

**HYBRID DIESEL-ELECTRIC BUS / TROLLEY BUS  
DEMONSTRATION PROJECT:  
TECHNICAL COMPARISON OF IN-USE PERFORMANCE**

**APPENDIX F**

**EMISSIONS TESTING DETAILS AND RESULTS  
USED FROM ENVIRONMENT CANADA**

## **Appendix F: Emissions Testing Details and Results from Environment Canada**

Any bus being purchased must be certified to meet current emission standards. Those standards are progressively tightening and the combination of emission controls and on-board diagnostics are becoming more reliable so new buses should inherently be cleaner over their lifetimes than equivalent-technology older buses that they are replacing. However, there is a certain degree of scepticism about emission controls and, particularly when differing technologies are being compared, (diesel vs hybrid vs trolley), it is worthwhile trying to measure their effectiveness.

In this study, there are two particular topics of interest:

1. How do the emissions of diesels, hybrids and trolleys compare when run under the same heavy duty route conditions? Answering this question requires:
  - measuring relevant aspects of those route conditions and the way each bus technology responds to them,
  - developing a test that loads the buses as if they were on the route,
  - measuring the emissions over the range of conditions, and
  - producing a weighted measure of those emissions.
2. Given that the hybrids meet an obsolete emissions standard, (2006) and we have 2007 vehicles on hand, do the 2007 vehicles see the expected degree of advantage when tested under the same conditions? Answering this question is not a definitive test but it helps to support the contention that 2010 buses will have the expected benefit in emissions compared with 2007/8/9 buses.

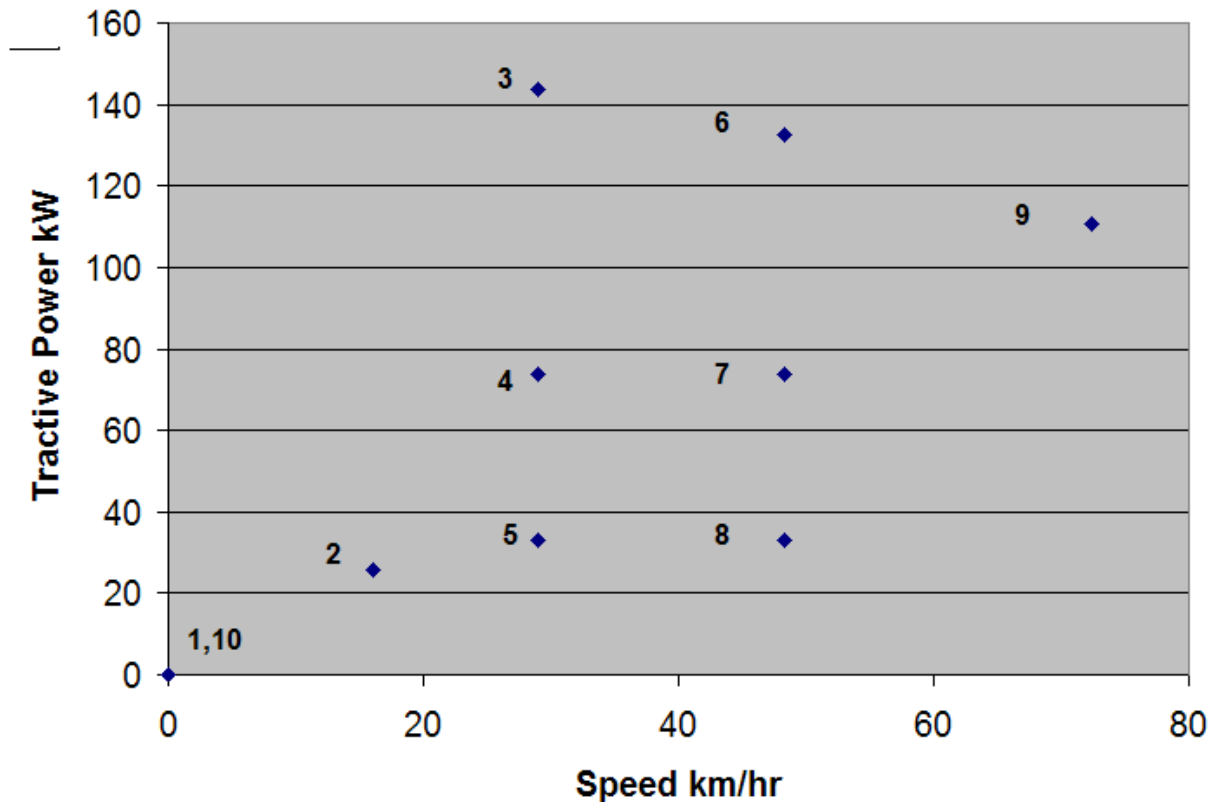
Emission testing is commonly carried out on a chassis dynamometer which allows the vehicle to run on rollers with a simulated road load while the researchers are able to connect stationary emissions measurement equipment to it. Tests use either a dynamic test schedule in which the vehicle accelerates or decelerates just like it is on the road or a multi-mode test schedule where the vehicle runs at a series of specified speed/load points and measurements are made while it is stable at each point. Running a dynamic test schedule requires a specialized dynamometer that can simulate the vehicle's rolling loss and inertia as well as a specialized emissions sampling system that can average emissions over a period of time while compensating for a wide range of power levels. There are no such dynamometers in Edmonton.

