3193.9	22.8	22.8	0.74	0.85	3.12
MX-SCANIA15-D2-MCS	4335-3	8.3	3261.6	23.7	22.9	0.64	0.88	3.06
MX-RTP3-D2S15-MCS	4353-3	7.5	2162.8	16.9	16.9	0.26	0.59	4.72
MX-RTP3-D2S15-MCS	4355-3	6.8	2071.4	15.4	14.7	0.17	0.53	4.93
MX-RTP3-D2S50-MCS	4362-3	8.3	2103.3	16.7	16.8	0.14	0.55	4.79
MX-RTP3-D2S50-MCS	4363-3	7.4	2080.7	16.6	15.8	0.09	0.50	4.85
MX-RTP3-D2-MCS	4364-3	6.9	2106.6	16.9	16.9	0.24	0.47	4.73
MX-RTP3-D2-MCS	4365-3	6.9	2096.0	17.0	16.3	0.24	0.47	4.76
MX-MB10-D2S15-MCS	4369-3	12.0	1964.3	12.3	12.3	0.11	0.79	5.18
MX-MB10-D2S15-MCS	4371-3	10.3	1963.7	12.1	11.5	0.08	0.70	5.18
MX-MB10-D2S50-MCS	4376-3	13.2	2024.7	12.6	12.7		0.89	4.96
MX-MB10-D2S50-MCS	4377-3	12.2	1970.6	12.4	11.7	0.12	1.98	5.09
MX-MB10-D2-MCS	4378-3	10.7	2007.0	12.8	12.7	0.02	0.77	4.95
MX-MB10-D2-MCS	4379-3	10.2	2000.9	12.8	12.1		0.75	4.97
MX-BUSSCAR-CNG-MCS	4383-3	3.1	2271.2	16.0	15.9	13.50/2.05	0.03	3.00
MX-BUSSCAR-CNG-MCS	4387-3	2.2	2239.4	15.6	13.3	13.55/2.49	0.02	3.04
MX-FAW-CNG-MCS	4393-3	1.4	2870.1	34.6	34.6	5.31/0.33	0.00	2.41
MX-FAW-CNG-MCS	4394-3	1.6	2847.1	32.0	28.8	5.95/0.38	0.00	2.43
MX-ALLISON-D2S15-MCS	4400-3	1.6	2438.9	13.2	13.2		0.03	4.21
MX-ALLISON-D2S15-MCS	4402-3	1.3	2475.0	12.7	5.6		0.02	4.15
MX-RTP1-D2S15-MCS	4408-3	1.2	2136.1	15.2	6.1		0.29	4.80
MX-RTP1-D2S50-MCS	4410-3	1.4	2172.9	17.0	16.9		0.32	4.66
MX-RTP1-D2S50-MCS	4411-3	1.2	2131.5	16.2	7.3		0.21	4.75
MX-SCANIA18-D2S15-MCS	4418-3	9.7	3282.0	21.8	21.8	0.27	0.95	3.11
MX-SCANIA18-D2S15-MCS	4419-3	10.1	3564.8	23.3	22.8	0.28	0.91	2.87
MX-SCANIA18-D2S50-MCS	4421-3	11.0	3397.0	21.3	21.1	0.13	1.05	2.97
MX-SCANIA18-D2S50-MCS	4422-3	11.0	3452.0	20.8	20.4	0.11	1.06	2.92

Table A- 4: Emissions and fuel economy from ETC tests

WVU Ref Num	Test ID	CO g/mile	CO ₂ g/mile	NO _x g/mile	NO _{x2} g/mile	FIDHC ⁽¹⁾ g/mile	PM g/mile	TEOM g/mile	Fuel Economy (mile/gal)
MX-VOLVO12-D2S15-ETC	4311-1	6.78	1050.07	10.5	10.5	0.41	0.87	0.69	9.09
MX-VOLVO12-D2S15-ETC	4313-1	9.70	1021.85	9.9	9.7	0.36	0.84		9.30
MX-SCANIA15-D2S15-ETC	4329-1	2.65	1663.66	11.7	11.7	1.03	0.48	0.31	5.78
MX-SCANIA15-D2S15-ETC	4331-1	2.60	1599.48	11.6	11.0	1.02	0.39	0.27	6.01
MX-RTP3-D2S15-ETC	4354-1	2.87	1247.35	8.8	8.8	0.19	0.41	0.30	8.20
MX-RTP3-D2S15-ETC	4356-1	2.39	1220.47	8.0	7.6	0.18	0.29	0.22	8.38
MX-RTP3-D2S15-ETC	4360-1	2.92	1281.33	9.5	9.5	0.19	0.32	0.23	7.98
MX-RTP3-D2S15-ETC	4361-1	2.61	1229.26	8.5	8.2	0.19	0.25	0.19	8.32
MX-MB10-D2S15-ETC	4370-1	2.24	1132.85	8.0	8.0	0.06	0.15	0.12	9.03
MX-MB10-D2S15-ETC	4372-1	2.11	1135.03	7.8	7.4	0.05	0.15	0.12	9.02
MX-BUSSCAR-CNG-ETC	4386-1	0.53	915.43	7.5	7.5	3.67/0.25	0.04	0.03	7.51
MX-BUSSCAR-CNG-ETC	4388-1	0.72	930.41	6.1	5.4	4.56/0.31	0.05	0.03	7.37
MX-ALLISON-D2S15-ETC	4399-1	0.74	1210.16	6.0	6.1	0.00	0.03	0.02	8.48
MX-ALLISON-D2S15-ETC	4401-1	0.58	1051.14	4.9	2.3		0.01	0.01	9.76
MX-RTP1-D2S15-ETC	4406-1	0.42	1084.99	7.3	7.3		0.21	0.12	9.46
MX-RTP1-D2S15-ETC	4409-1	0.51	1097.79	6.7	3.4		0.20	0.11	9.35
MX-SCANIA18-D2S15-ETC	4417-1	2.13	1735.08	10.8	10.6	0.23	0.25	0.18	5.90

