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Particle size distributions from CRT-equipped NYC transit buses

New York Experience with Continuously Regenerating Technology (CRT) Retrofits on Urban Transit Buses

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The sampling train for the particle size measurements was different from that used for the other regulated and unregulated emissions. Kittleson and others have found that the measured particle size distribution is a strong function of the sampling and dilution methods. A CVS system alone, with its variable dilution factor during transient cycles and long residence time, is unsuitable for making repeatable size distribution measurements. As our primary aim was to compare discrete particulate production numbers between the various test cycles and bus, fuel and after-treatment technologies, it was felt that consistency among measurements was of greatest importance. In addition, as the project was expected to address the effect various technology changes might have on air quality and human health, an attempt was made to skew the dilution parameters towards 'real world' values for temperature, humidity, residence time, and dilution factor.

A 3/8 inch probe mounted in the transfer line sampled raw vehicle exhaust just before it exited the vehicle's exhaust system. A constant volume displacement pump draws 1 lpm raw exhaust into the diluter, where it is thoroughly mixed with 100 lpm of filtered dilution air. The temperature, while not directly regulated, typically runs about 25 C, and the humidity from 20 – 30%. The transit time of the complete system from probe to instruments is less than .1 second. These parameters were chosen as a compromise among the competing factors influencing particle growth and formation and the actual values that might be encountered as the exhaust leaves the vehicle and mixes with the ambient air.

Particle size distribution measurements were made during the emissions testing using two distinct instruments and methods. The Scanning Mobility Particle Sizer (SMPS), TSI model #3934, measures mobility diameter through the range .005- 1 micron. The instrument can scan through one of three preset size ranges, which takes approximately 5 minutes to produce a complete size distribution, or measure one pre-selected size in real time. During the transient test cycles (CBD and NYBus), the SMPS was set to measure the concentration of 10nm or 100nm particles in real time, with three 10-minute cycles repeated for each size. In addition, three 10-minute steady-state cycles were run (at idle, 15 and 30 mph), while the SMPS completed two 5-minute size distribution scans from 5 – 200 nm. The Electrical Low Pressure Impactor (ELPI), from Dekati Ltd. in Finland, measures aerodynamic diameter using an impactor. It has twelve stages, each covering a subset of the size range between .035-10 micron. The impaction method allows for the accumulation of particulate in each size bin and the generation of composite data for mass or number, while the real time readout capability enables the storage and 'playback' of this accumulation process during the sampling/testing time frame. One caveat that must be appreciated is that because of the low pressures in the impactor, the measurement of the smallest size particles are subject to a large degree of error due to a variable loss of volatiles. This limits the practical range of this instrument to ~ .06-10 micron. It should also be understood that mobility and aerodynamic diameter may in principle be related through equations involving the shape and density of the measured particles. To the extent that these parameters remain unknown, one may make the assumption of spherical shape and unit density, and so relate the different size metrics approximately.

Diesel particulate matter typically exhibits a bimodal mass-weighted size distribution, with a nucleii mode between .01 and .05 micron, and an accumulation mode between .1 and 1 micron. A third mode is sometimes observed at 7-8 microns. The number-weighted size distribution is characterized by a single mode between .007 and .05 micron. The fractional alveolar deposition, as a function of aerodynamic diameter, increases greatly for sizes below .05 micron, so it is felt that these ultrafine particles are of the greatest importance when considering human health effects. As the size distributions for diesel buses running on low sulfur fuel with CRT's are the unknown to be measured, and to effectively address the issues of potential production of ultrafine particles and related health effects, we felt that the SMPS must be run using the scanning size distribution method. This type of scanning measurement only makes sense when the vehicle is run in a steady-state mode, ie. for ~10 minutes, so that 2 scans of 5 minutes each may be generated and averaged. The ELPI, while effective at capturing the real-time changes in particle size distributions, is limited to particles larger than ~60 nm, and only resolves the distribution into twelve relatively wide size bins. In the figures, the composite average particle concentration over the six 10-minute test cycle runs is given for each size bin, so that comparison among the different fuel and after-treatment changes may be made.

Project Objectives

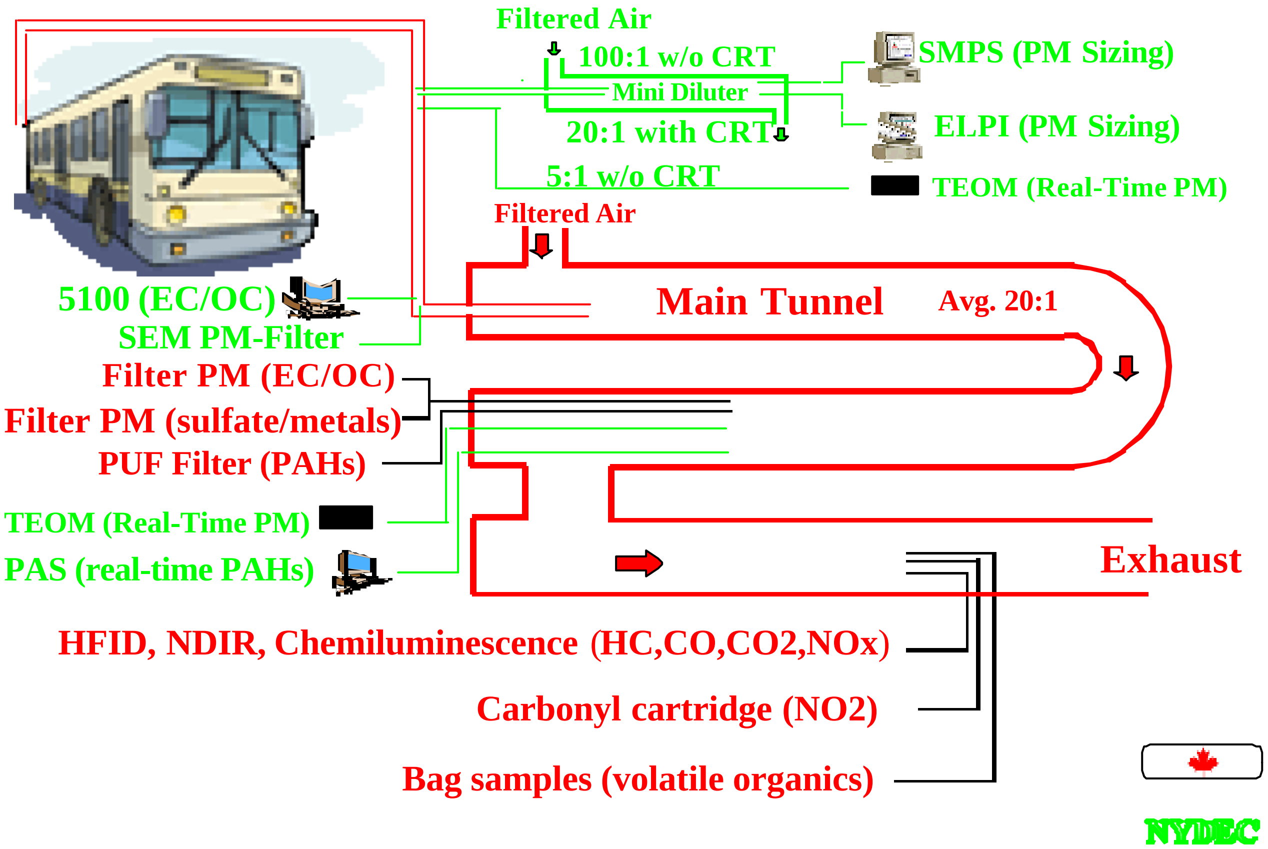
- Evaluate the emissions reductions available using CRT ™ technology in conjunction with reduced sulfur diesel fuel
- Evaluate the applicability of the technology to both new 4-stroke and older 2-stroke diesel engines
- Evaluate the maintainability and durability of CRTs in rigorous New York City bus service
- Evaluation of new technologies for the measurements and monitoring of PM and toxic emissions