Running a multi-mode test schedule is less demanding of the dynamometer but requires careful analysis to select appropriate test modes and weighting factors so that the vehicle can be tested over the right range of operating conditions and the emissions produced can then be numerically weighted and added to give a representative emission. In this project, the test modes were developed based on detailed analysis of data gathered by the on-board vehicle monitoring systems while the buses were running a heavy-duty trolley route (Route 5). A common set of 10 operating modes was developed covering speeds from 0 to 72 km/hr and tractive power levels from 0 to 144 kW, as shown in Figure F.1.

Each bus was tested by running it through these modes sequentially, spending about 10 minutes at each operating point to provide sufficient time for emissions measurements and particulate filter sampling using a portable lab operated by Environment Canada researchers. The operating conditions proved problematic for some buses which could not actually reach the desired power levels or could reach them but not sustain them once battery power was diminished. In every case, the approach was to match the specified speed while making abest attempt to hold the specified power and to record the actual power produced.

The attached Environment Canada report (ERMD Summary Report #07-08S) describes the measurement equipment and procedures used and presents emissions data with simple equal weighting of the test modes. Emissions values as measured by Environment Canada were expressed on a grams per second basis. The subsequent processing was as follows. First, each emission rate is adjusted to the correct power level by multiplying by a ratio of the specified test mode power level divided by the actual power produced. Next, the emission rate in grams per second is multiplied by a mode weighting factor equal to the number of seconds that a particular bus technology would spend in that operating mode during an hour of running the heavy duty route (Route 5) and then divided by the distance travelled during that standard hour. The result is an emission value expressed in grams/kilometre and weighted according to the way an individual bus technology actually responds to the demands of the heavy duty trolley route. The results do not necessarily correspond to certification values since the test conditions are quite different. However, they are useful for ranking the buses for their emission performance on a route with the right energy and power levels for the heavy duty trolley route.

Figure F.1. Schematic of Bus Test Modes



Based on test results for the various 2006 - emissions - standard buses, the following observations could be made.

-The NO<sub>x</sub> emissions for 2006-certified buses proved to be similar at 9.95 g/km, 9.71 g/km and 9.94 g/km for 2006 diesel, Hybrid 1 and Hybrid 2 respectively. The hybrids had a very marginal advantage over the 2006 diesel even though these steady-load test conditions did not give hybrids any particular advantage, possibly because they used some battery charge during the highest power modes.

-When tested at the same conditions, the 2007-certified diesel bus would be expected to have lower emissions than its 2006 counterpart because it meets a lower certification emission standard, (1.2 g/kW.hr vs 2.5 g/kW.hr at certification test conditions). On the ten-mode test sequence, 2007 diesel buses produced 3.83 g/km which is about 38% of the 2006 level. The reduction in certification standards would have suggested a 48% level so this confirms that the emissions were reduced in accordance with the change in certification standards.

-The particulate matter (PM) emissions provide another illustration of changing standards. The 2006 diesels averaged 0.14 g/km of particulate while Hybrid 1 averaged 0.15 g/km. The Hybrid 2 models were certified to 2006 standards but had diesel particulate filters installed. They emitted only 0.06 g/km on average which was comparable but not quite matching the 0.047 g/km emitted by the 2007-certified diesel buses. These conditions don't match the certification test conditions because there are no significant transients and hence they produce relatively low PM emissions. However, it is interesting to note that even under these conditions, the buses with DPF aftertreatment provide substantially lower particulate emissions, (approximately 2-fold to 4-fold).

Table 7.3 Emissions Comparison on kg/km and g/km Basis

	Clean Diesel	Hybrid 1	Hybrid 2	New Trolley (+20% Backup)
GHG (CO <sub>2</sub> e) kg/km	1.966	1.725	1.581	1.93
2007 NO <sub>x</sub> (g/km)	3.83	3.74	3.83	2.88
2010 NO <sub>x</sub> (g/km)	0.64	0.62	0.62	2.23
PM 10 (g/km)	0.0472	0.0495	0.019	0.48
HC (g/km)	0.0251	0.0199	0.003	0.01
CO (g/km)	0.37	0.341	0.042	0.07
SO <sub>x</sub> (g/km)	0.0183	0.016	0.015	2.62

Based on the observations above, it appears reasonable to suggest that the hybrids would benefit from 2007 emissions controls and be able to at least match or marginally improve on the

2007 diesel emissions. (The argument for marginal improvement is based on the capability of the hybrid system to moderate transients, which could not be tested under our test conditions.) Following the same approach, it appears reasonable to expect that both diesels and hybrids will produce correspondingly lower NO<sub>x</sub> emissions when the NO<sub>x</sub> standard is reduced another 6-fold in 2010. On this basis, the predicted 2010 NO<sub>x</sub> emission values in the chart are based on:

1. -our present measurements of 2006-certified buses, adjusted to the 2007 standard based on relative performance of 2006 and 2007 diesels as described
2. -a further 6-fold reduction for 2010 with the small advantage maintained for the hybrids.

