ARB's Study of Emissions from "Late-model" Diesel and CNG Heavy-duty Transit Buses

Presentation to South Coast Air Quality Management District

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Project Scope

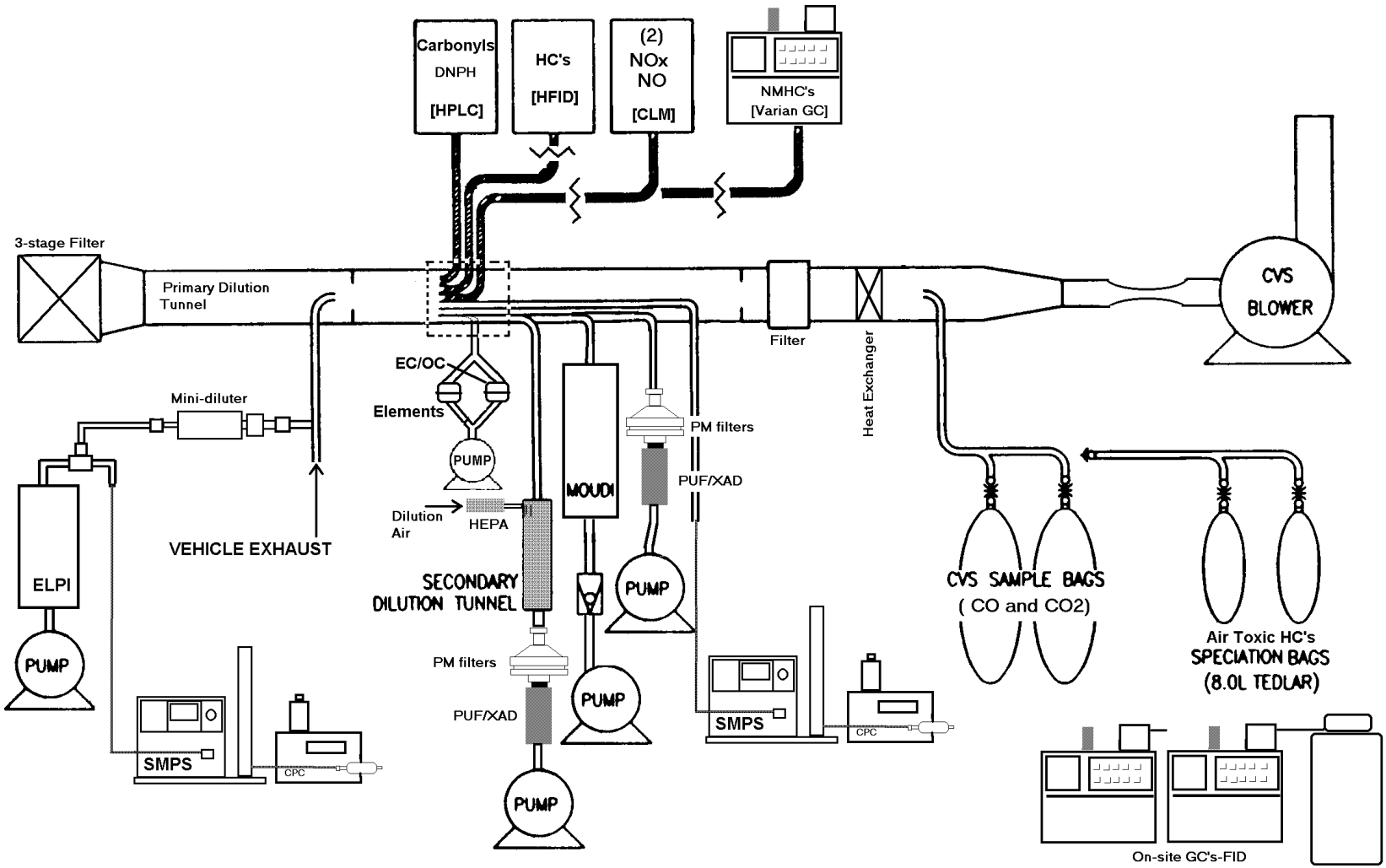
- Dynamometer Testing at ARB's Heavy-duty Vehicle Emissions Laboratory (HDVEL) in Los Angeles
- Five driving schedules and corresponding tunnel blanks: 1) Idle, 2) Steady State (55mph, ~60% rated power), 3) CBD, 4) UDDS, 5) NYCB
- Pollutants: TPM, THC/NMHC, NO_x, CO, NO_2, and CO_2
- On-site Analysis for Speciation of VOC's
- Carbonyl Compounds
- Phase distribution of PAH's
- PM extractions for Ames Bioassay
- Elemental Carbon/Organic Carbon Split
- Elements Analysis
- Size-segregated mass emissions (MOUDI)
- Particle number and size distribution (SMPS and ELPI)
- Fuel and lube oil analysis

Test Fleet

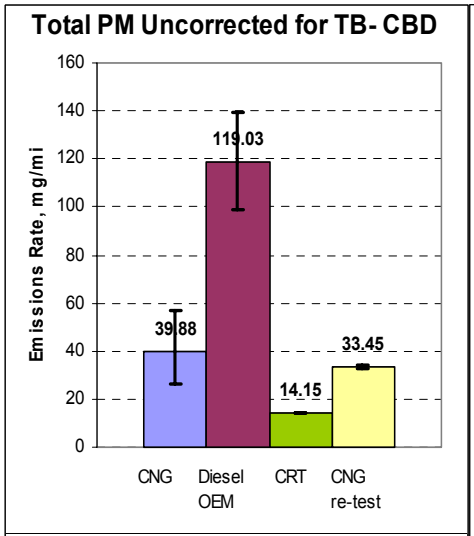
	"CNG" "CNG re-test"	"Diesel (OEM)"	"CRT"
Model	2000 DDC Series 50G	1998 DDC Series 50	1998 DDC Series 50
Aftertreatment	None	OEM Catalyzed Muffler	CRT™
Fuel	CNG	ECD-1	ECD-1
Odometer	19,629	15,169	15,569
Weight	33,150 lbs	30,510	30,510