Program Outline

- Fleet demonstration *(Feb 2000* - *Jan 2001)*
  - 25 Series 50 Buses; 275 Hp 1999 model year
  - Operate for 9-12 months in revenue service
  - Check back pressure and exhaust temperature
- Emissions testing *(April 2000; Feb 2001)*
  - 2 Series 50 Buses with CRT
  - Check emissions with chassis dyno under CBD & NYC Bus cycle
  - Measure at the start and at the end of program

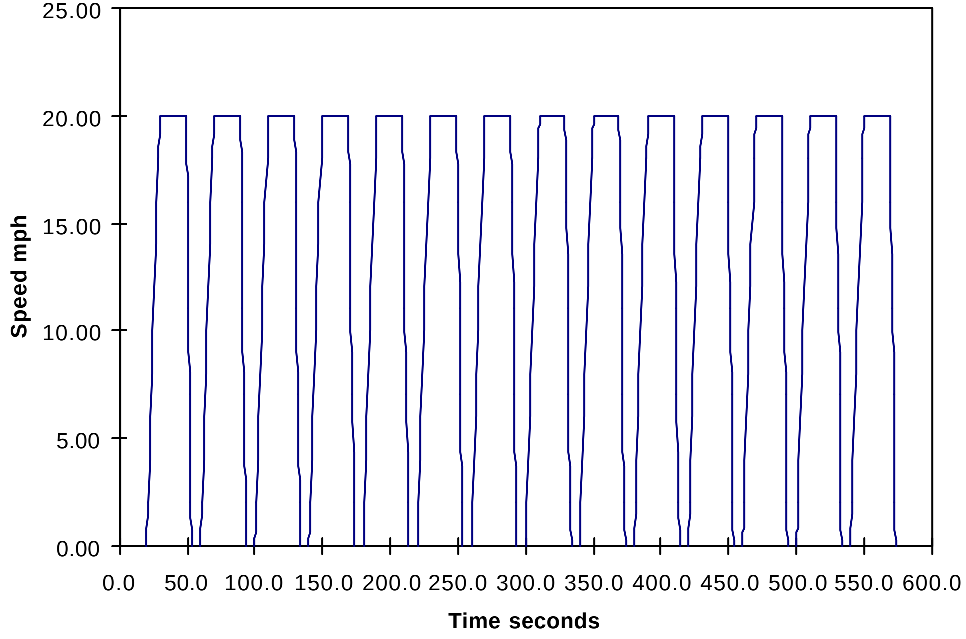
Emissions Testing

- 2 Series 50 buses tested at the beginning of the program
  - Each bus tested with OEM Catalyst/standard fuel (350 ppm S), with OEM Catalyst/ultra low sulfur fuel (30 ppm), and with CRT system/ultra low sulfur fuel (30 ppm)
- Test on chassis dynamometer using CBD and New York bus cycles
- Collect info on criteria pollutants (CO, HC, NOx, PM), plus particle size and toxicity
- Re-test both buses after 9 - 12 months of service with installed CRT filter system
- Comparison of CRT filter Data with recent CNG Test Data