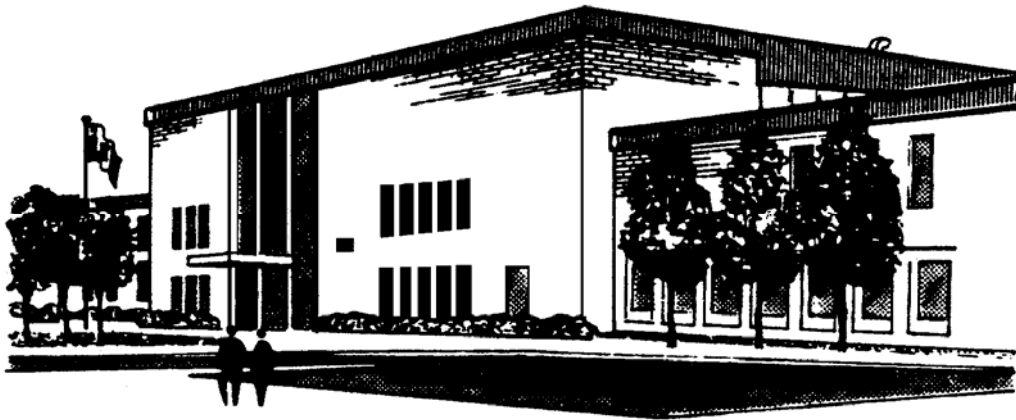
Note that the predicted trolley NO<sub>x</sub> emissions are also reduced by the 2010 technology because the backup buses are assumed to be new technology.

The same approach has been applied to adjust the measured PM emissions to the 2007-on PM emission standard though the magnitude of the change is more questionable here since the buses were being tested under conditions where PM emissions were already low and one of the 2006 buses already had a DPF.

The bottom line is that the evolving NO<sub>x</sub> and PM emissions changes for diesel engines are expected to make future buses, whether diesel or hybrid, considerably cleaner than even the buses of the recent past and, as a consequence, considerably cleaner than the alternative of coal-fired electrical power.

**Evaluation of Exhaust Emissions from Hybrid and Diesel Urban Transit Buses Tested over Ten Steady State Modes in Edmonton, Alberta**

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**ERMD SUMMARY REPORT # 07-08S**  
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In October 2007, staff from the Emissions Research and Measurement Division (ERMD) of Environment Canada undertook exhaust emission measurements of 10 Edmonton Transit System (ETS) buses. The purpose of this study was to compare the exhaust emissions from different engine technologies over ten equally weighted test modes. The results of this study may be used by the City of Edmonton to assist in the decision making process relating to the procurement and modernization of the city's urban transit fleet.

This summary report presents the results on the weighted emission rates (g/min) of the from the testing of 4 diesel and 6 hybrid diesel electric urban transit buses of various make and models as seen in Table 1. Testing took place using Waterous Power Systems' heavy duty chassis dynamometer in Edmonton, Alberta. The Waterous Power Systems dynamometer is incapable of simulating transient driving cycles.

**It is important to note that the results presented in this document do not include corrections for state of charge (SOC) as the calculations for SOC are pending. SOC is fundamental in understanding the function of a hybrid electric (HEV) drive-train and the resultant exhaust emissions.**

This test program examines the influences of speed and road load over a number of steady state driving conditions for both the diesel and HEVs. Two important functions of HEVs can be regenerative braking, and acceleration assist, neither of which would be reflected over the ten minute steady state test cycles to which the emissions in this summary report refer. Consequently the potential emission reduction advantages of the HEV's may not be measurable under these conditions. At this point, as could be expected, the diesel electric hybrid emission rates take their place interspersed among the diesel emission rates.

Supplementary data, in the form of one minute snap shots of each mode forming a ten minute "transient" test, was collected and may present a clearer picture of hybrid efficiency in the final report. This data, along with data collected by researchers from the University of Alberta over the duration of the test program, should offer a thorough picture of net energy and emission changes.

The urban transit bus emissions were sampled and analyzed using the ERMD's Mini Dilution Tunnel (MDT). The MDT has been used to sample emissions during a variety of test programs including the NY Ferry Private Fleet Emission Reduction demonstration<sup>1</sup> and the Montreal Biomer Biodiesel demonstration. The primary function of the mini-dilution system is to collect a known quantity of raw exhaust (partial flow) from the exhaust system of an engine and mix this with a known quantity of ambient dilution air so that a "dry" particulate sample could be obtained. The sample is drawn through a stainless steel probe, and Teflon cored heated line. Diluting the raw exhaust with HEPA filtered ambient air, while maintaining a constant temperature and flow velocity, conditions the sample and minimizes condensation, a major obstacle to particulate matter collection in the field. This technique can be used in order to determine average weighted emission rates over defined periods of operation. The dilute sample travels ten tunnel diameters at which

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<sup>1</sup> New York State Energy Research and Development Authority, "NYC Private Ferry Fleet Emissions Reduction Technology Study and Demonstration", NYSERDA Report 06-15, September 2006.

point samples are collected for analysis. Total particulate matter (TPM) was collected on 47 mm Emfab™ filters. Before the final filter weight was taken, each filter was conditioned at 40% ± 5% Relative Humidity, and 23 ± 3 degrees Celsius for a minimum of 8 hours, as was done prior to the recording of the filter's initial weight. A 1000 SCFM Laminar flow element was used to measure engine air intake for the calculation of the mass emission rate of each pollutant.