Appendix B: Additional Figures

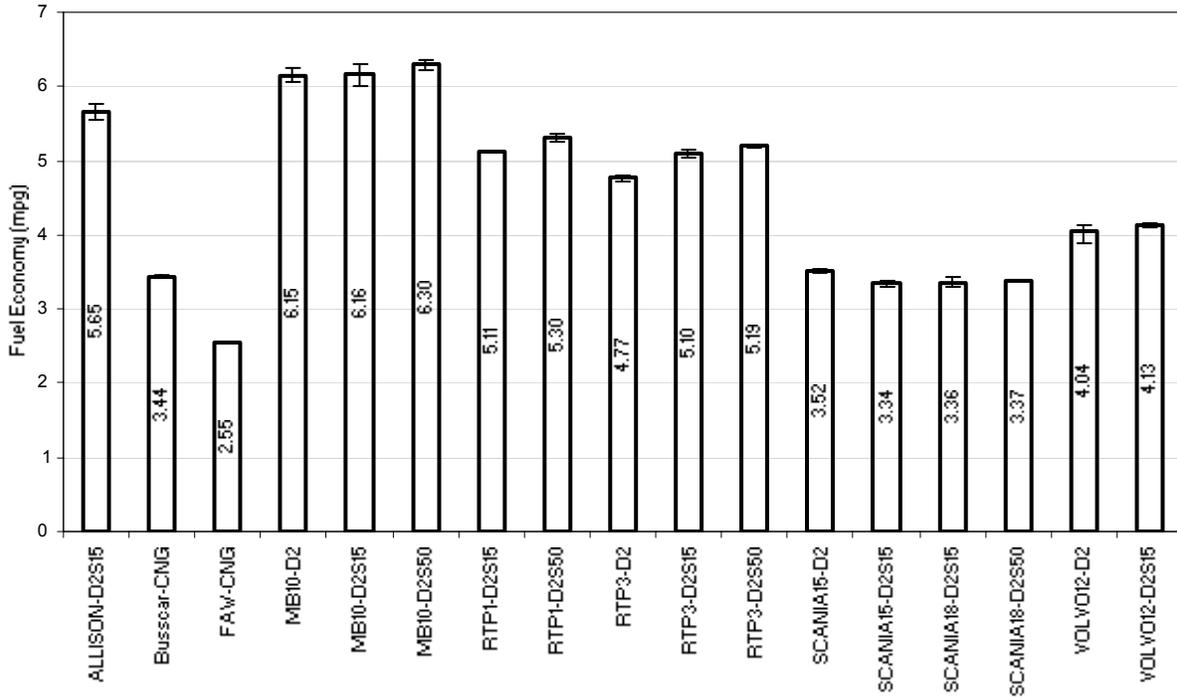


Figure B - 1: Fuel economy over the MX1 mode of the MCS

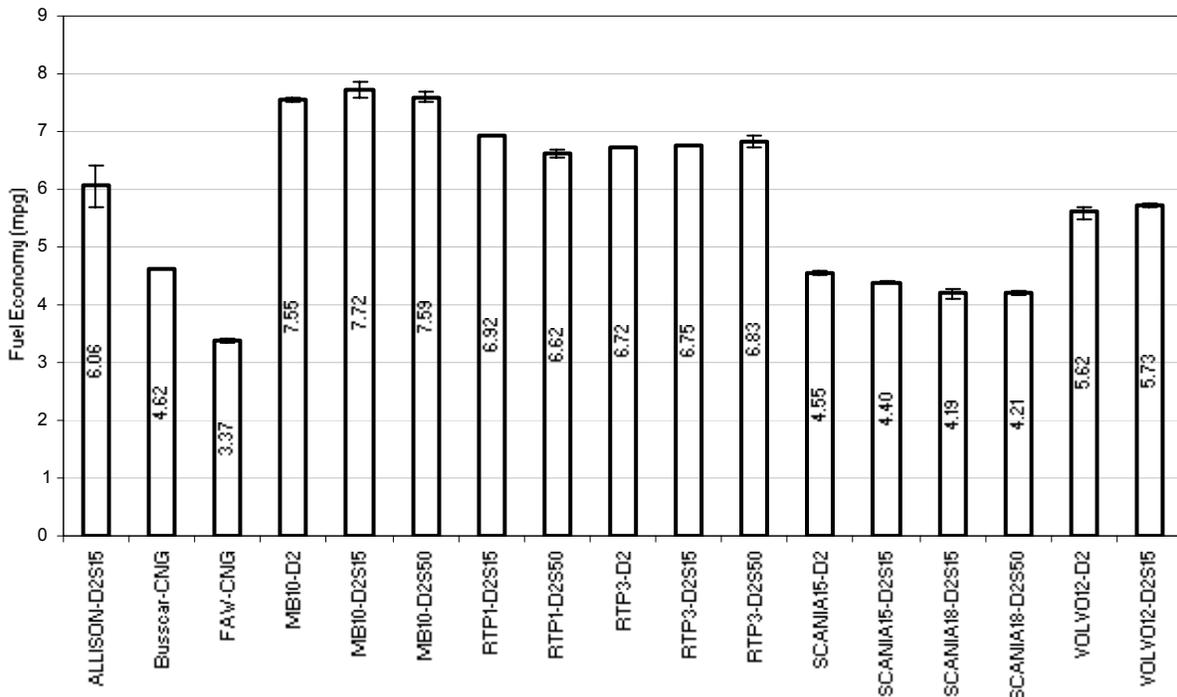


Figure B - 2: Fuel economy over the MX2 mode of the MCS

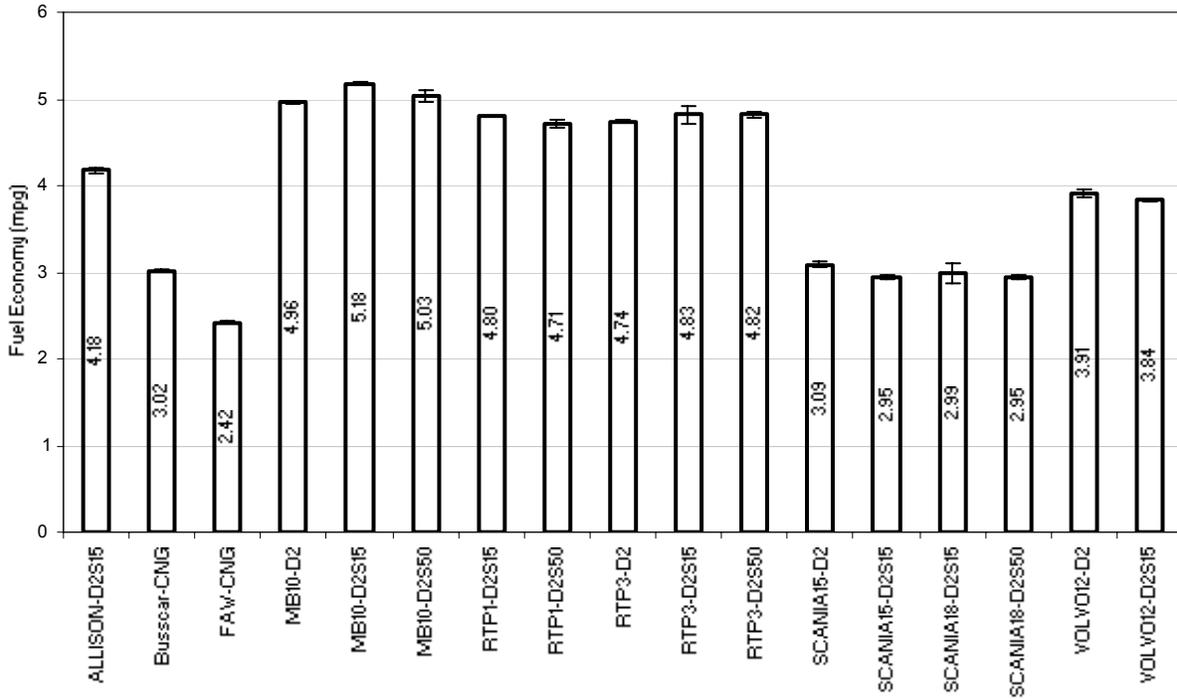


Figure B - 3: Fuel economy over the MX3 mode of the MCS

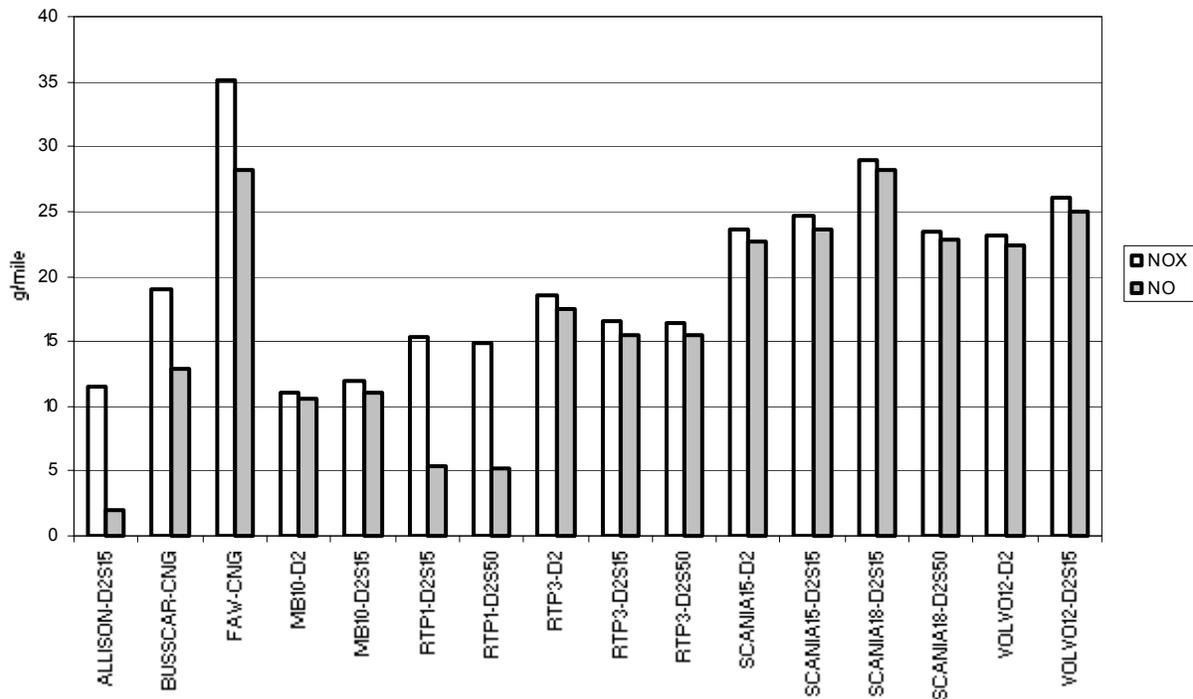


Figure B - 4: NO_x emissions over the MX1 segment of the MCS

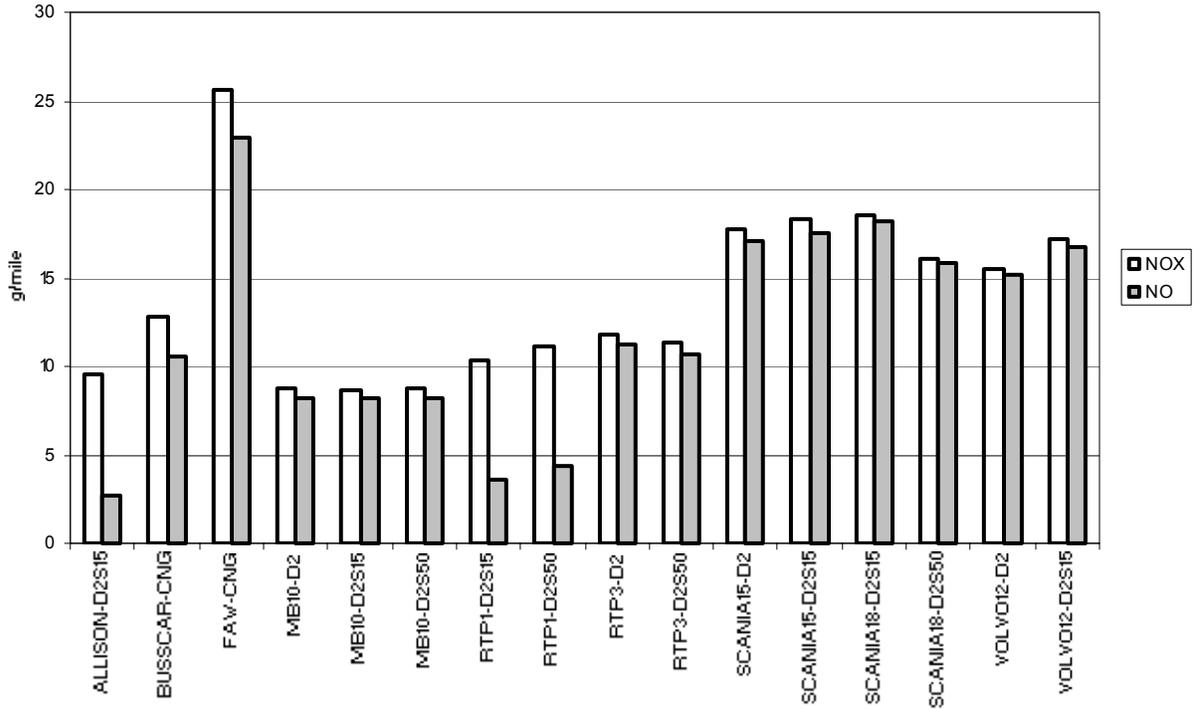