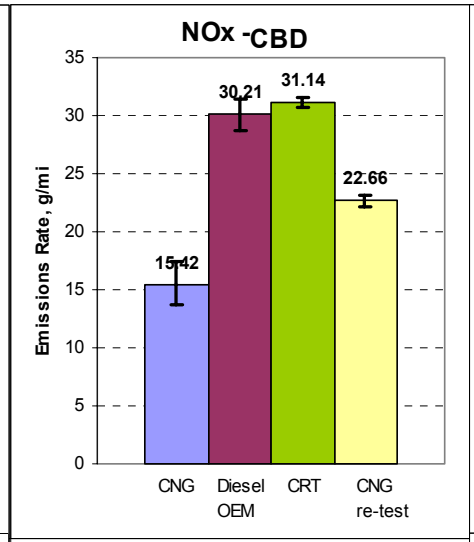
- Los Angeles County Metropolitan Transit Authority fleet
- 8.5 liter, 4-stroke, turbocharged, 4-cylinder, New Flyer Low 40 passenger transit buses

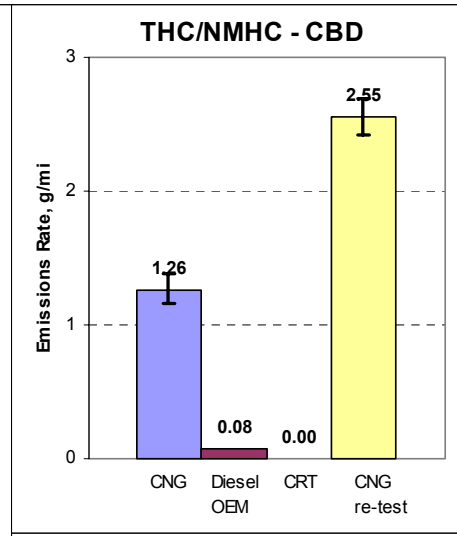
Experimental Setup

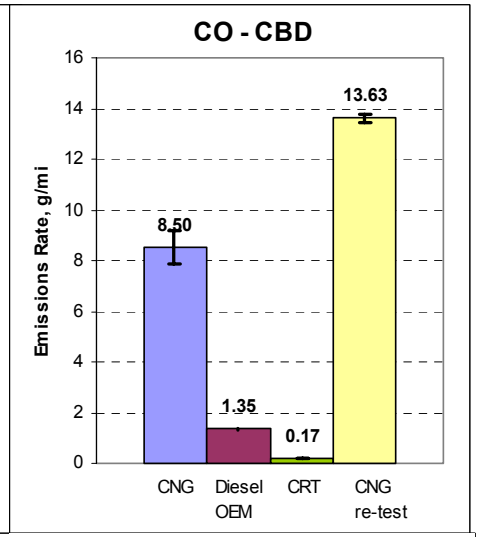


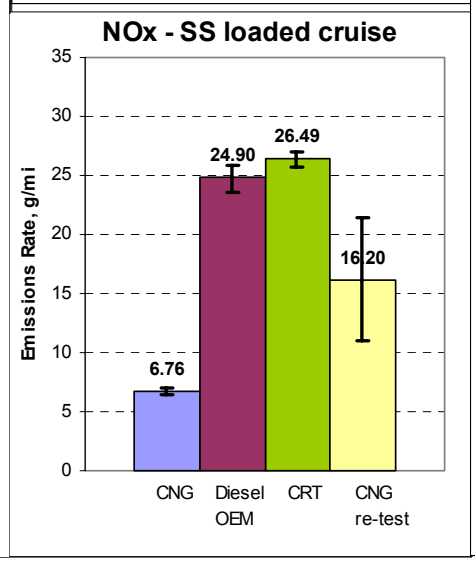
Regulated Emissions

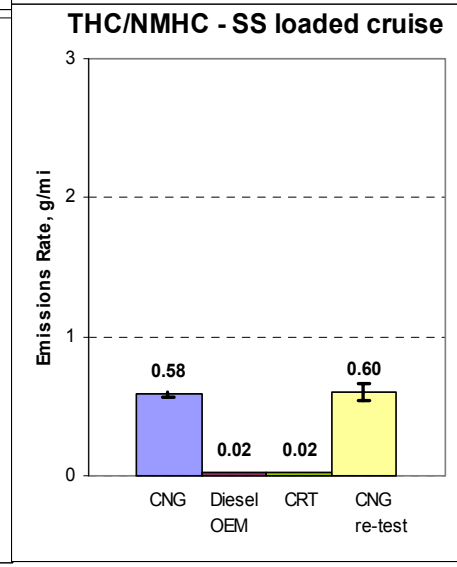










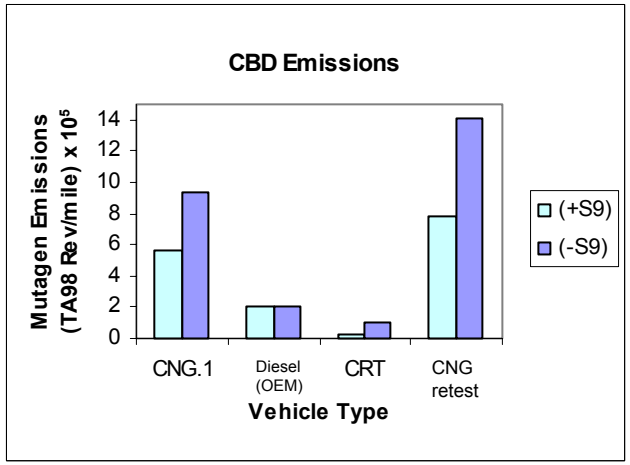


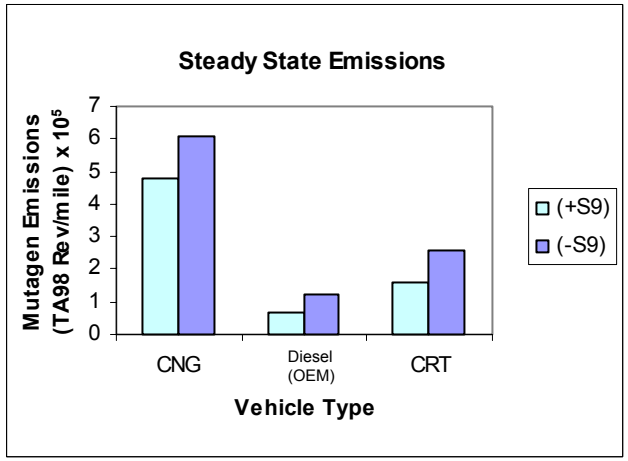
Bioassay Analysis

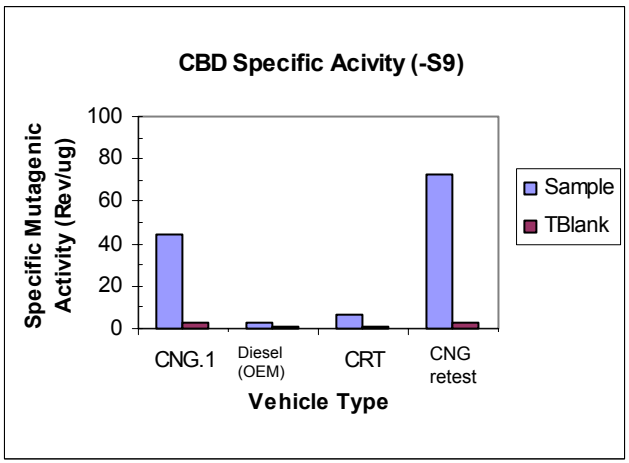
Procedure

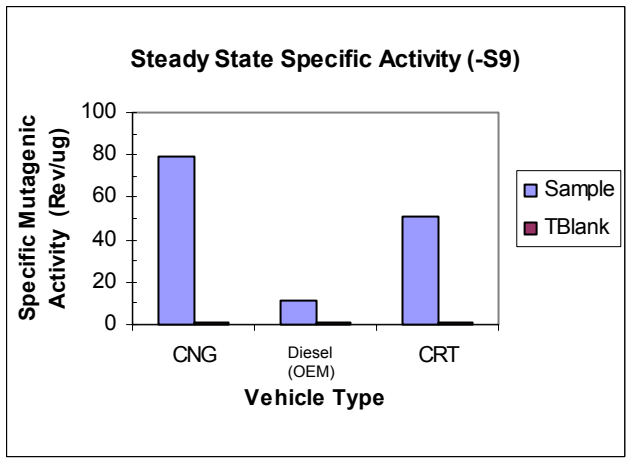
- Collection of PM on Filter
- Collection of vapor-phase on PUF
- Solvent Extraction
- Salmonella/Microsuspension procedure
- TA98 and TA 100 Tester Strains with and w/o +S9 Metabolic Enzymes