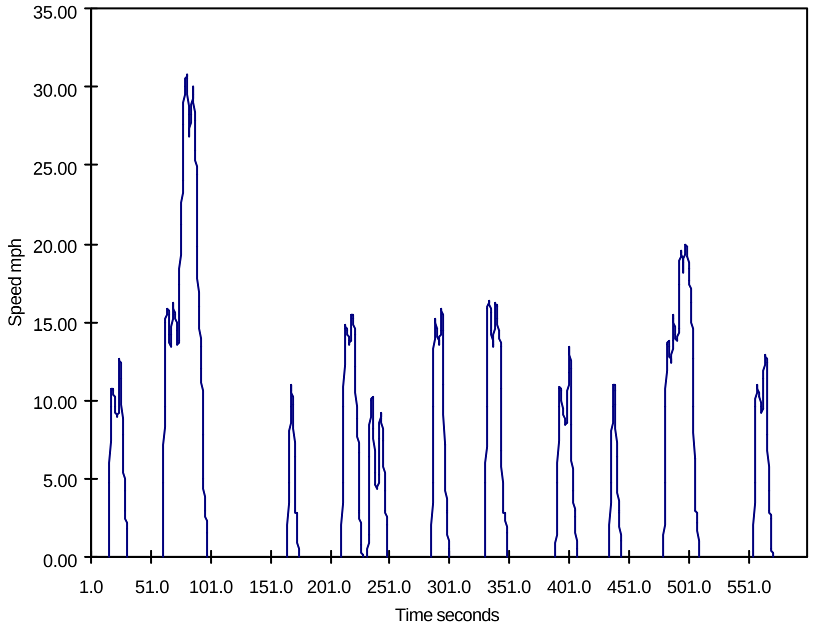


Sampling Diagram of CRT Testing Program

Emissions Test Cycles

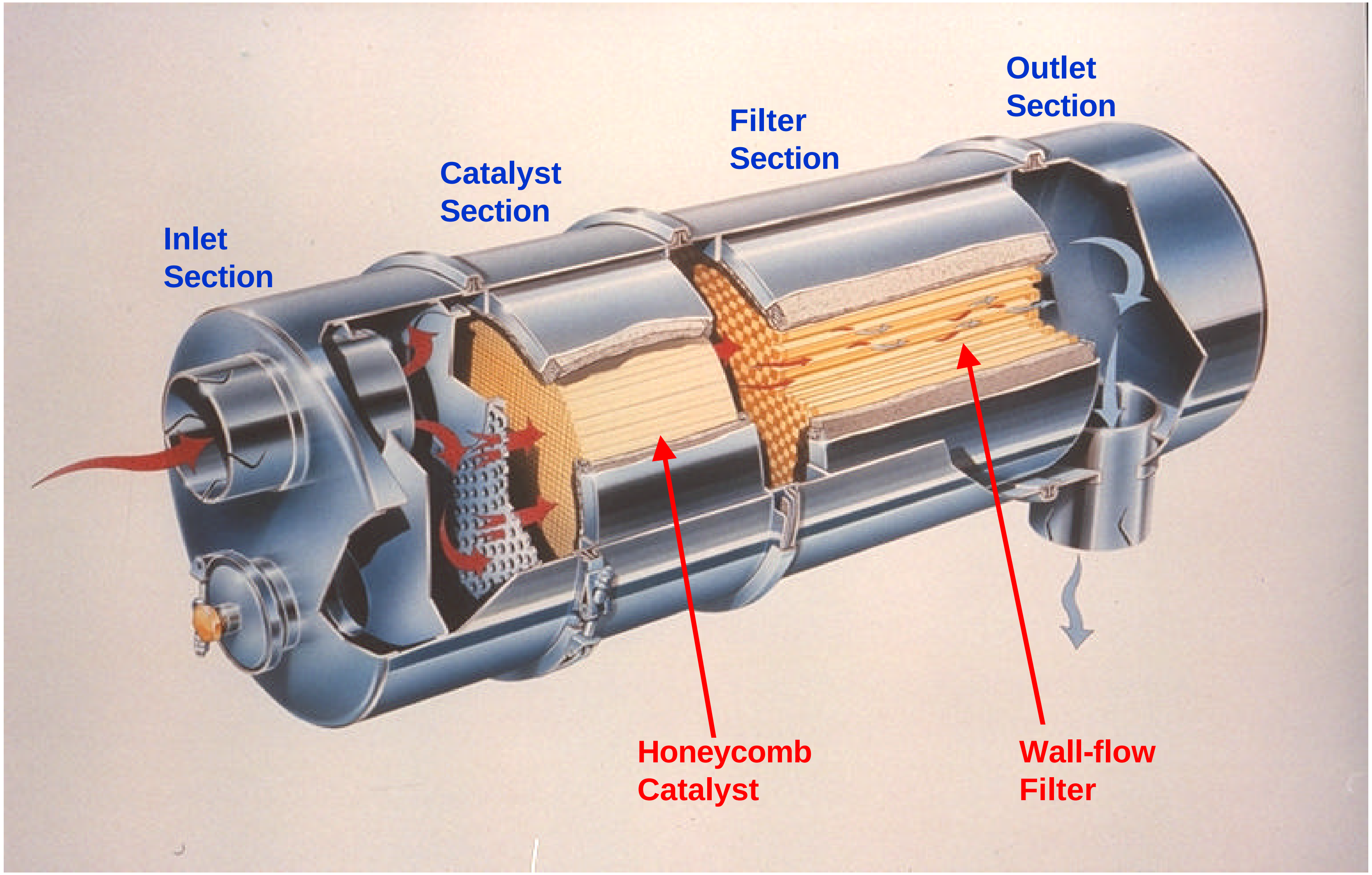


CBD Cycle



NY Bus Cycle

CRT™ Particulate Filter



Unique Patented Johnson Matthey System

Regulated Emissions Test Results - CRT™

Bus ID	Test Cycle	Configuration	Fuel	FE (mpg)	CO2 g/mile	NOx g/mile	THC g/mile	CO g/mile	PM g/mile
NYCT #6019	CBD	OEM	LSD	3.3	2942	25.6	0.18	1.8	0.21
NYCT #6019	CBD	OEM	ULSD	3.4	2948	25.6	0.06	1.2	0.16
NYCT #6019	CBD	CRT	ULSD	3.1	3236	26.4	0.03	0.16	0.04
% Reduction Baseline to ULSD					-0.2	0.0	66.7	34.7	23.8
% Reduction Baseline to ULSD & CRT					-10.0	-3.1	83.3	91.4	82.4