Figure B - 5: NO_x emissions over the MX2 segment of the MCS

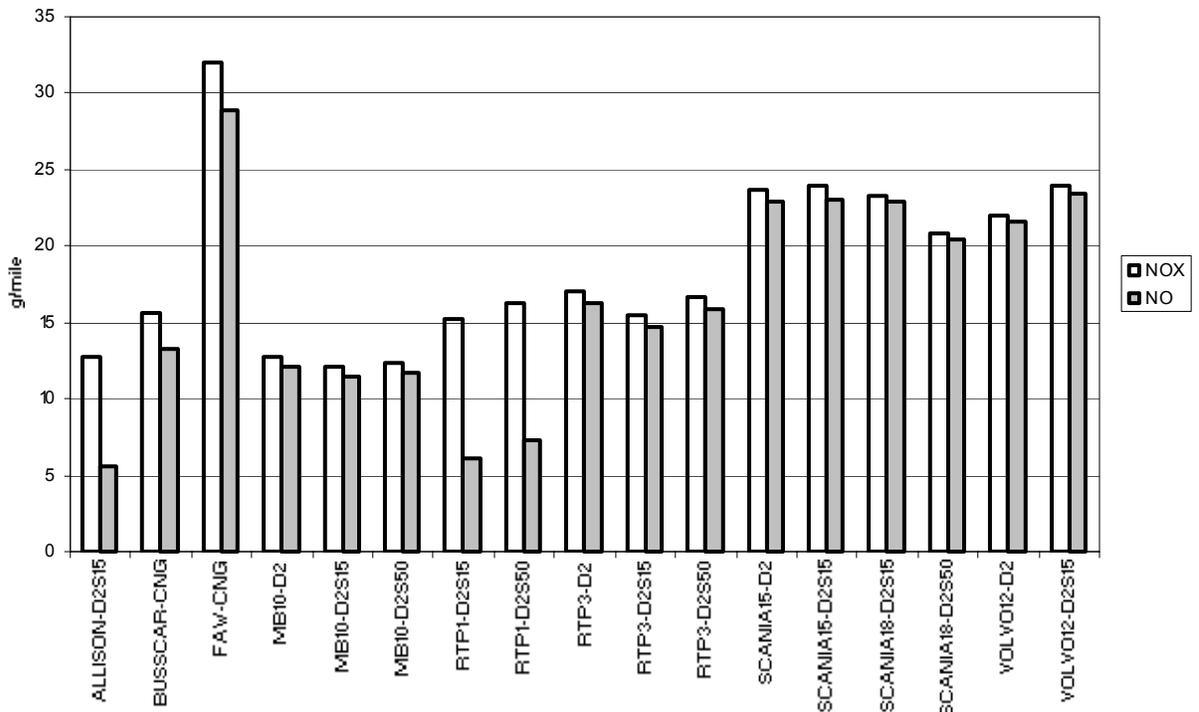


Figure B - 6: NO_x emissions over the MX3 segment of the MCS

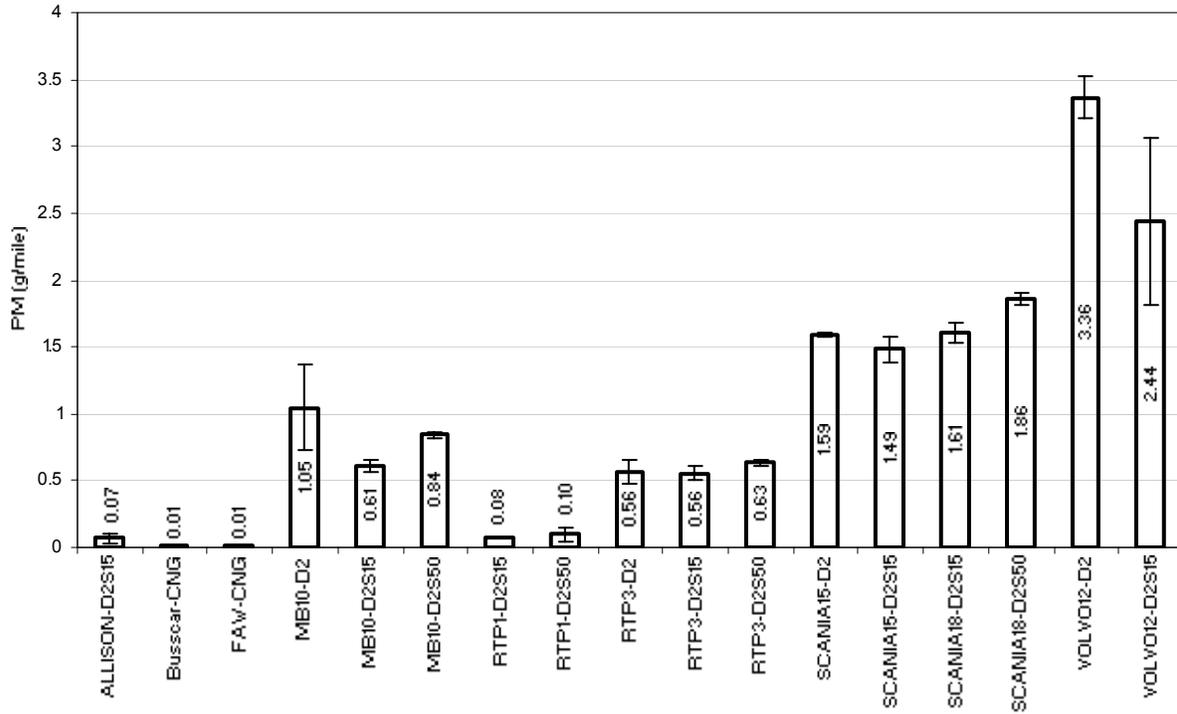


Figure B - 7: Particulate emissions over the MX1 segment of the MCS

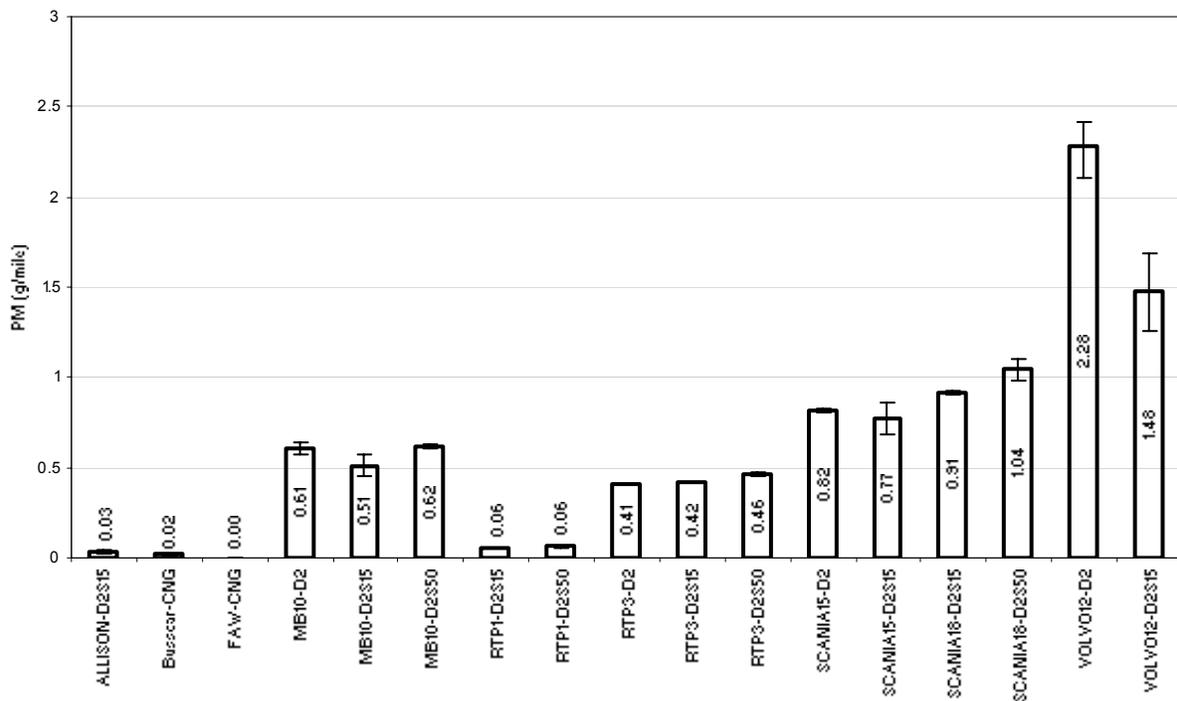


Figure B - 8: Particulate emissions over the MX2 segment of the MCS

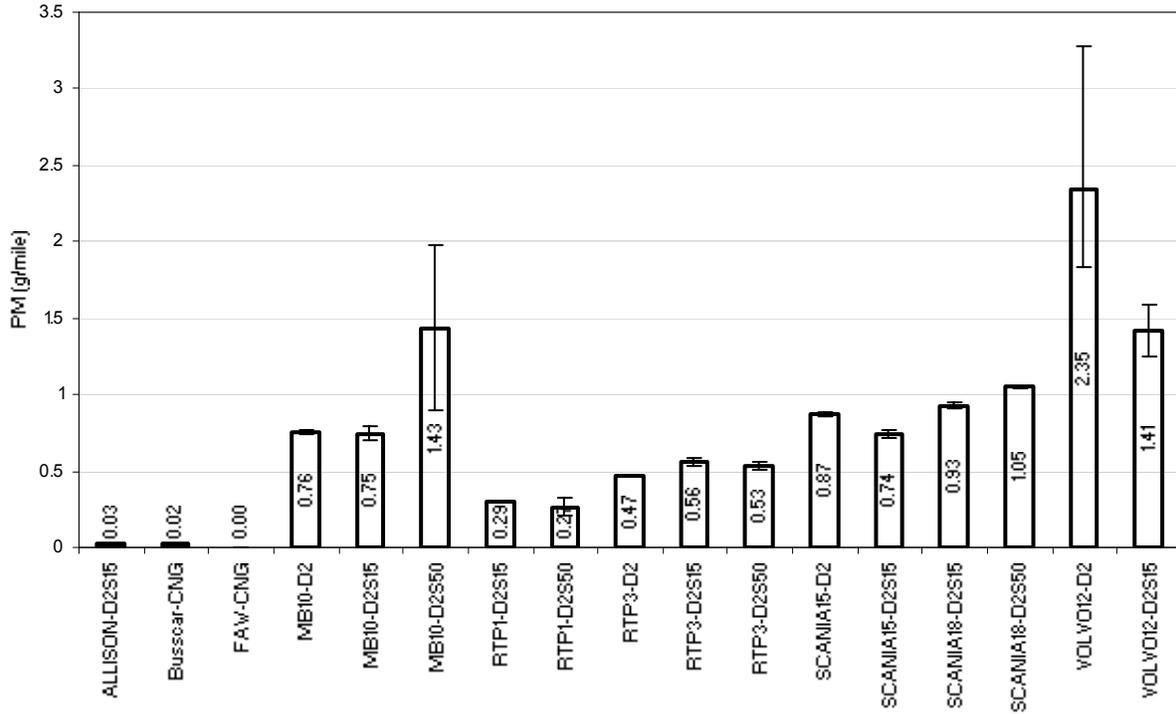