Mutagenicity Results







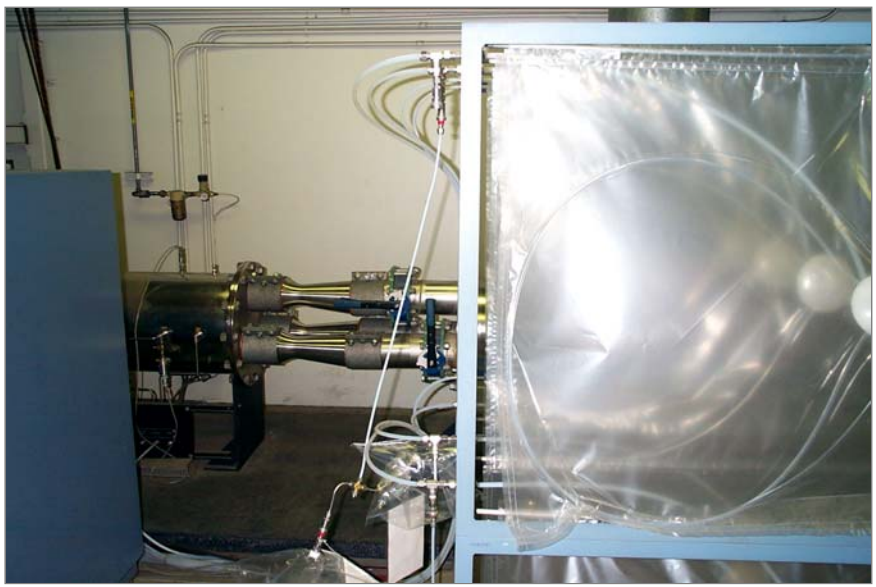


Toxic Gas-Phase HC's - Sampling Methodology

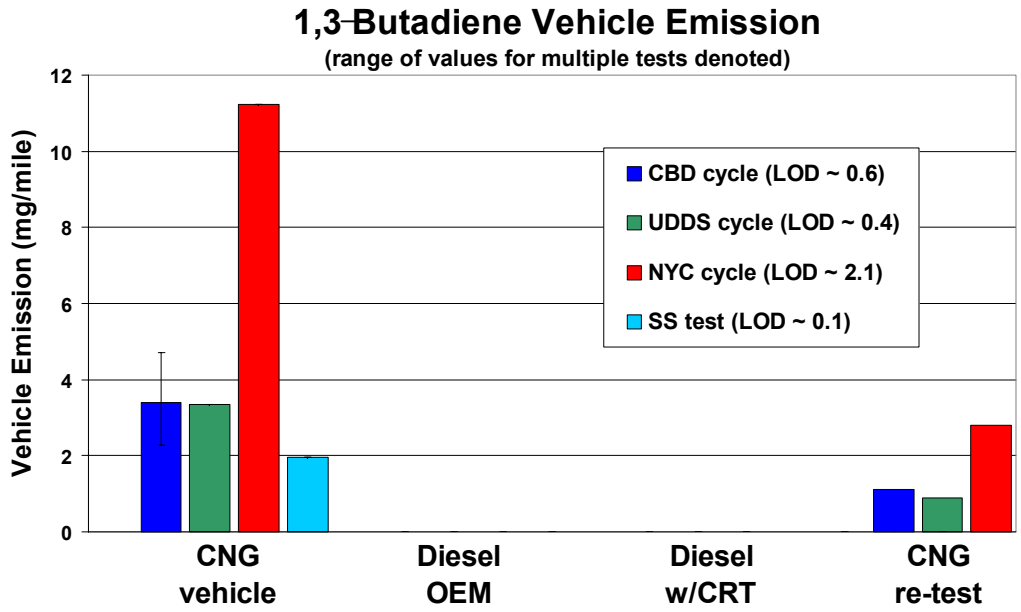
Target Analytes

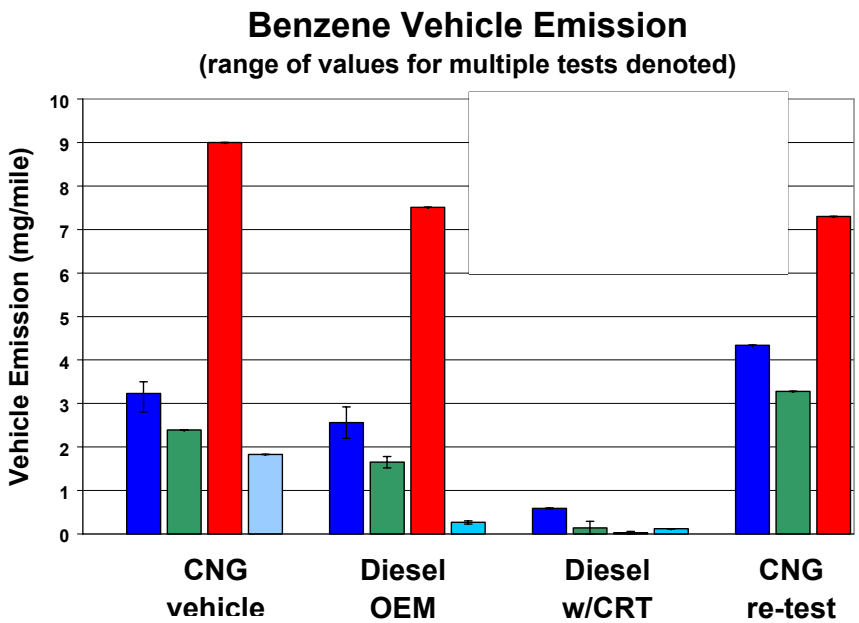
- 1,3-Butadiene
- Benzene
- Toluene
- Ethylbenzene
- m,p-xylene
- o-xylene
- Styrene

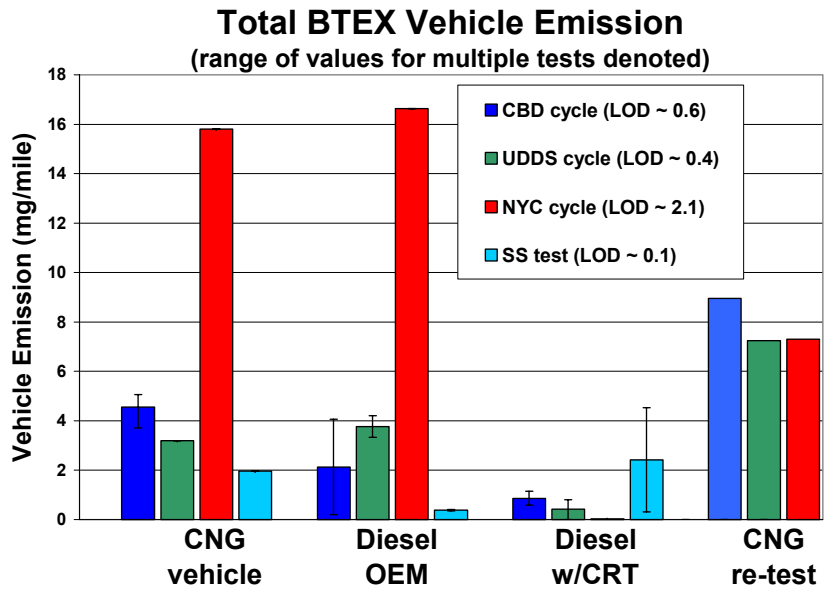
Tedlar Bag Collection



On-site GC-FID's


1,3-Butadiene Vehicle Emission
(range of values for multiple tests denoted)
Vehicle Emission (mg/mile)
0
2
4
6
8
10
12
CBD cycle (LOD ~ 0.6)
UDDS cycle (LOD ~ 0.4)
NYC cycle (LOD ~ 2.1)
SS test (LOD ~ 0.1)
CNG vehicle
Diesel OEM
Diesel w/CRT
CNG re-test


Benzene Vehicle Emission
(range of values for multiple tests denoted)
Vehicle Emission (mg/mile)
0
1
2
3
4
5
6
7
8
9
10
CNG vehicle
Diesel OEM
Diesel w/CRT
CNG re-test


Total BTEX Vehicle Emission
(range of values for multiple tests denoted)
Vehicle Emission (mg/mile)
0
2
4
6
8
10
12
14
16
18
CBD cycle (LOD ~ 0.6)
UDDS cycle (LOD ~ 0.4)
NYC cycle (LOD ~ 2.1)
SS test (LOD ~ 0.1)
CNG vehicle
Diesel OEM
Diesel w/CRT
CNG re-test