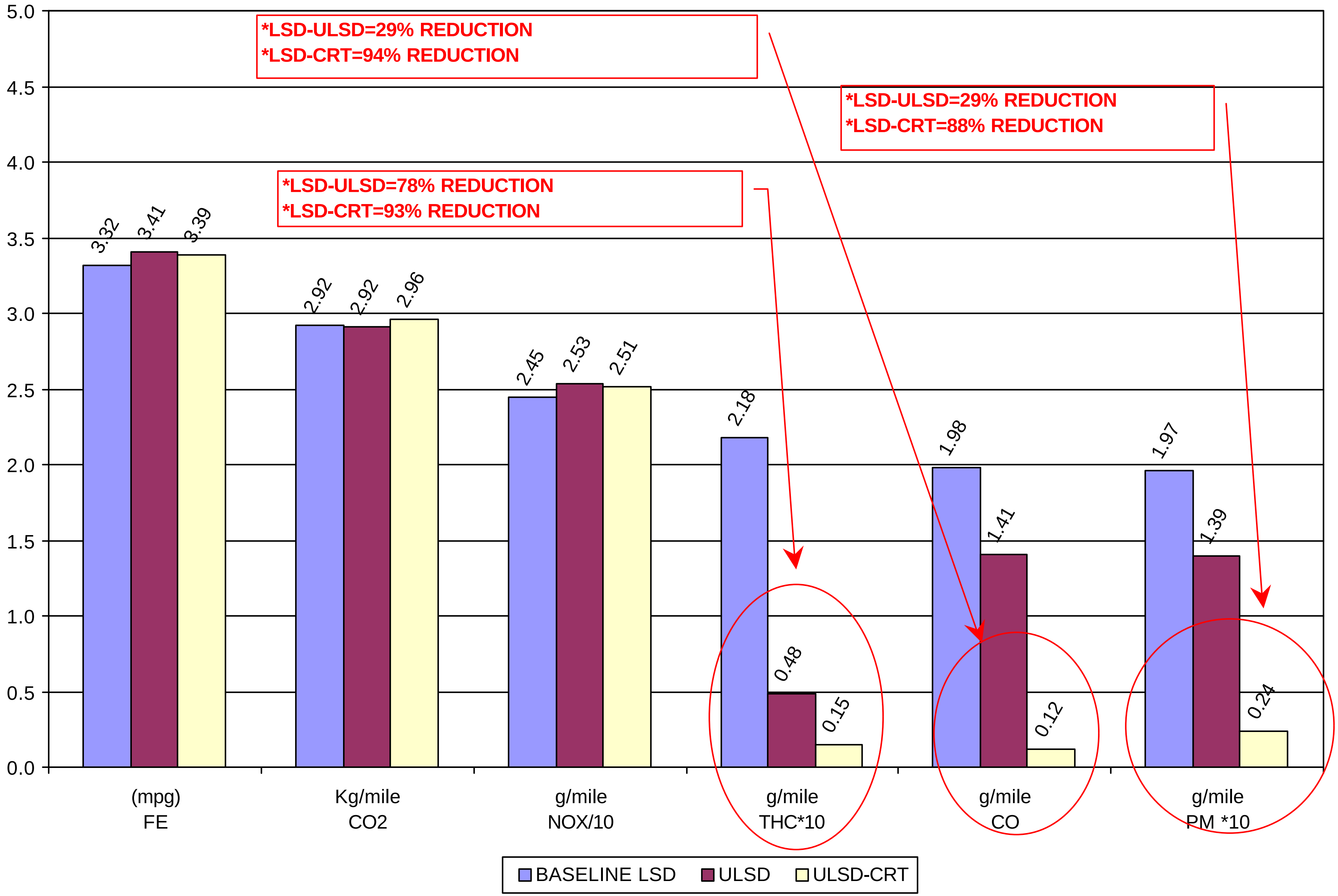
Bus ID	Test Cycle	Configuration	Fuel	FE (mpg)	CO2 g/mile	NOx g/mile	THC g/mile	CO g/mile	PM g/mile
NYCT #6019	NYBUS	OEM	LSD	1.5	6483	70.3	0.91	13	0.55
NYCT #6019	NYBUS	CRT	ULSD	1.4	7177	73.3	0.06	0.23	0.04
% Reduction Baseline to ULSD & CRT					-10.7	-4.3	93.4	98.3	93.3

Bus ID	Test Cycle	Configuration	Fuel	FE (mpg)	CO2 g/mile	NOx g/mile	THC g/mile	CO g/mile	PM g/mile
NYCT #6065	CBD	OEM	LSD	3.3	2897	23.3	0.26	2.1	0.18
NYCT #6065	CBD	OEM	ULSD	3.5	2884	25.1	0.04	1.6	0.12
NYCT #6065	CBD	CRT	ULSD	3.7	2679	23.8	0	0.09	0.01
% Reduction Baseline to ULSD					0.5	-7.6	85.7	23.9	35.0
% Reduction Baseline to ULSD & CRT					7.5	-2.1	100.0	95.9	94.0