Figure B - 9: Particulate emissions over the MX3 segment of the MCS

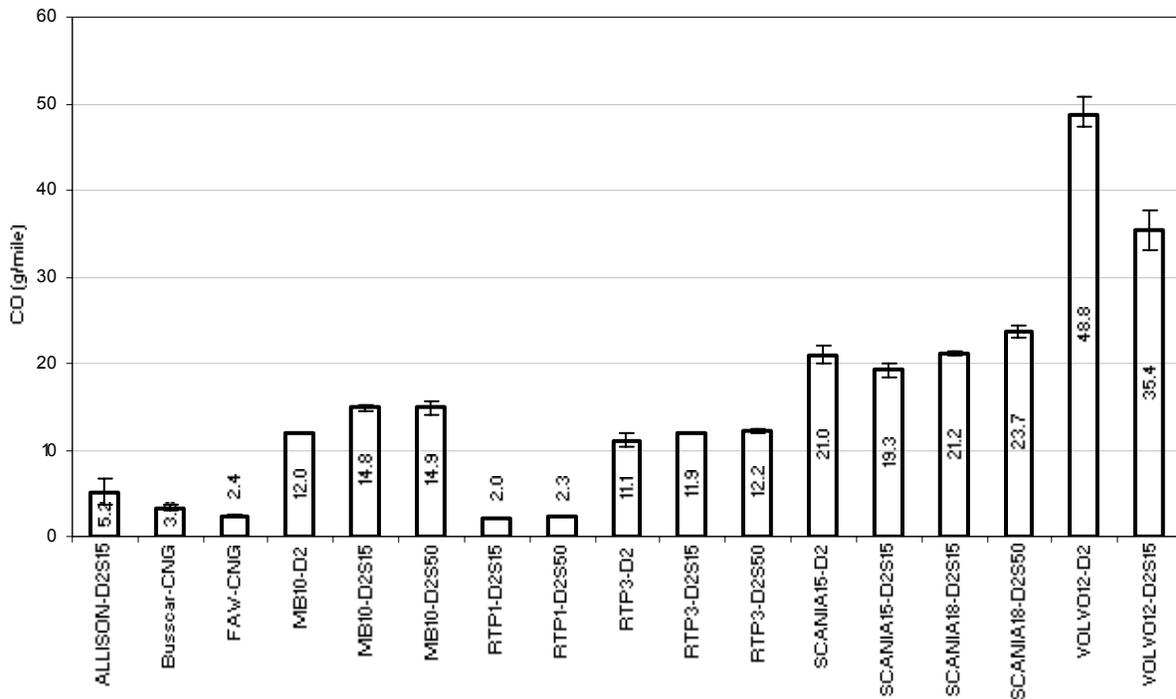


Figure B - 10: Carbon monoxide emissions over the MX1 segment of the MCS

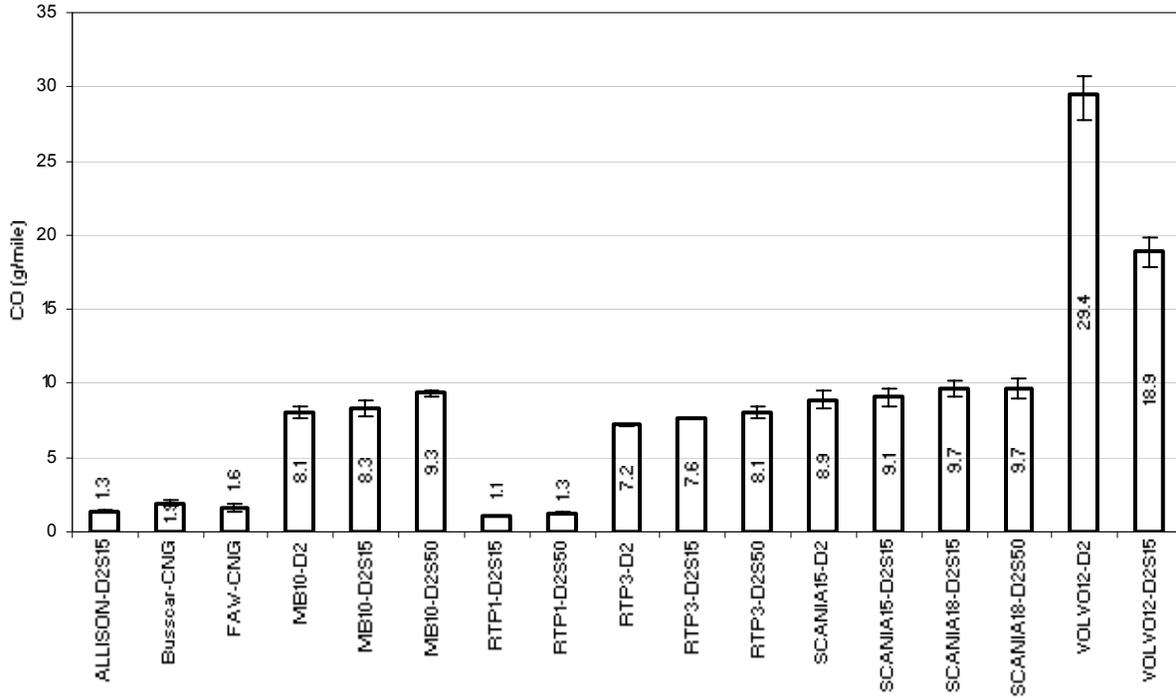


Figure B - 11: Carbon monoxide emissions over the MX2 segment of the MCS

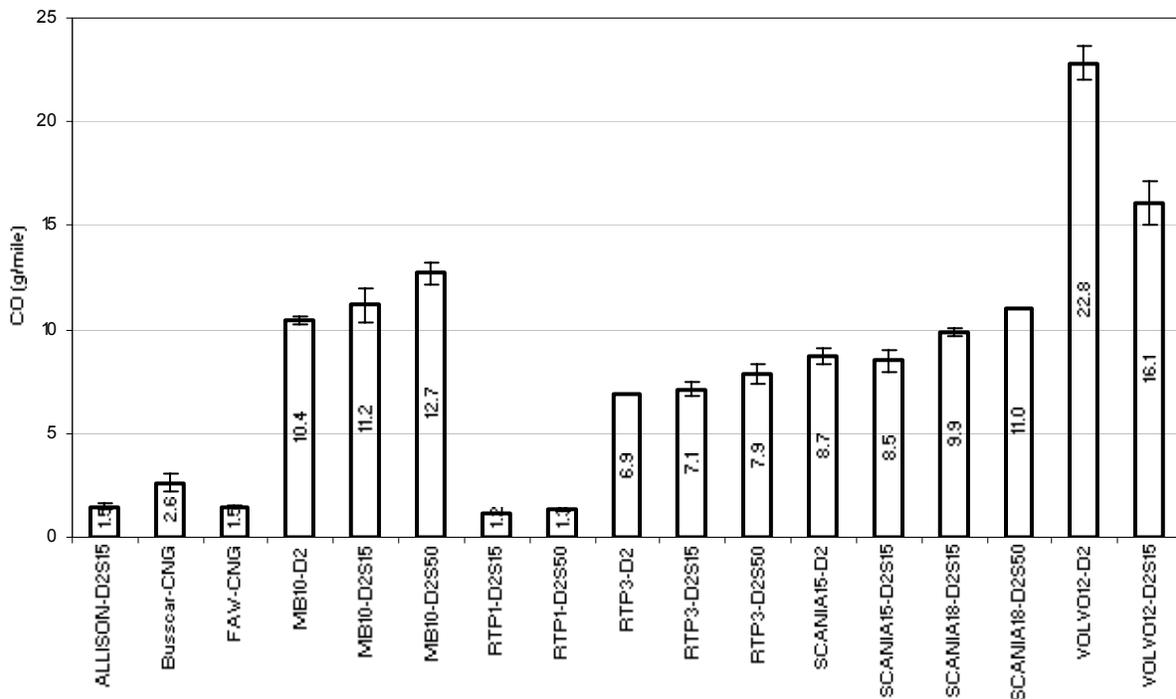


Figure B - 12: Carbon monoxide emissions over the MX3 segment of the MCS

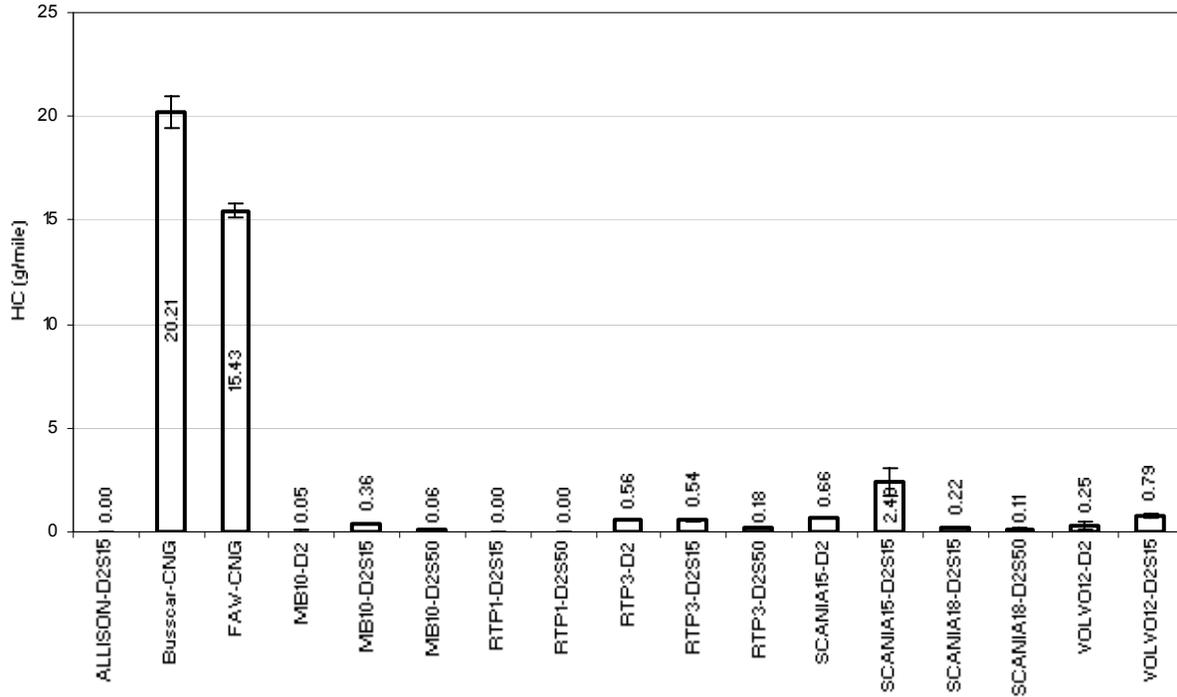