Carbonyl Compounds

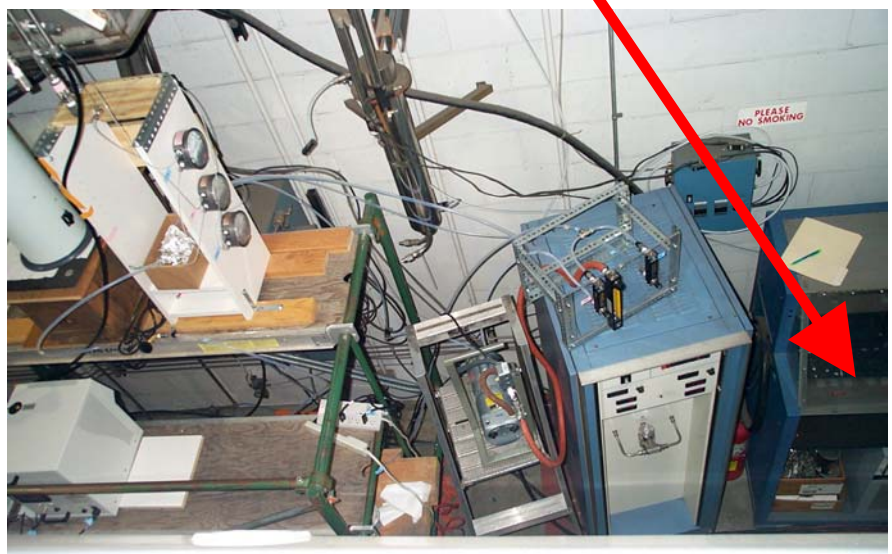
Sampling Methodology and Analysis

- Collection on DNPH cartridges
- High-precision Liquid Chromatography Analysis

Target Analytes

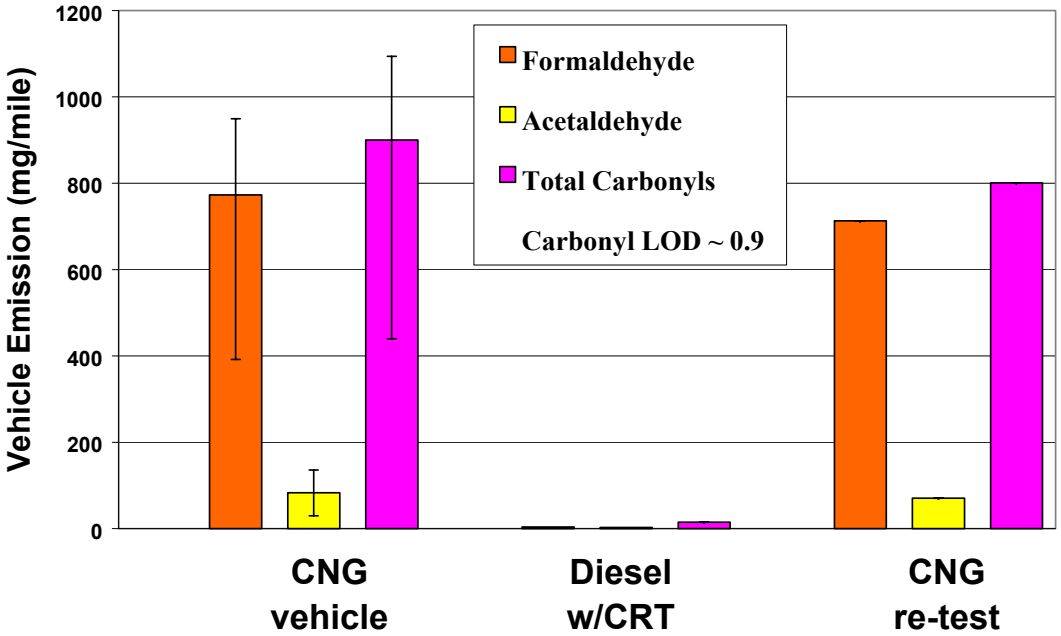
- Formaldehyde
- Acetone
- Propionaldehyde
- Methyl ethyl ketone
- Butyaldehyde
- Valeraldehyde
- Hexanal
- Acetaldehyde
- Acrolein
- Crotonaldehyde
- Methacrolein
- Benzaldehyde
- M-tolualdehyde

Aldehydes Bench



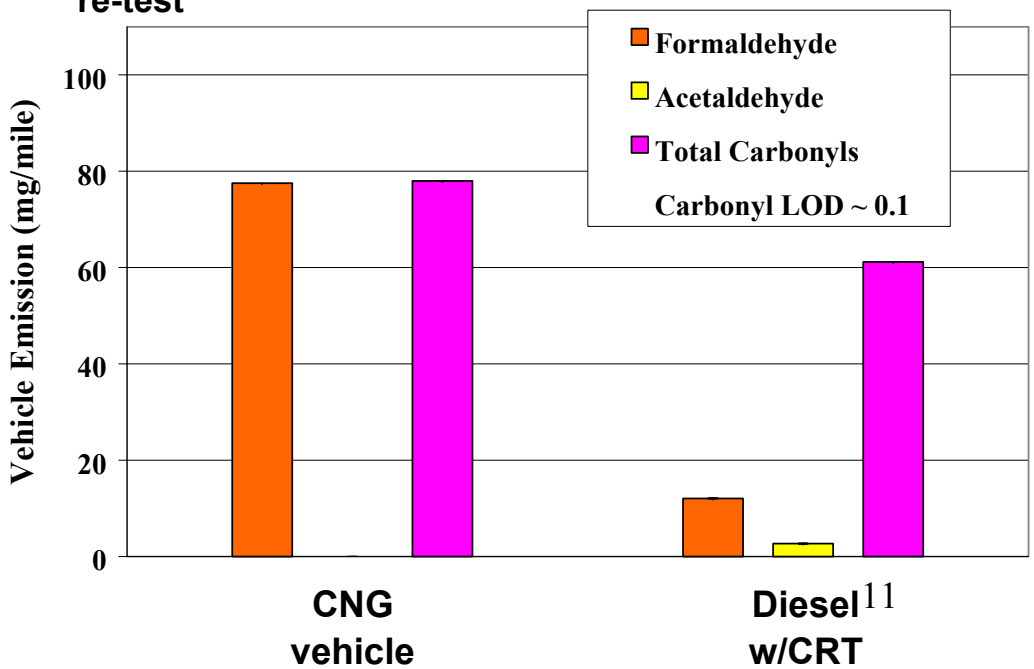
Carbonyl Emission for CBD Cycle

(range of values for multiple tests denoted)