Emission rates were determined for total hydrocarbon (THC), carbon monoxide (CO), oxides of nitrogen (NO<sub>x</sub>), total particulate matter (TPM), as well as carbon dioxide (CO<sub>2</sub> - a major contributor to the greenhouse gas inventory). NO<sub>x</sub> and THCs were sampled, via a heated line, by means of a heated flame ionization detector and a heated chemiluminescence analyser respectively. CO<sub>2</sub> and CO were analysed by non-dispersive infrared detectors.

Testing took place over ten test modes as described Table 2. Modal emission results for NO<sub>x</sub>, TPM, and fuel consumption (FC) are presented in Figures 1 through 3. These figures show the general trends followed over the ten test modes. The average weighted emission rates in grams per minute can be found in Table 3, and are illustrated in Figures 4 through 9. High background levels of CO and THC were measured during the testing of Bus #4553 making the emission levels unquantifiable.

**Table 1. Test Matrix**

Test Date	Engine Technology	Engine Year	ETS Bus ID
October 10 <sup>th</sup> , 2007	New Flyer diesel bus	2007	4554
October 11 <sup>th</sup> , 2007 (2 full repeats)	New Flyer diesel bus (baseline for Hybrids)	2006	4498
October 12 <sup>th</sup> , 2007	New Flyer-ISE series diesel-electric hybrid	2006	6004
October 12 <sup>th</sup> , 2007	New Flyer-Allison parallel diesel-electric hybrid	2006	6001
October 15 <sup>th</sup> , 2007	Orion-BAE series diesel-electric hybrid	2006	6005
October 16 <sup>th</sup> , 2007	Orion-BAE series diesel-electric hybrid	2006	6006
October 17 <sup>th</sup> , 2007	New Flyer diesel bus	2007	4553
October 17 <sup>th</sup> , 2007	New Flyer diesel bus (baseline for Hybrids)	2006	4500
October 18 <sup>th</sup> , 2007	New Flyer-Allison parallel diesel-electric hybrid	2006	6002
October 18 <sup>th</sup> , 2007	New Flyer-ISE series diesel-electric hybrid	2006	6003

**Table 2. Test Cycle**

Test Mode	Target Speed (km/hr)	Target Power (kW)
1	0	0
2	16	26
3	29	144
4	29	74
5	29	33
6	48	133
7	48	74
8	48	33
9	72	111
10	0	0