Figure B - 13: Hydrocarbon emissions over the MX1 segment of the MCS

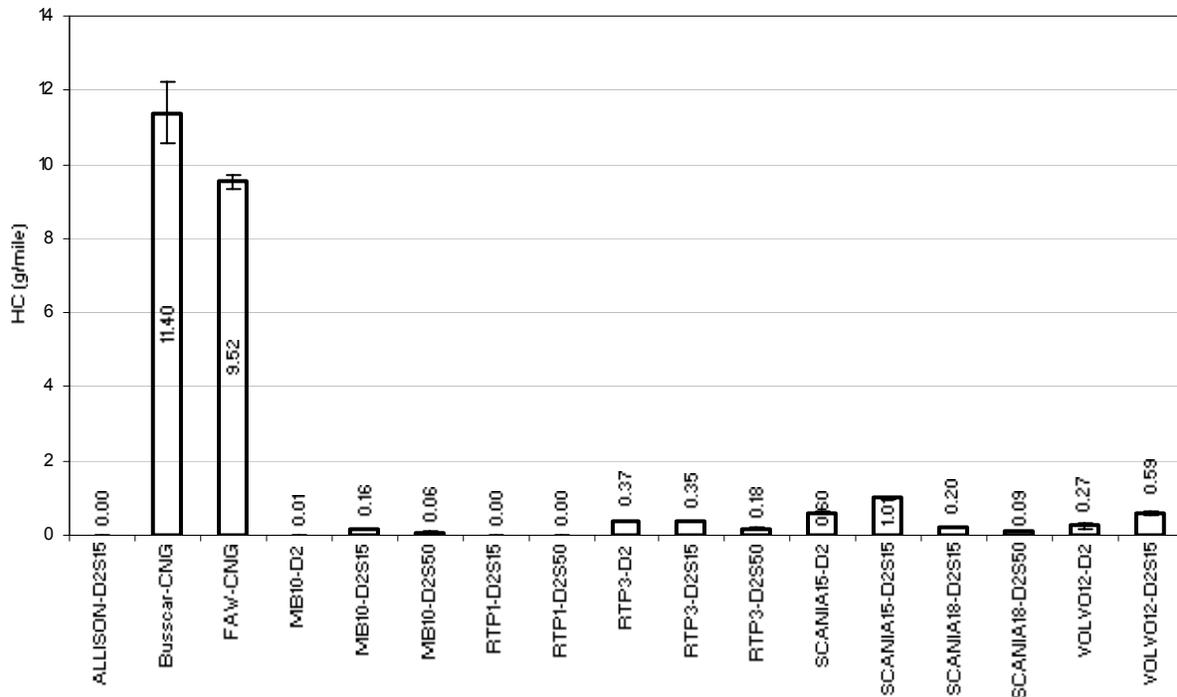


Figure B - 14: Hydrocarbon emissions over the MX2 segment of the MCS

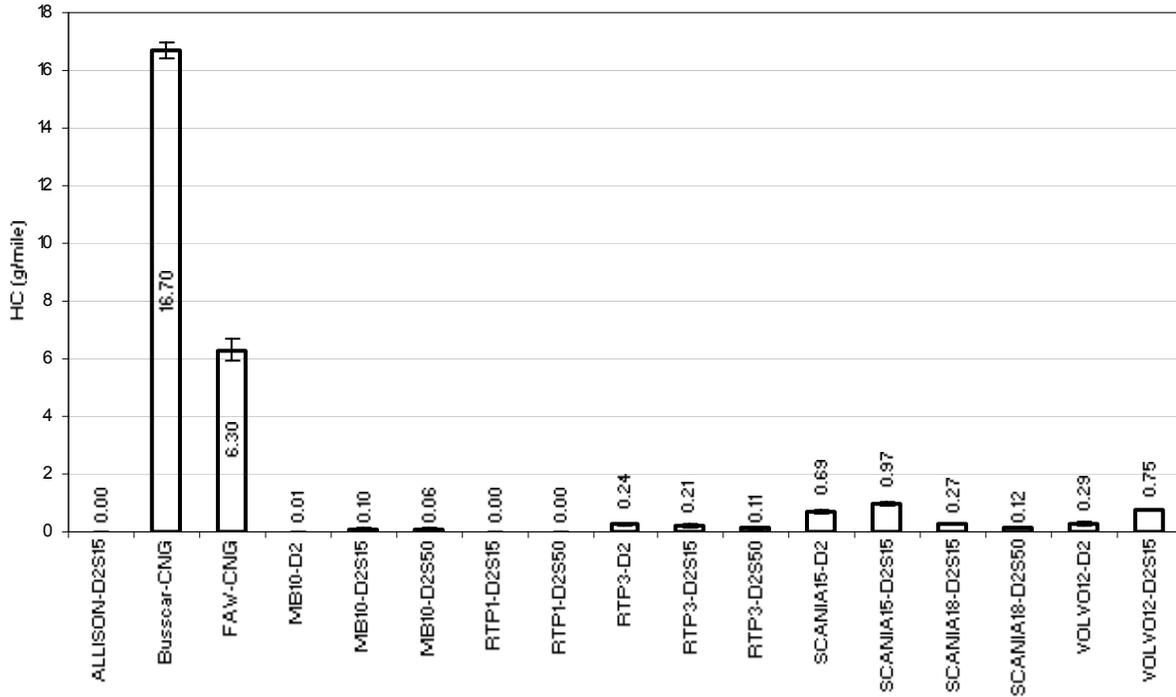


Figure B - 15: Hydrocarbon emissions over the MX3 segment of the MCS

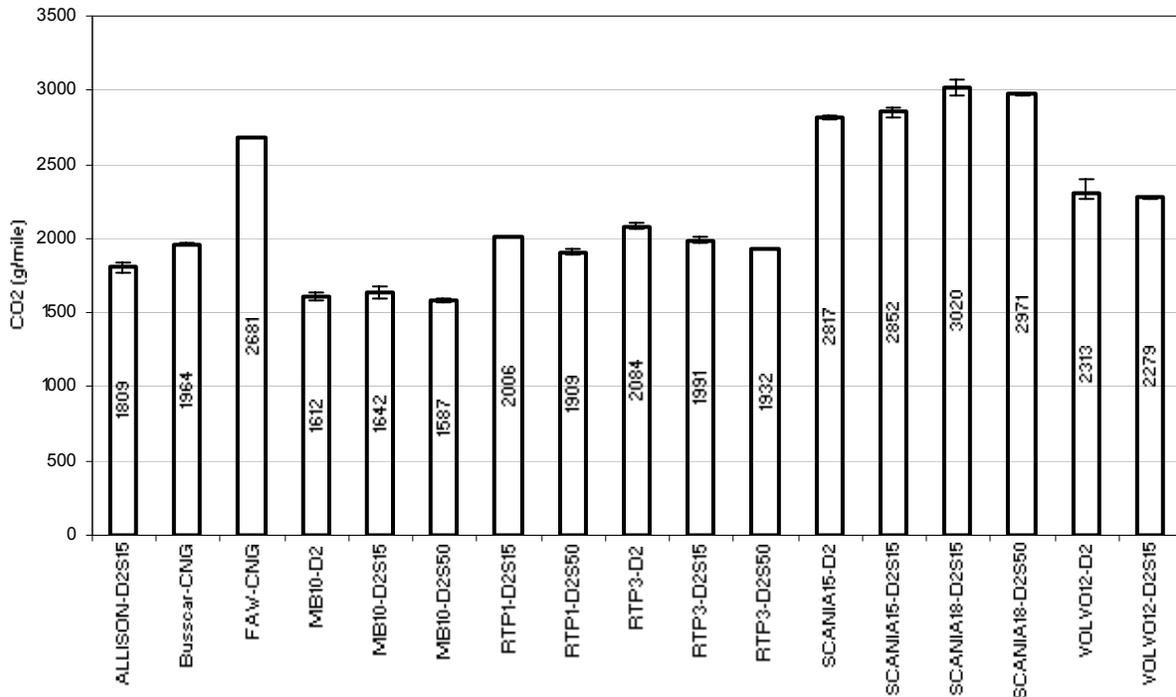


Figure B - 16: Carbon dioxide emissions over the MX1 segment of the MCS

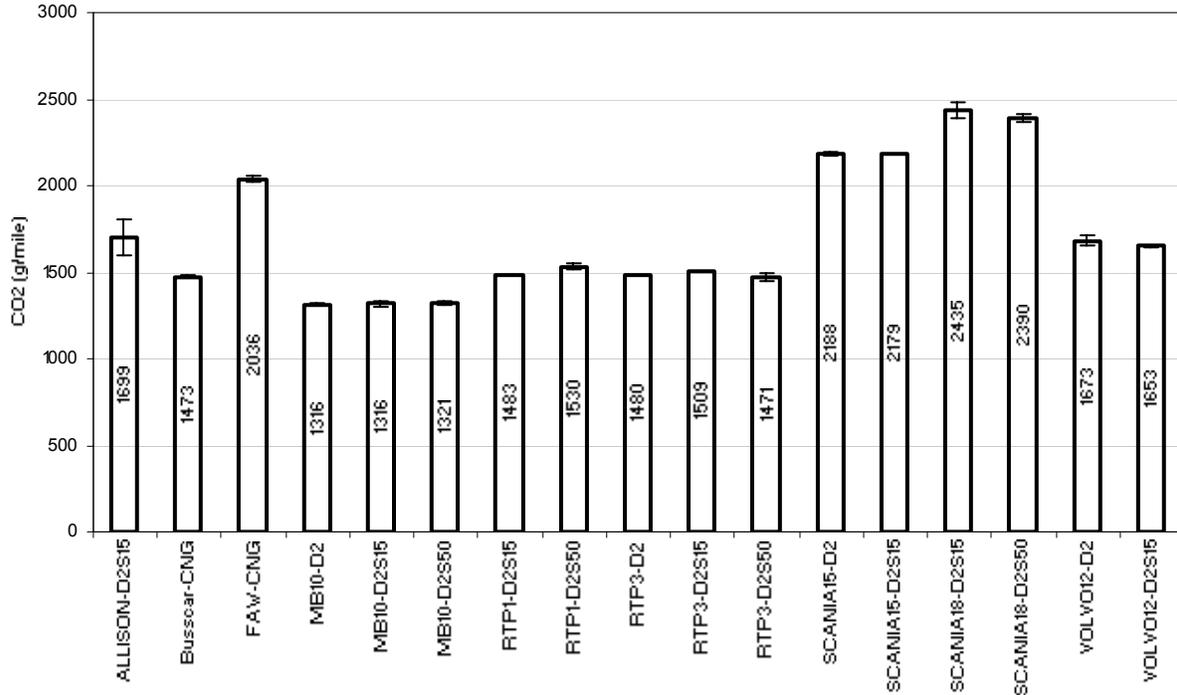