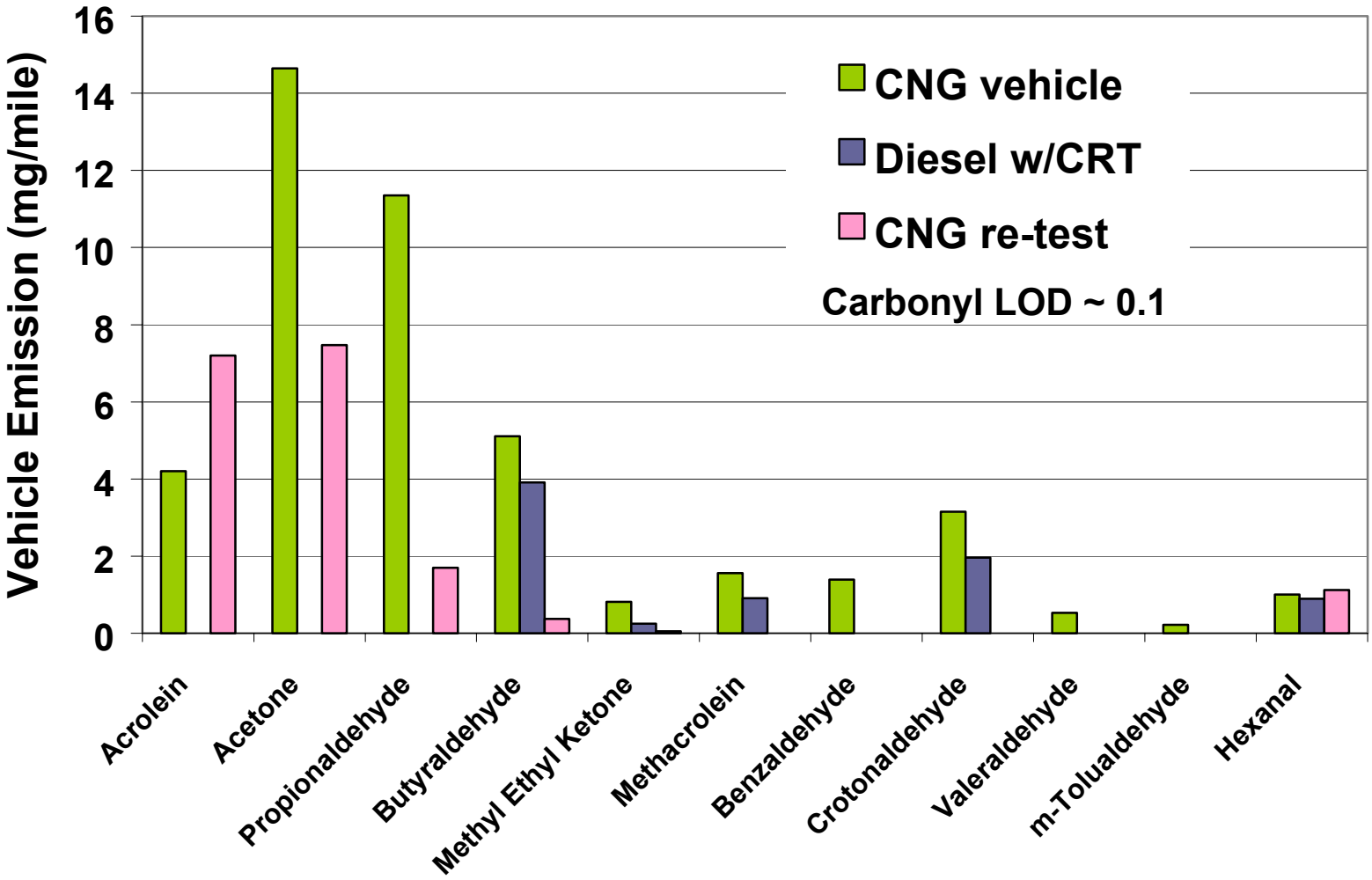


Carbonyl Emission for SS tests

(range of values for multiple tests denoted)