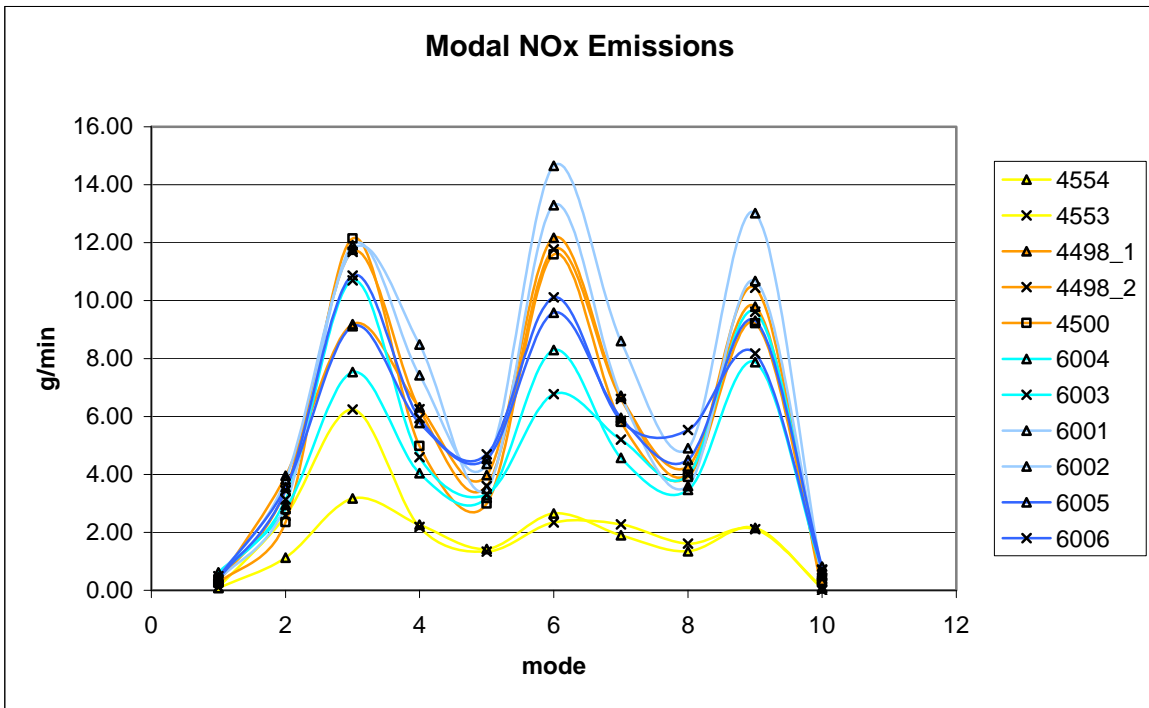


Figure 1. NOx: Modal Emission Rates

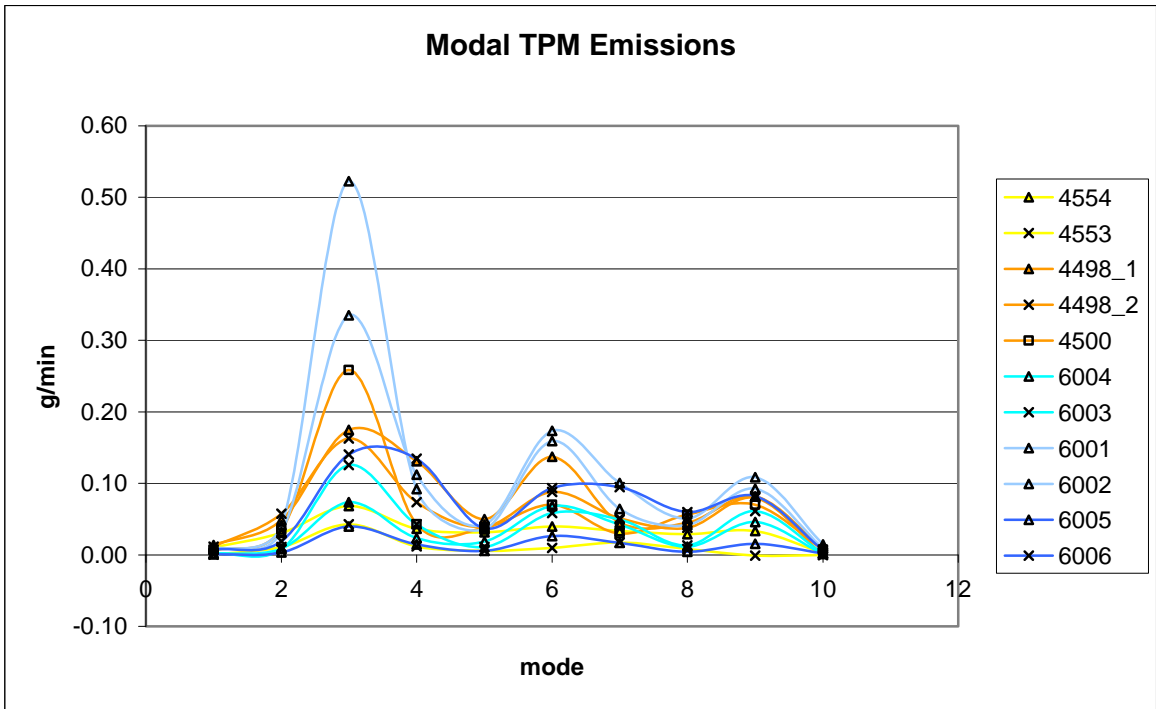
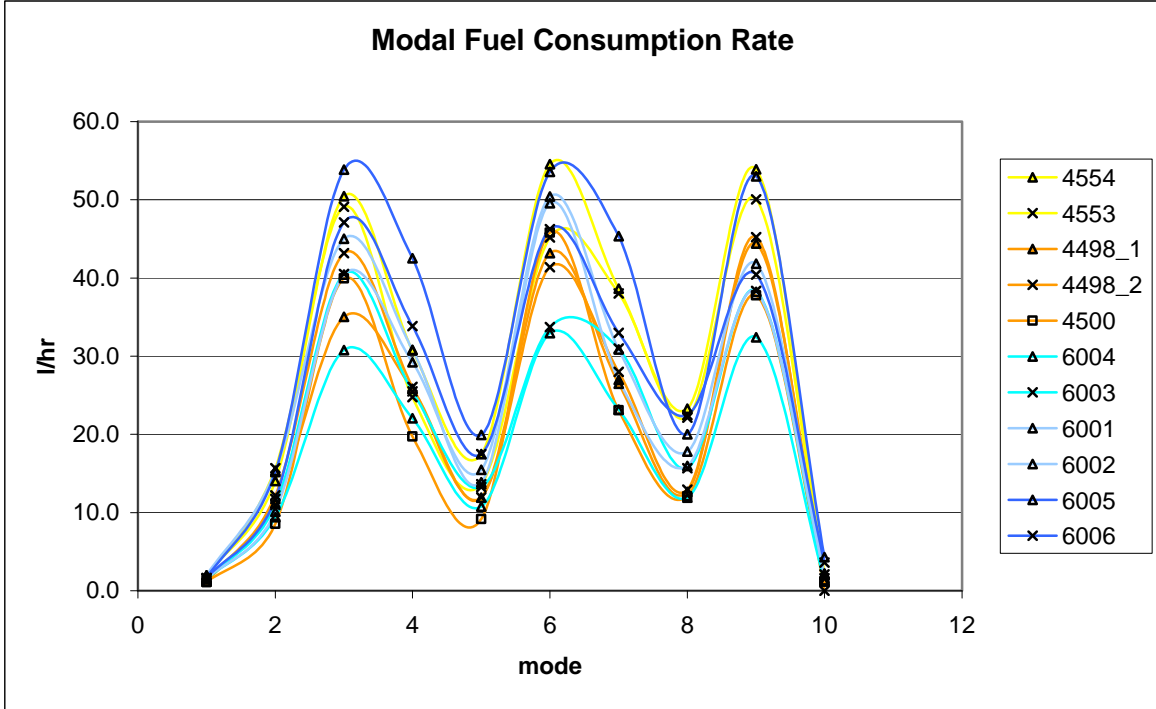