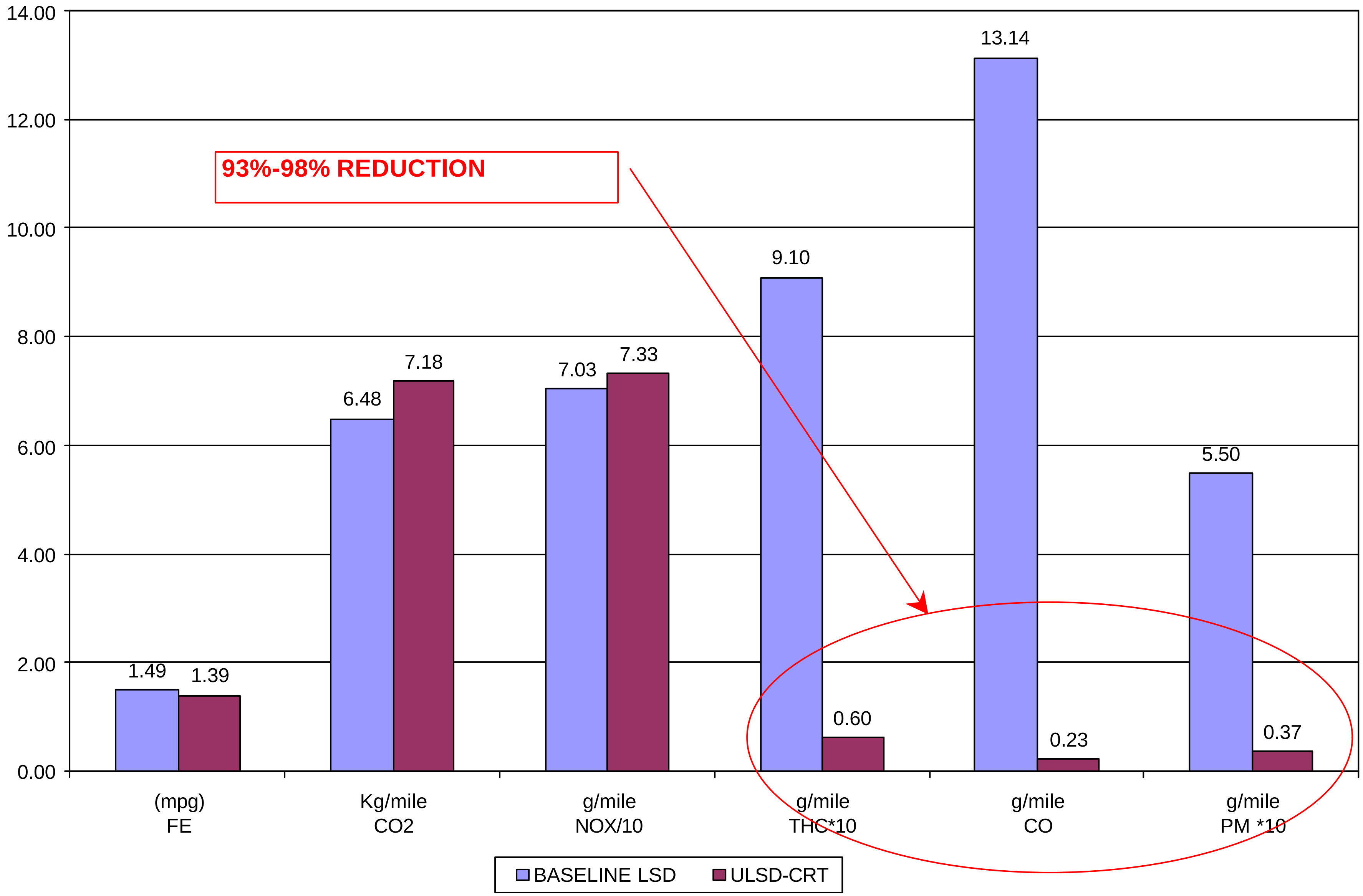
Emissions Testing Results

- ***Fuel effects:*** Going from ***Baseline LSD to ULSD*** *on the CBD Cycle* results in 76% average reduction in THC, 29% average reduction in CO, and 29% average reduction in PM
- ***CRT effects:*** *On CBD cycle***,** *reduction* in Average Emissions compared to ***Baseline Fuel & Catalyst Muffler*** - 92% for THC, 94% for CO, and 88% for PM
- Emissions reductions on **NY Bus Cycle** with the **CRT** filter are even higher than on CBD: 93 - 98% Reduction in THC, CO, and PM
- The PM Emissions appear to be **independent of duty cycle** with the CRT - CO2 emissions and Fuel Economy indicate that NY Bus Cycle requires twice as much work as CBD, but there is ***NO INCREASE IN PM OUT***

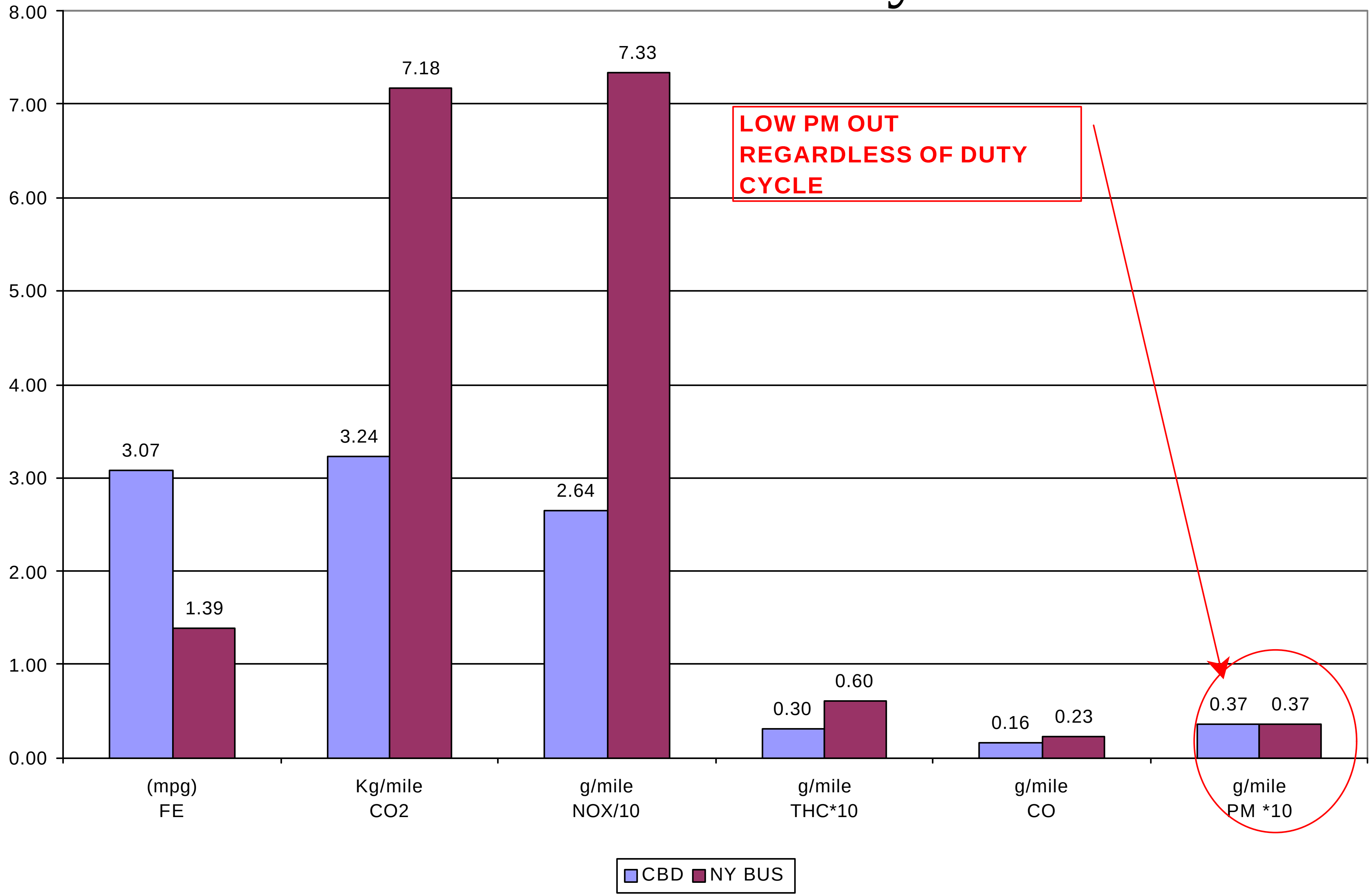
Average Series 50 Emissions Results CBD Cycle