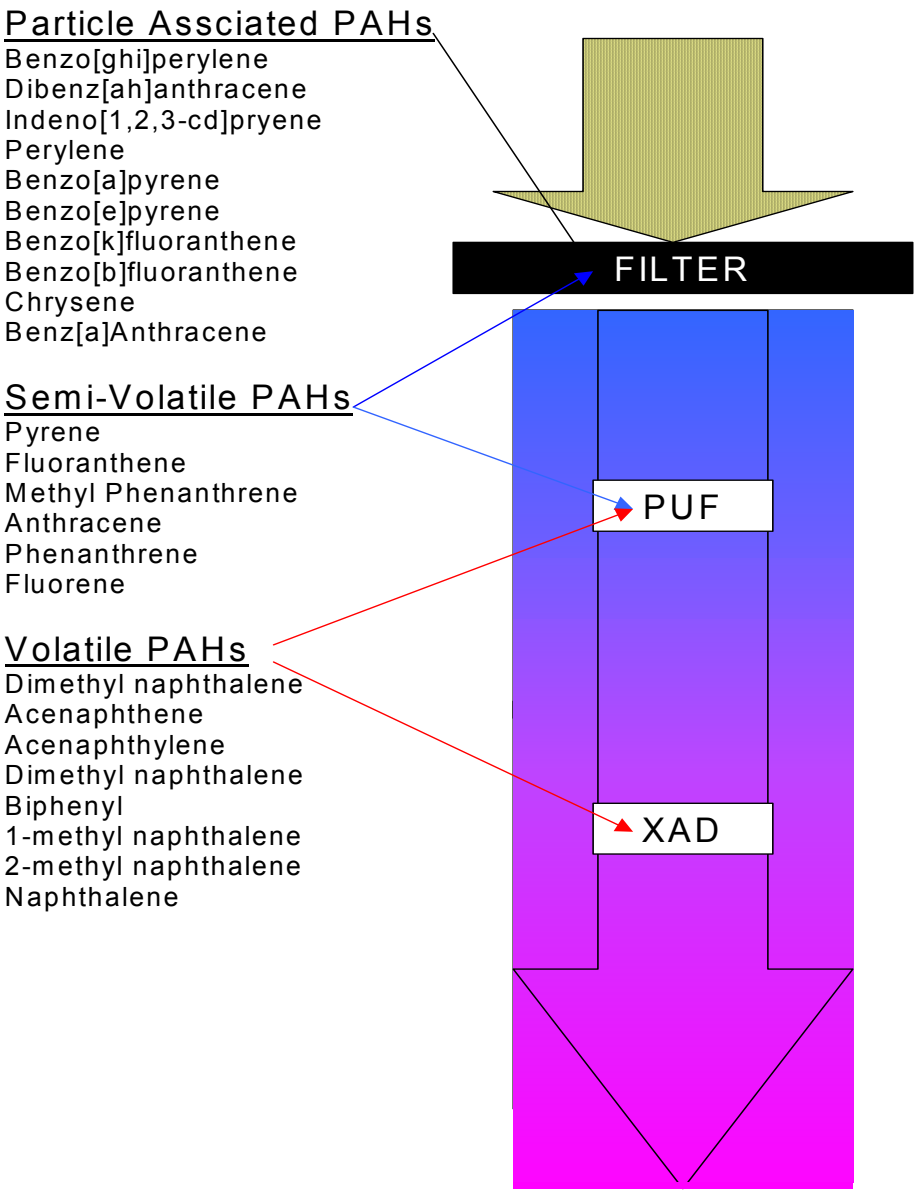


Additional Carbonyls for CBD Cycle



Polycyclic Aromatic Hydrocarbons

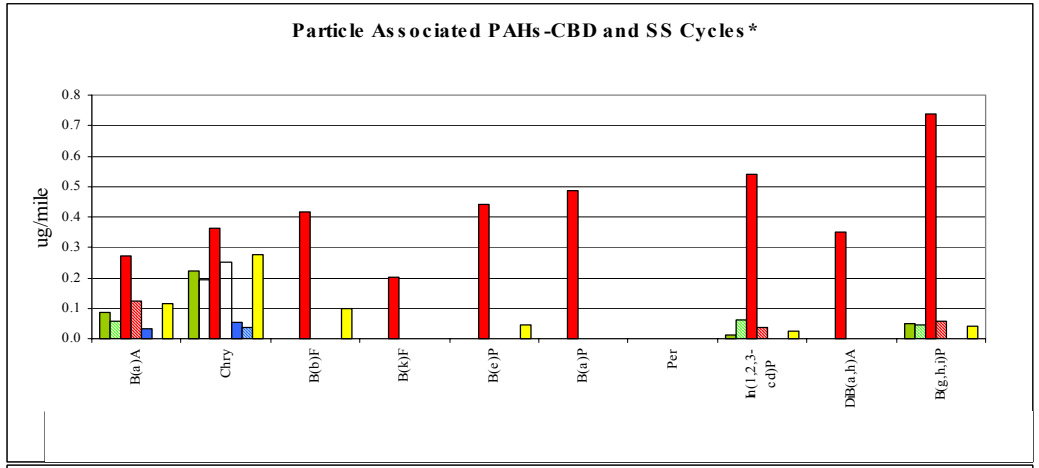
TARGET PAHS

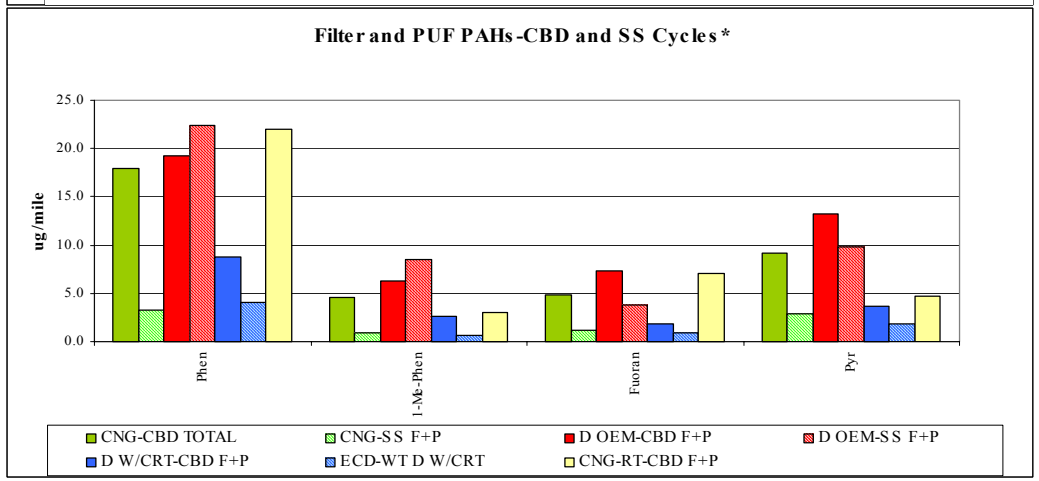


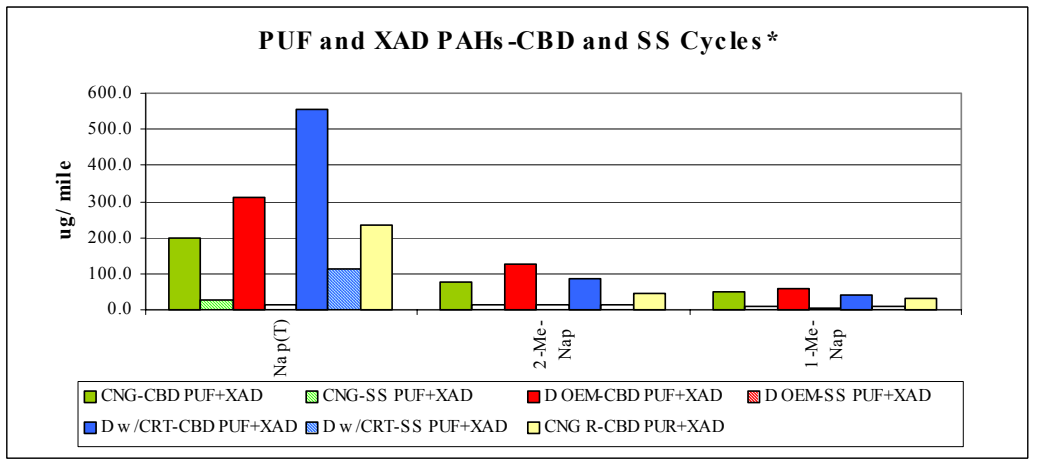
Particle Associated PAH's	OEHHA Unit risk for cancer by inhalation per million (ug/m3)E-1
Benz[a]anthracene	
Chrysene	**11**
Benzo[b]fluoranthene	**110**
Benzo[k]fluoranthene	**110**
Benzo[a]pyrene	**1100**
Dibenz[ah]anthracene	**1200**

Expected PAH phase distribution in ambient and CARB diesel exhaust samples

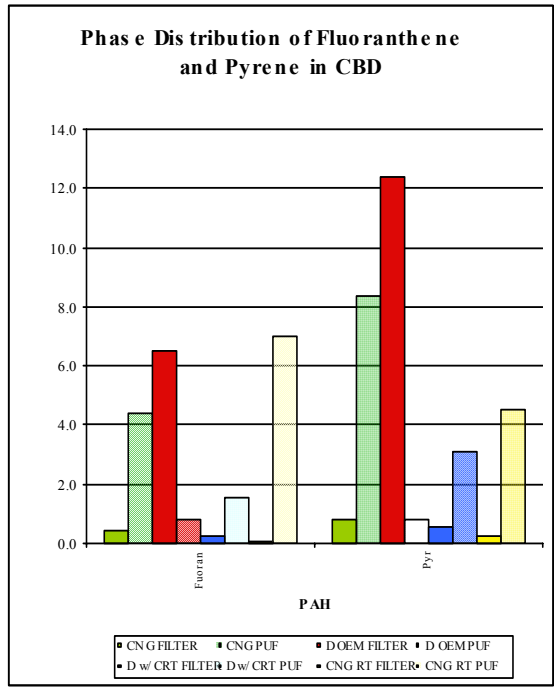
*All results not corrected for tunnel blanks and XAD values corrected for background contamination