Figure 2. TPM: Modal Emission Rates



**Figure 3. Modal Fuel Consumption Rate**

**Table 3. Average Weighted Emissions over Ten Test Modes in g/min**

ETS BUS ID	CO	CO <sub>2</sub>	NO <sub>x</sub>	THC	TPM	FC (l/hr)
4554	0.12	1327	1.62	0.03	0.03	30.71
4553	bql	1212	2.09	bql	0.01	28.10
4998_1	0.38	985	5.70	0.04	0.07	22.53
4998_2	0.44	1026	5.81	0.09	0.06	22.22
4500	0.46	916	5.36	0.12	0.06	20.90
6004	0.10	814	4.31	0.03	0.03	18.69
6003	0.10	980	4.85	0.08	0.04	22.64
6001	0.16	1108	6.87	0.06	0.10	25.84
6002	0.11	1108	6.28	0.08	0.11	25.84
6005	0.04	1096	5.36	bql	0.01	34.79
6006	0.05	1190	5.57	0.02	0.07	29.00

bql indicates below quantification limit

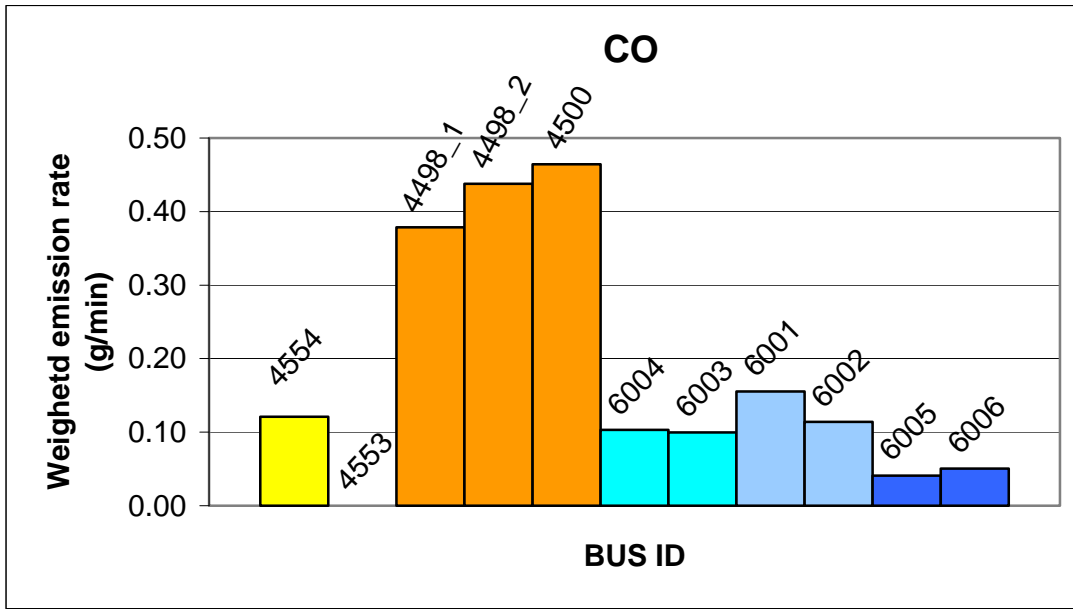


Figure 4. Weighted CO Emissions (g/min)