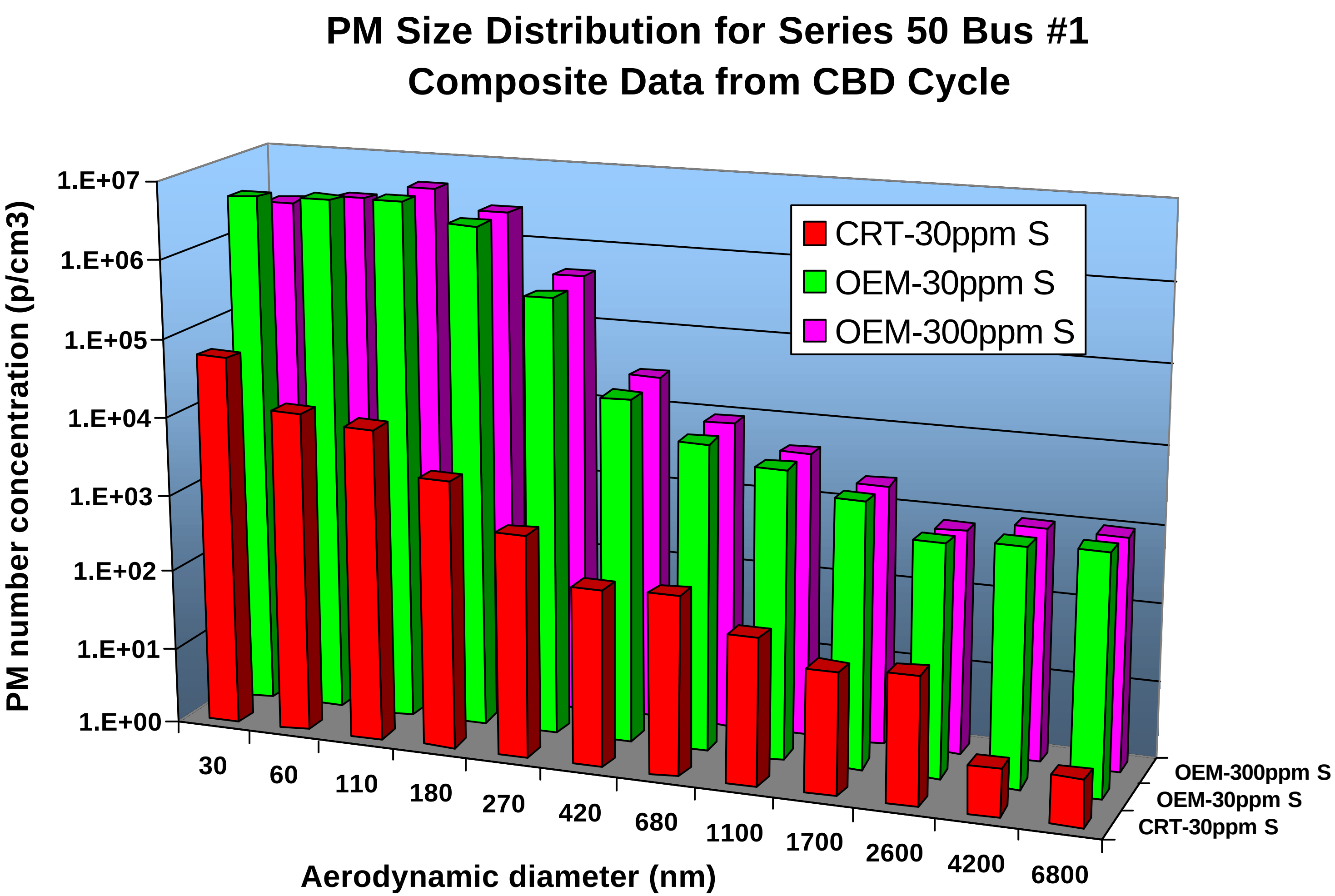


Series 50 Emissions Results
NY Bus Cycle



Emissions Test Results
CBD vs. NY Bus Cycle




PM Size Distribution for Series 50 Bus #1
Composite Data from CBD Cycle
PM number concentration (p/cm3)
1.E+07
1.E+06
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
CRT-30ppm S
OEM-30ppm S
OEM-300ppm S
30
60
110
180
270
420
680
1100
1700
2600
4200
6800
Aerodynamic diameter (nm)
OEM-300ppm S
OEM-30ppm S
CRT-30ppm S

Clean Diesel - Moving Forward

- CRT Project - Continue Durability testing until November
- CRT Project - At conclusion of durability phase, emissions test same buses
- CRT Project - Fuel matrix portion of project - explore different fuel chemistries and how they affect emissions
- CRT Project - Explore short term durability of “best” fuel chemistry from matrix
- MTA NYCT has contracted for Ultra Low Sulfur Diesel Fuel for its entire fleet for the next three years starting in September 2000
- MTA NYCT has contracted to retrofit 500 buses with CRT filters starting from September 2000

Emissions Comparison
Clean Diesel vs. CNG

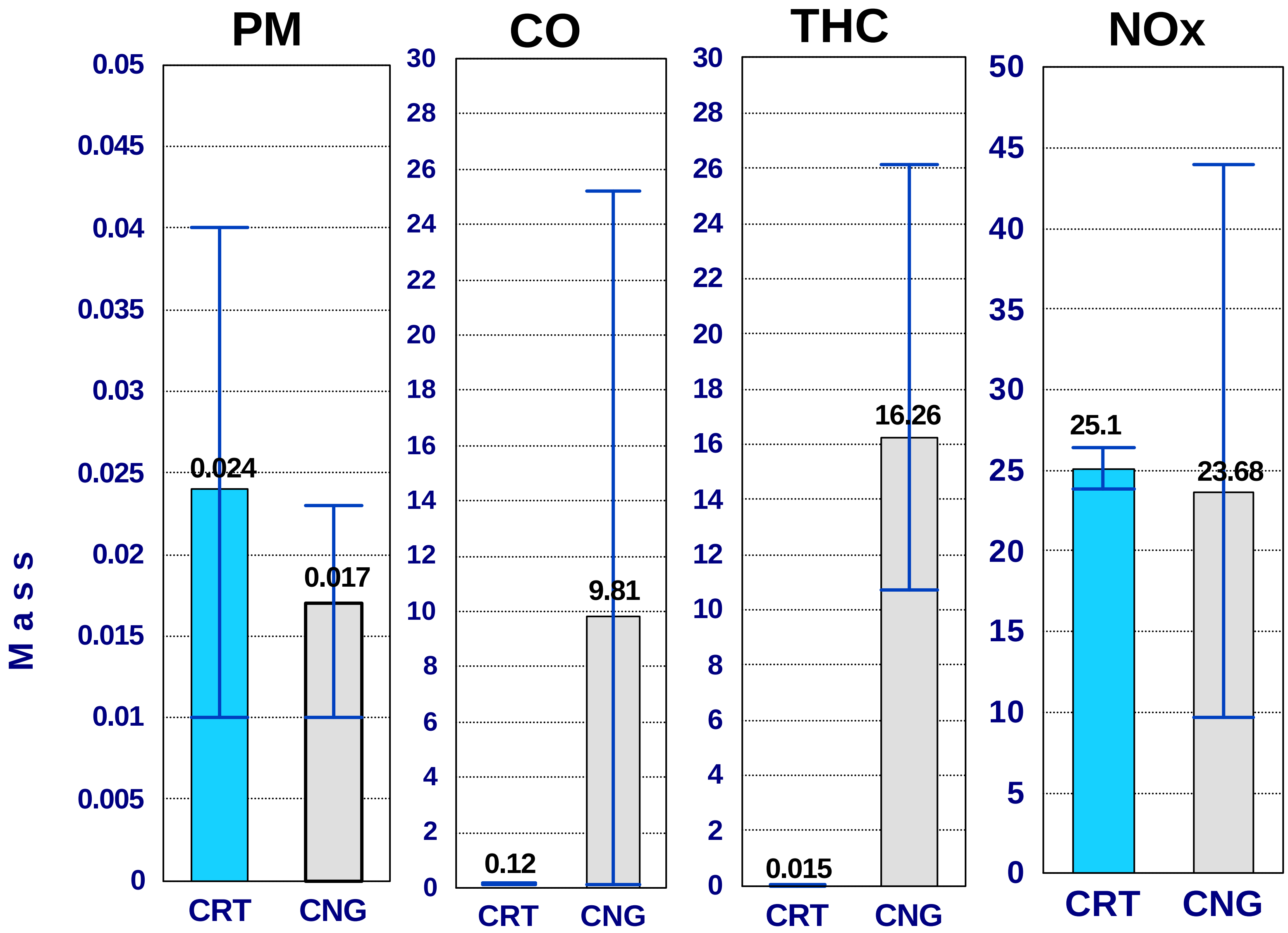
- Data on CNG emissions gathered from 3 test sites
  - CARB Testing (LA MTA)
  - NAVC Test Program (WVU)
  - NYCT Testing (Environment Canada)
- All CNG buses tested were equipped with oxidation catalysts
- CNG test data showed large variability in some emission components - for comparison to CRT, the average is shown, along with “error bars” showing the range of individual results
- In addition to regulated emissions, data is included on total CARBONYL emissions. This is a class of hydrocarbon species, primarily consisting of aldehydes and ketones. Many of these compounds such as Formaldehyde, Acetaldehyde, Acrolein and Propionaldehyde are considered very toxic and are listed in EPA’s Hazardous Air Pollutants (Title II HAP) list.