Figure B - 17: Carbon dioxide emissions over the MX2 segment of the MCS

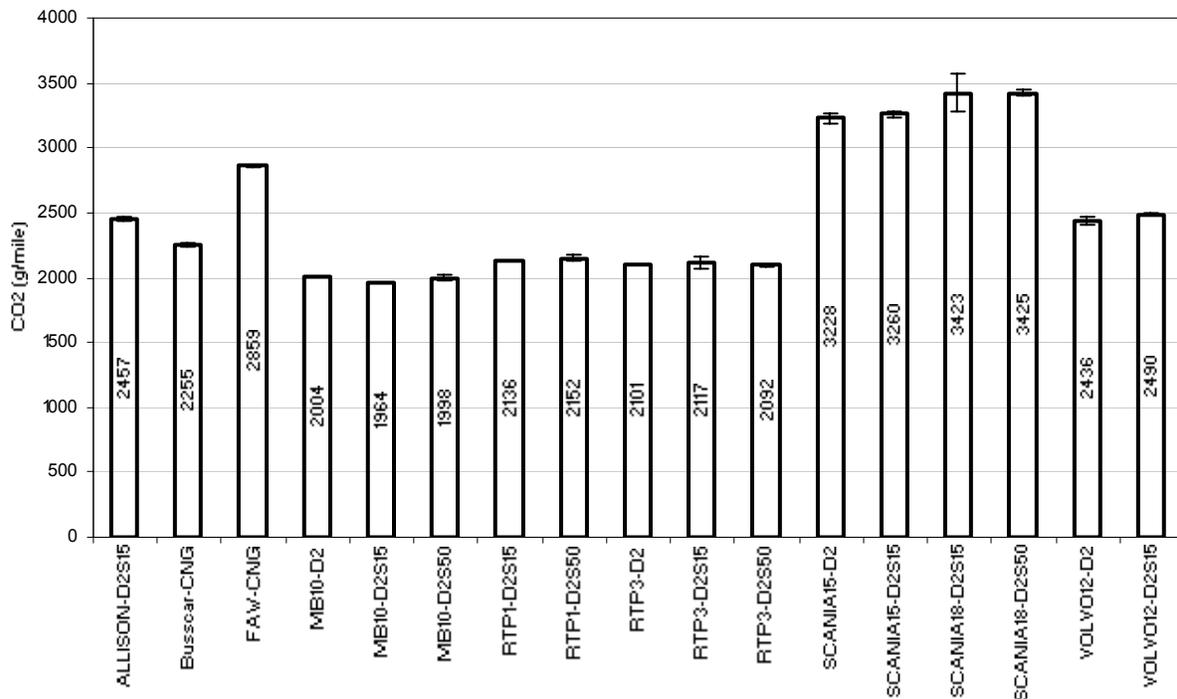


Figure B - 18: Carbon dioxide emissions over the MX3 segment of the MCS

Appendix C: Continuous Emissions Data

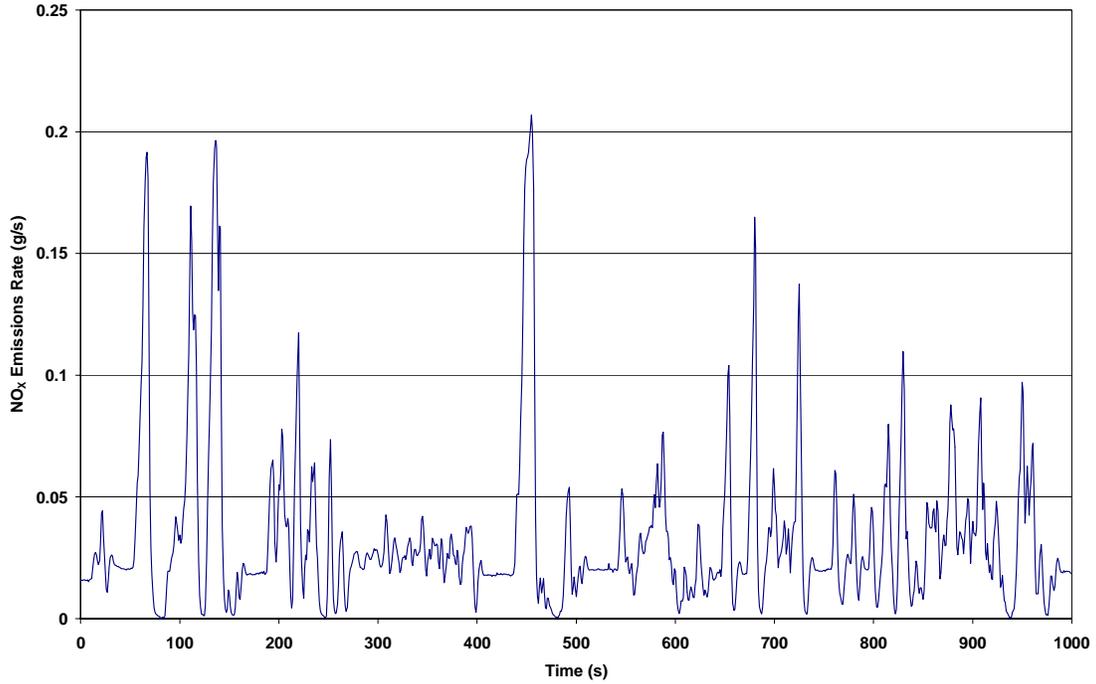


Figure C - 1: Continuous NO_x emissions from RTP3 over the MX1 segment of the MCS

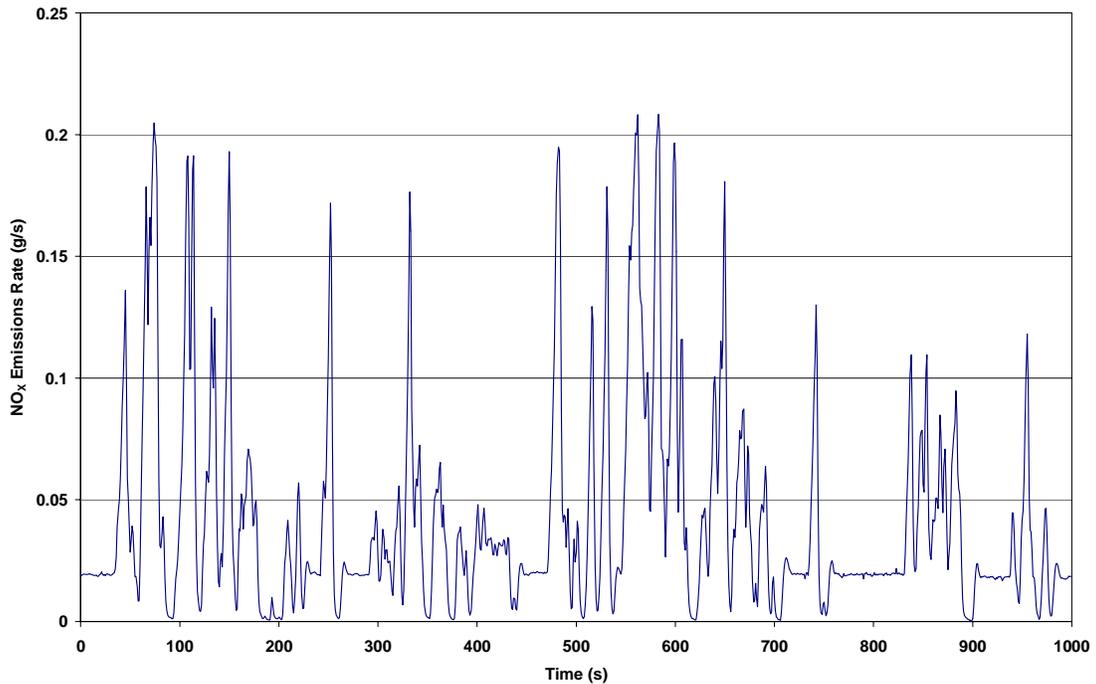


Figure C - 2: Continuous NO_x emissions from RTP3 over the MX2 segment of the MCS