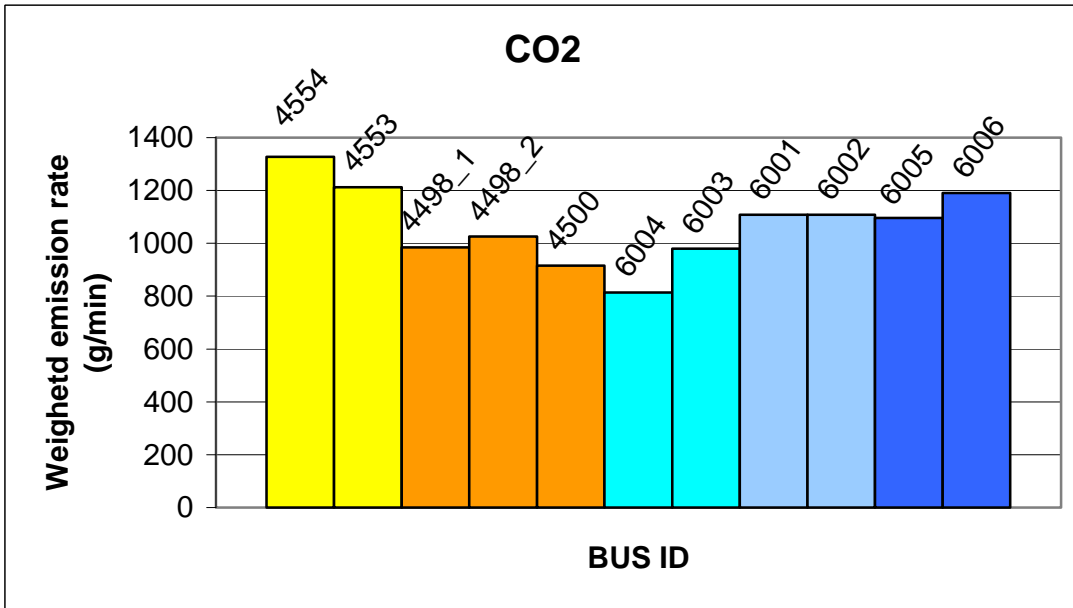


Figure 5. Weighted CO2 Emissions (g/min)

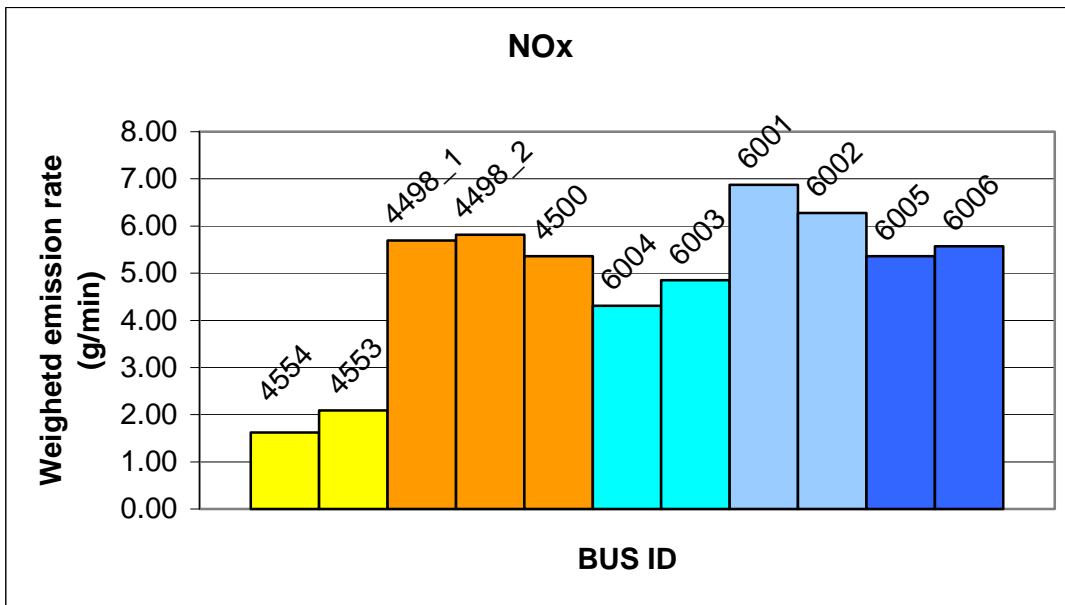


Figure 6. Weighted NOx Emissions (g/min)

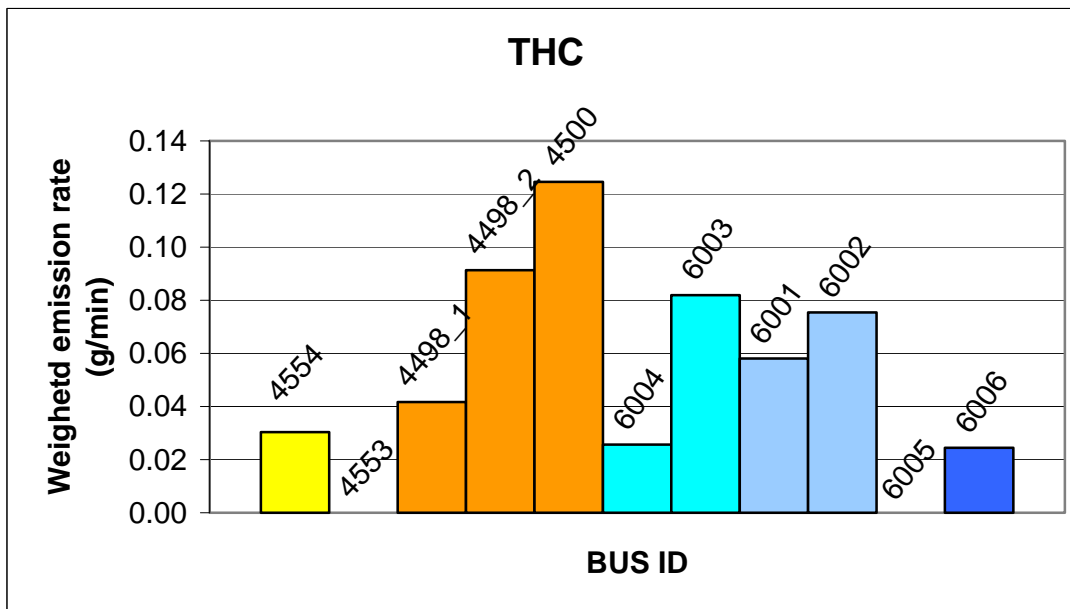


Figure 7. Weighted THC Emissions (g/min)