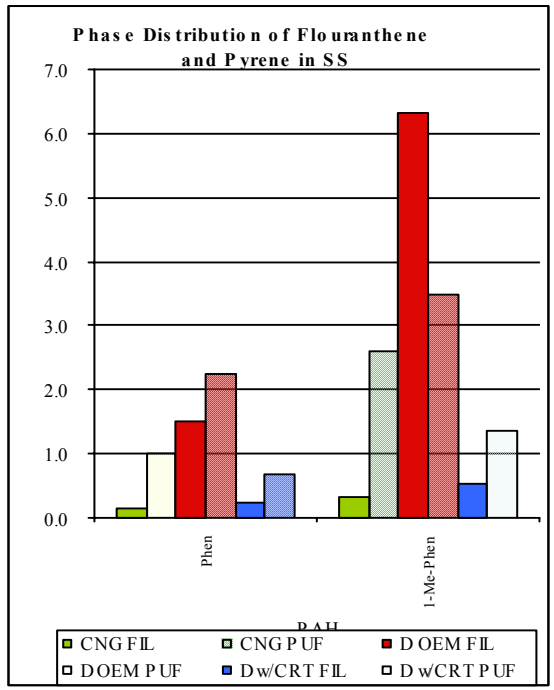






- **CBD and SS Results PAHs in PM**
  - –Diesel (OEM)-Most PAHs Detected
  - –CNG CBD - Most PAHs m.w. 252 Not Detected except for BaP
  - –CNG SS- All PAHs m.w. 252 Not Detected
  - –CRT- CBD and SS Only Benz[a]anthrancene and Chrysene Detected
- **CBD and SS Semi-volatile PAHs**
  - –Diesel (OEM) Generally the Highest Levels
  - –CNG Similar Levels to Diesel OEM
  - –CRT Lowest Levels
- **CBD and SS Volatile PAHs**
  - –At Similar Levels
- **Fluoranthene and Pyrene Phase Distribution**
  - –CBD Diesel(OEM)-Primarily in Filter
  - –SS Distributed more evenly between the Filter and PUF
  - –CRT and CNG-Primarily in PUF