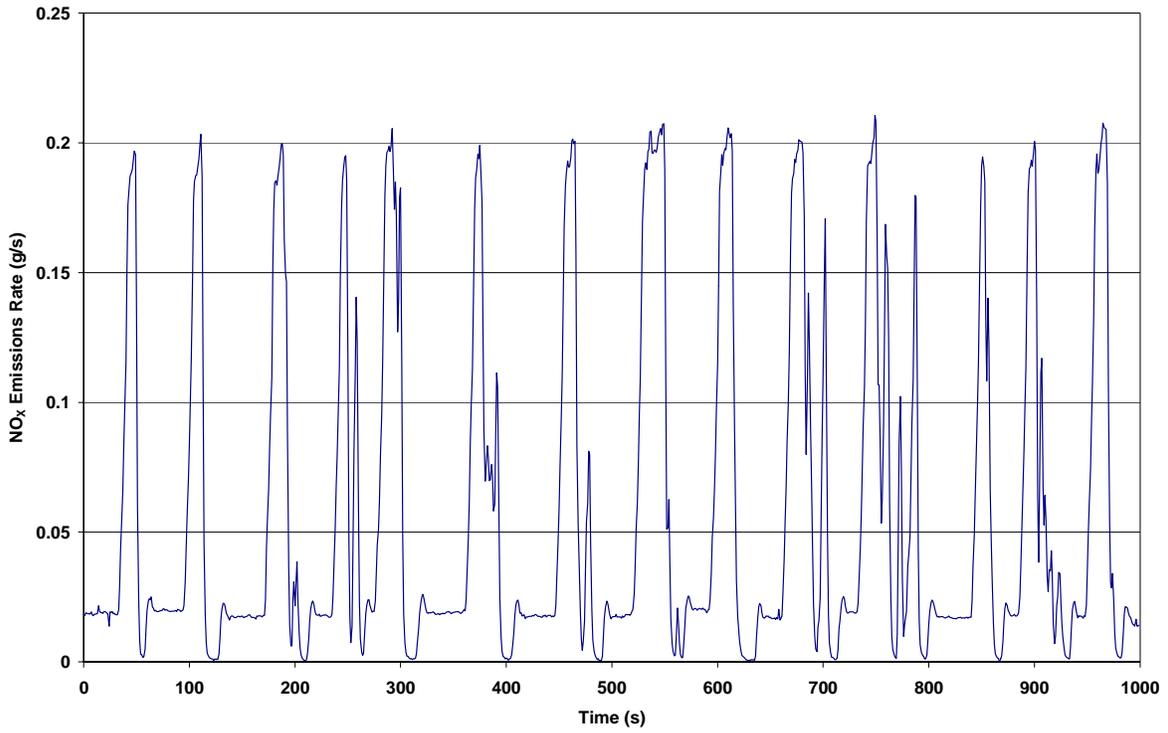


Figure C - 3: Continuous NO_x emissions from RTP3 over the MX3 segment of the MCS