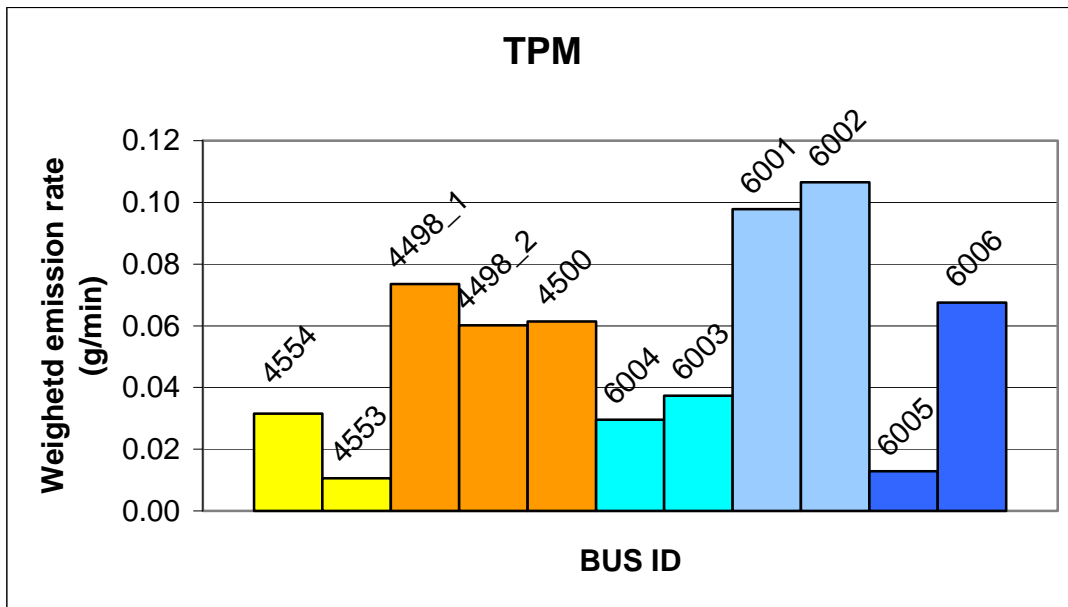


Figure 8. Weighted TPM Emissions (g/min)

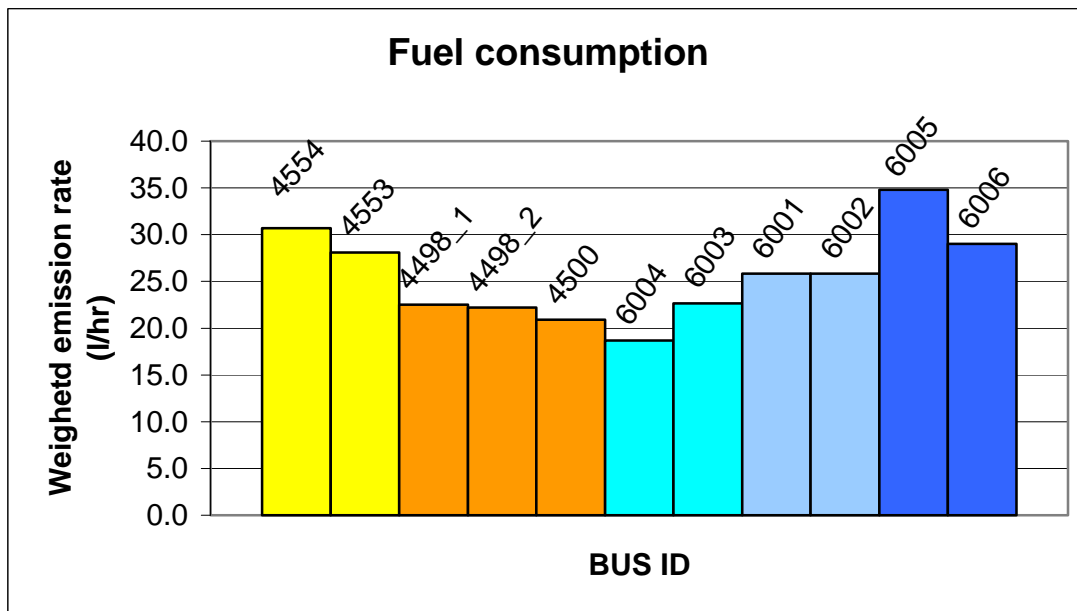


Figure 4. Weighted FC Emissions (l/hr)