Regulated Emissions Test Results - CNG Buses

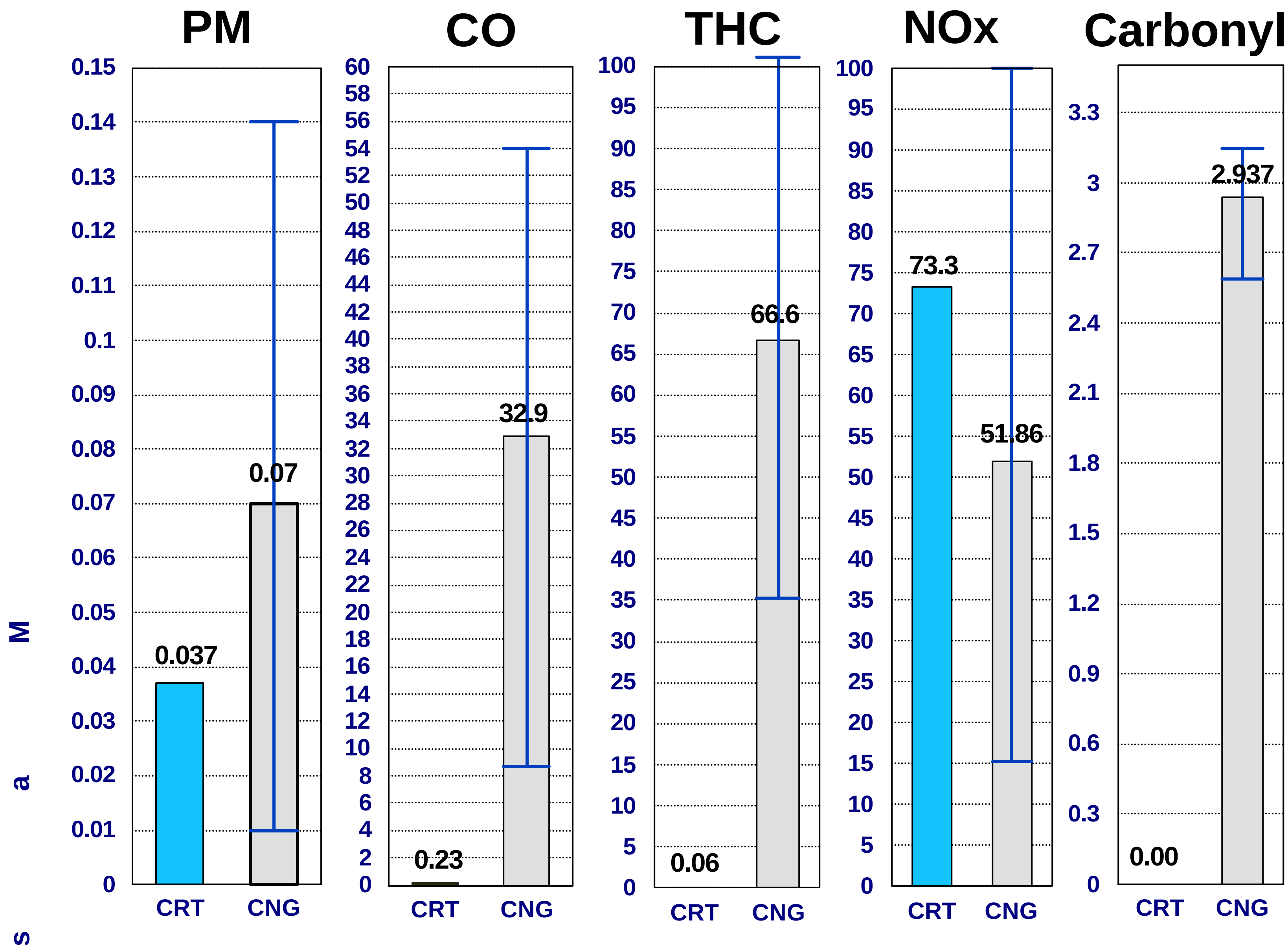
Engine Type	Bus No.	Location	Test Cycle	Test Location	F.E. (mpg)	CO2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)
1999 Ser 50G **	824	NYCT	CBD	Env. Canada		2112	44	19	20	0.090
1999 Ser 50G	824	NYCT	CBD	U. West Virginia	3.2	2264	15.9	23.1	12.9	0.020
1999 Ser 50G	854	NYCT	CBD	U. West Virginia	3	2421	13.8	18	12.4	0.010
1998 Ser 50G		NYDOT	CBD	U. West Virginia	2.6	2785	9.7	26.06	10.8	0.020
1998 L10G		Mass PA	CBD	U. West Virginia	3.1	2392	25	15.2	0.6	0.020
1996 L10G	4642	LAMTA	CBD	MTA/CARB	4.39	2239	27.43	10.722	25.16	0.023
1996 L10G	4740	LAMTA	CBD	MTA/CARB	3.74	2688	42.39	11.34	0.08	0.013
Average Emission			**CBD**		**3.37**	**2505**	**23.66**	**16.26**	**9.81**	**0.017**
1999 Ser 50G	824	NYCT	NY Bus	Env. Canada		5064	60	77	54	0.060
1999 Ser 50G	824	NYCT	NY Bus	U. West Virginia	1.3	5560	29.8	101	42	0.010
1999 Ser 50G	854	NYCT	NY Bus	U. West Virginia	1.3	5660	22.6	57.9	32.3	0.010
1998 Ser 50G		NYDOT	NY Bus	U. West Virginia	1.1	6535	15.3	73.34	31.7	0.110
1998 L10G		Mass PA	NY Bus	U. West Virginia		6090	113	70.24	29	0.140
1996 L10G	4642	LAMTA	NY Bus	MTA/CARB	1.9	4754	22.47	51.26		0.085
1996 L10G	4740	LAMTA	NY Bus	MTA/CARB	1.74	5696	99.89	35.15	8.67	0.105
Average Emission			**NY Bus**		**1.47**	**5623**	**51.87**	**66.56**	**32.95**	**0.074**