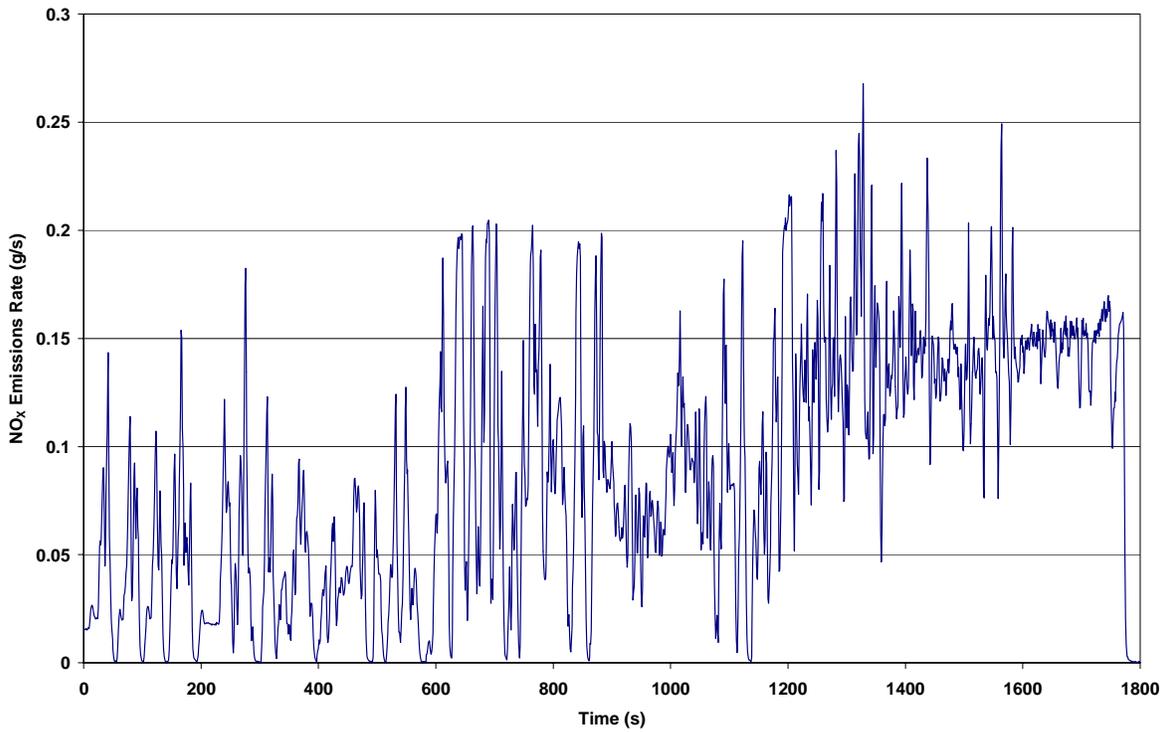


Figure C - 4: Continuous NO_x emissions from RTP3 over the ETC

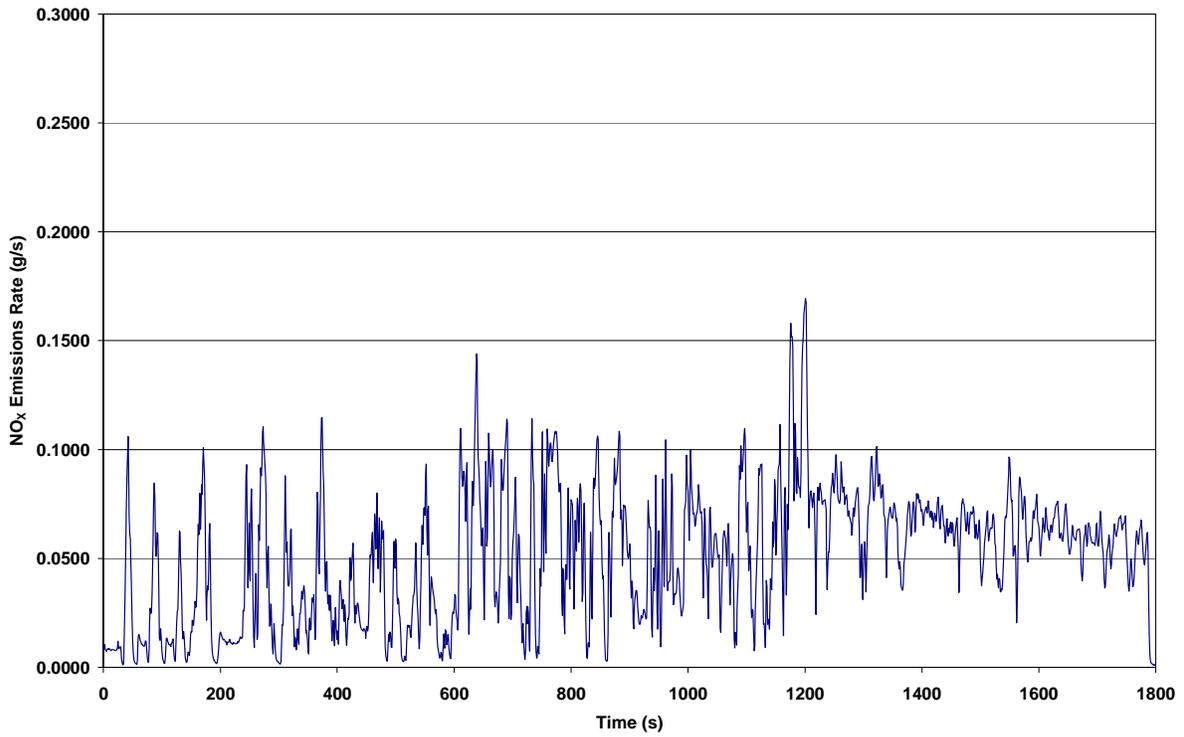


Figure C - 5: Continuous NO_x emissions from the ALLISON Hybrid over the ETC

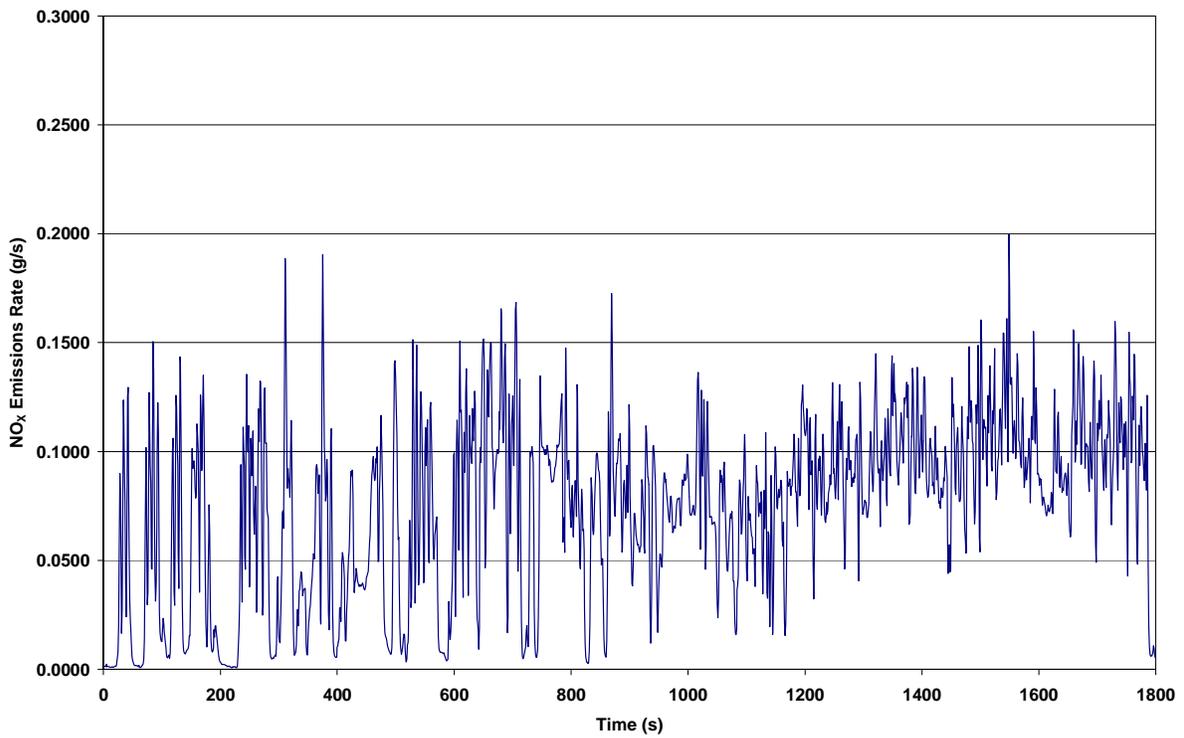


Figure C - 6: Continuous NO_x emissions from the BUSSCAR CNG over the ETC

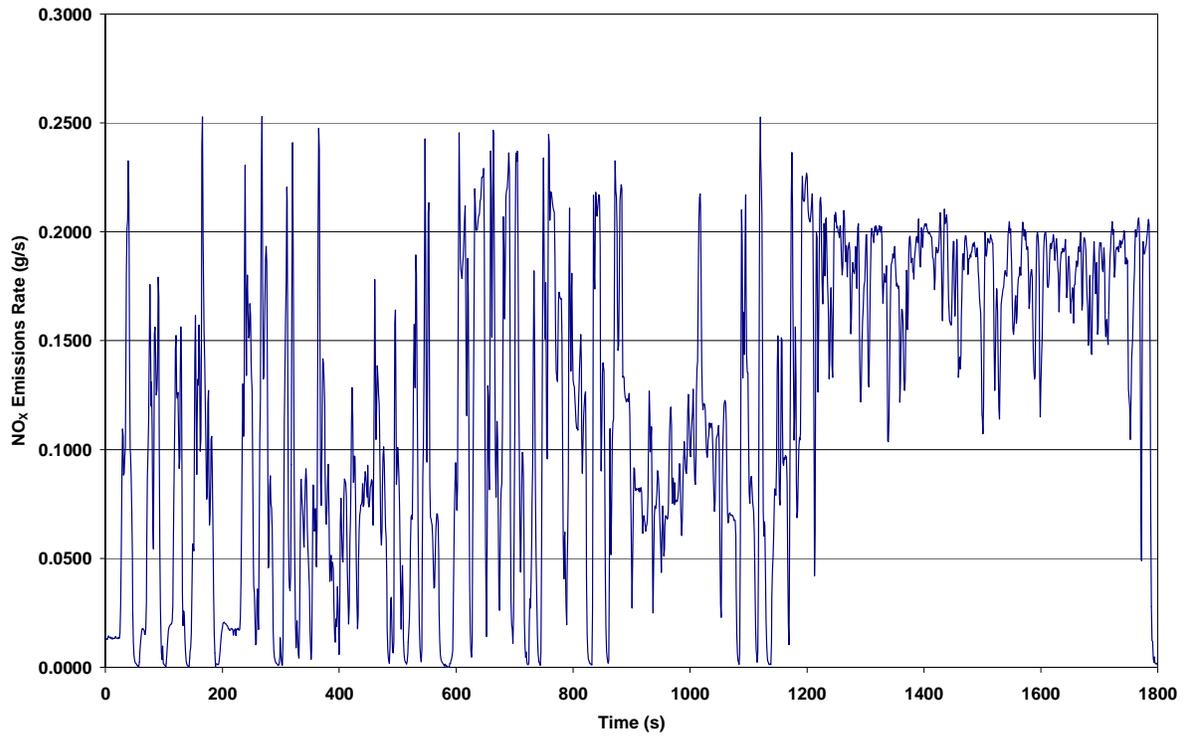


Figure C - 7: Continuous NO_x emissions from the SCANIA15 over the ETC

Table D - 1: Vehicle information as provided by the bus manufacturers.

	BUS 1	BUS 2	BUS 3	BUS 4	BUS 5	RTP 1	RTP 3	BUS 6	BUS 7	BUS 8
VEHICLE										
Make	Gillig	Anhui Ankai	Busscar	FAW AMI	Mercedes Benz	Mercedes Benz	Mercedes Benz	Scania	Scania	Volvo
Model	Phantom	HFF6110GK50	Urbanuss Plus	CA6160	Boxer	Torino 2002	Torino 2002			Prototype
Fuel	Diesel	GNC	GNC	GNC	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel
Type	Conventional	Conventional	Conventional	Articulate	Conventional	Conventional	Conventional	Tandem Axle	Articulate	Conventional
Hybrid System	Dual parallel GM - Allison hybrid electric system, with Variable Electric Transmission, Dual Potency Inversor Module and Energy Storage System	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Gross vehicle Weight (kg)	35,000	10,500	15,760	15,500	N/A	14,000	14,000			16,000
BODY										
Make	Gillig	Ankai	Busscar	FAW	Marco Polo	Marco Polo	Marco Polo	N/A	N/A	Volvo
Length (mm)	12,200	11,120	11,300	15,986		10,800	10,800			11,000
Width (mm)	2,430	2,500	2,500	2,490		2,550	2,550			2,500
Max. height (mm)	2,590	3,040	3,300	3,210	N/A	3,100	3,100			3,220
Floor height (mm)	N/A	2,000	N/A	1,950		980	980			970
Axles	2	2	2	3	2	2	2	3	3	2
Gross weight (kg)	15,880	N/A	N/A	N/A	N/A	8,500	8,500			10,250
Max. weight passenger load (kg)	7,480	5,500	N/A	5,980	N/A	6,600	6,600			6,230
PASSENGERS										
Sitted	40	32	41	35		28	28			32
Standing	70	N/A	N/A	N/A	N/A	60	60			57
Total	110	N/A	N/A	N/A	N/A	88	88	120	160	89

Table D - 2 (cont.): Vehicle information as provided by the bus manufacturers.

	BUS 1	BUS 2	BUS 3	BUS 4	BUS 5	RTP 1	RTP 3	BUS 6	BUS 7	BUS 8
TRANSMISSION										
Make	GM - Allison hybrid electric system	Allison	Spicer	Allison		Allison	Allison			ZF
Model	EP 40	B300	ES567B	B400	N/A	B300	B300	ZF4HP590 NBS	ZF5HP602C	ZF5HP552-N
Type	Variable electric transmission	Automatic gear box	Synchronized	With retarder	N/A	N/A	N/A			N/A
No. Gears	Infinite variable	4	7	4	5	5	5	4	5	5
Shift control	Electronic	Automatic	Manual	Automatic	N/A	Automatic	Automatic	Automatic	Automatic	Automatic
Gear relation	Variable	1:1	N/A	1:1	N/A	N/A	N/A			N/A
Differential relation	5.25	6.5	5.29	6.33	N/A	6.17	6.17			2.43
CHASSIS										
Model	Gillig	HFF6110GK50	OISA	CA6160DK17		OMC	OMC			B7R
ENGINE										
Make	Cummins	Cummins	Cummins	Cummins	Mercedes Benz	Mercedes Benz	Mercedes Benz	Scania	Scania	Volvo
Model	ISB	B5.9-230G	BG-230 Plus	C8.3G Plus	OM 924 LA	900	900	DC9 (02) 260	DC9 (03) 300	D7C
Environmental Certification	EPA 2002	EPA 2004	EPA 2004	EPA 2004	N/A	EPA 98	EPA 98	EURO III	EURO III	EURO III
Type	Turbocharged	Turbocharged		Turbocharged		OM-906-LA	OM-906-LA	Electronic	Electronic	Electronic
No. Cilinders	6	6	6	6		6	6	6	6	6
Max. Potency (HP @ RPM)	260 @ 2400	230 @ 2800	230 @ 2800	280 @ 2400		230 @ 2300	230 @ 2300	260	300	300 @ 2200
Max. Pair (lb/ft @ RPM)	660 @ 1400	500 @ 1600	500 @ 1600	850 @ 1400	N/A	698	698			1270NM @ 1200 RPM
Compression Relation	16.5:1	10:1	10.5:1	10:1	N/A	17.4:1	17.4:1	17:1	17:1	19.5:1
Displacement (L)	5.9	5.9	5.9	8.3	N/A	6.37	6.37	9	9	7.3
Injection	N/A	Electronic	N/A	Electronic		Electronic	Electronic			Electronic
Turbocompressor	Yes	Yes	N/A	Yes		Yes	Yes			Yes
Intercooler	Yes	N/A	N/A	Cooled with air		Yes	Yes			Yes

	BUS 1	BUS 2	BUS 3	BUS 4	BUS 5	RTP 1	RTP 3	BUS 6	BUS 7	BUS 8
Location	In front of cooling packet	Rear	Rear	Front		In front of radiator	In front of radiator		Rear	Rear
FUEL TANK(S)										
Capacity (L)	378.5	80 L x 6 + 50 L x 2 (580 L water @ 3000 psi)	80 L x 6 (480 L water @ 3600 psi)	90 L x 6 (540 L water @ 3000 psi)	N/A	208	208	400	400	300
WHEELS										
Number	6	6	6	10		6	6			6
Size	11.0 R 22.5	10.00 R 20	11 R 22.5	11 R 20		11 R 22.5	11 R 22.5			295 / 80 R 22.5
EMISSIONS CONTROL										
Yes/No	Yes	Yes	Yes	Yes	N/A	Yes	No			N/A
Type	Continuously Regenerating Technology	Catalytic Converter	Catalytic Converter	Catalytic Converter	N/A	Continuously Regenerating Technology				N/A
Make	Johnson Matthey	Fleetguard	Donaldson	Fleetguard	N/A	Johnson Matthey				N/A
Model	CRT Filter System	3927832	M110857	3928277	N/A	CRT Filter System				N/A