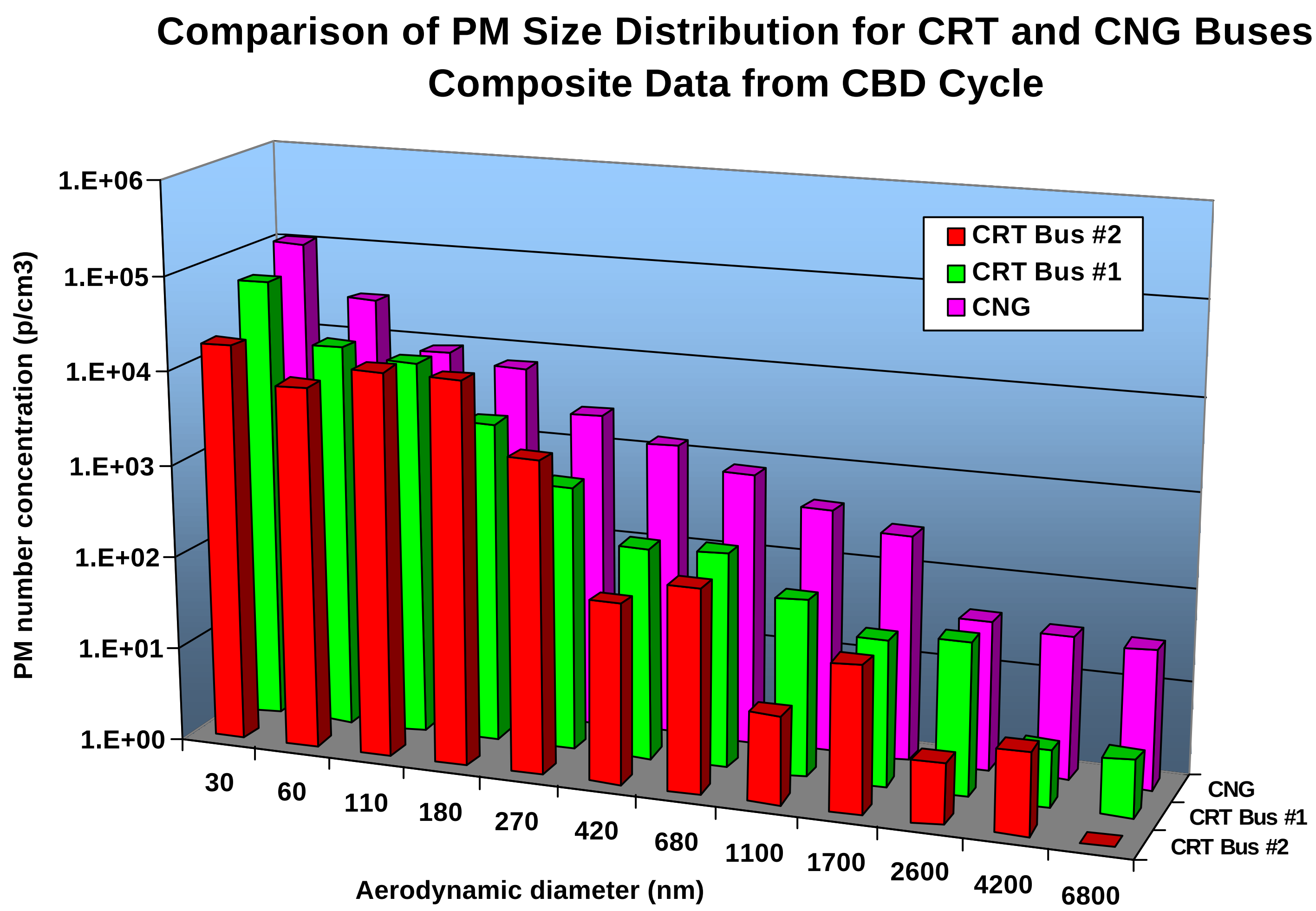
*** Emission data appears to be significantly different from the rest; Hence not used for average and in graphs*

Emissions Test Results - CRT vs. CNG
CBD Cycle



Emissions Test Results - CRT vs. CNG
NY Bus Cycle




Comparison of PM Size Distribution for CRT and CNG Buses
Composite Data from CBD Cycle
PM number concentration (p/cm3)
1.E+06
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
CRT Bus #2
CRT Bus #1
CNG
30
60
110
180
270
420
680
1100
1700
2600
4200
6800
Aerodynamic diameter (nm)
CNG
CRT Bus #1
CRT Bus #2

Conclusion
Clean Diesel vs. CNG

- PM emissions from CRT-equipped buses appear to be equivalent to those from CNG buses
  - Average PM emissions with CNG is lower on CBD cycle, but higher on NY Bus cycle
  - Much wider range of values with CNG, especially on NY Bus cycle
- CO and HC emissions from CRT-equipped buses are much lower than those from CNG buses
- NOx emissions are generally lower from CNG buses than from CRT-equipped buses, but show a wider range of variability
- Carbonyl emissions from CNG buses are much higher than from CRT-equipped buses.
- NOx/NO2 partitioning changes for CRT- equipped bus