EC/OC and Elemental Analysis

EC/OC Procedure

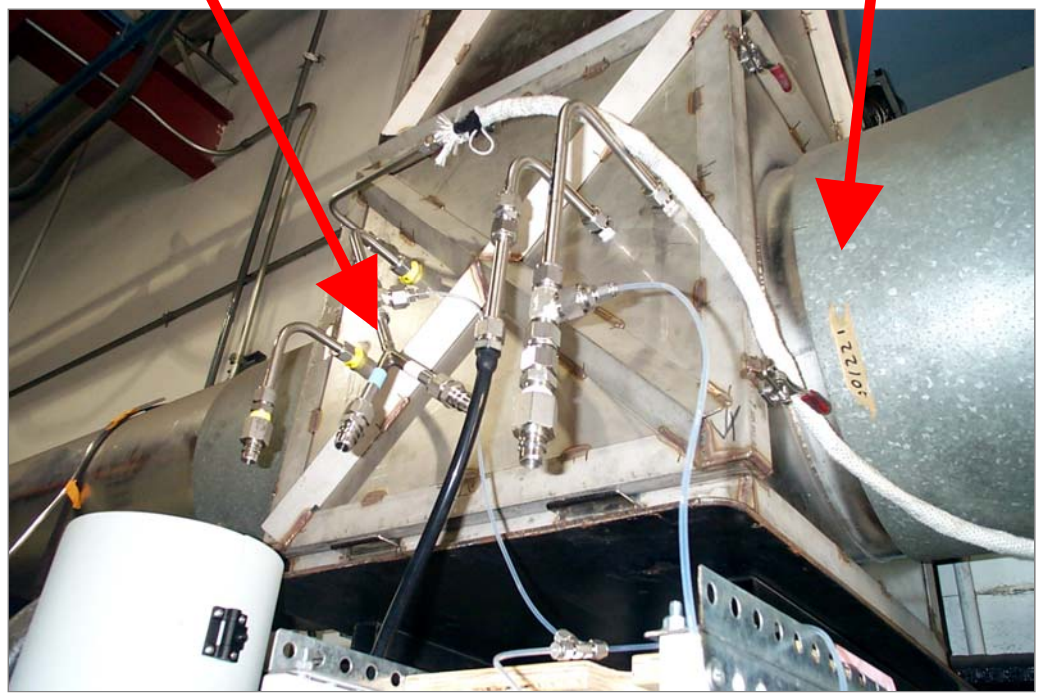
- Quartz-Filter Collection of PM
- DRI/IMPROVE Optical/Thermal Analysis

Elemental Analysis

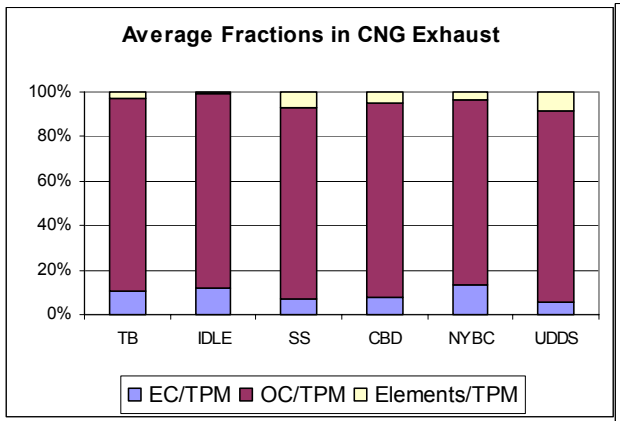
- Teflon-Filter Collection of PM
- X-ray Fluorescence

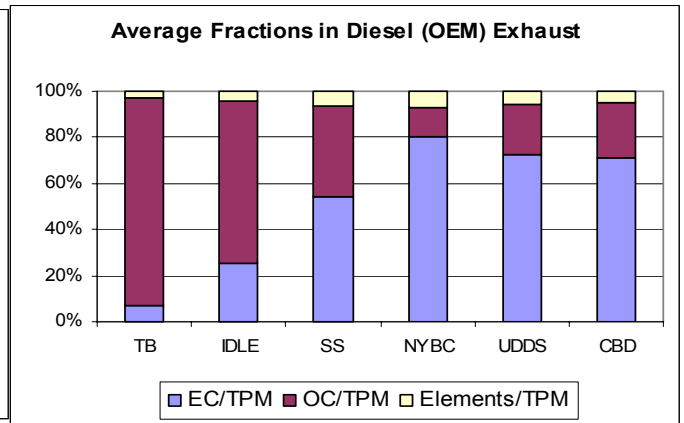
Primary Dilution Tunnel

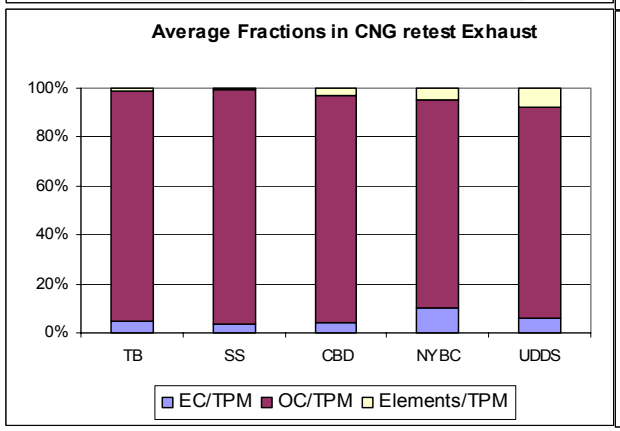
Sampling Probes

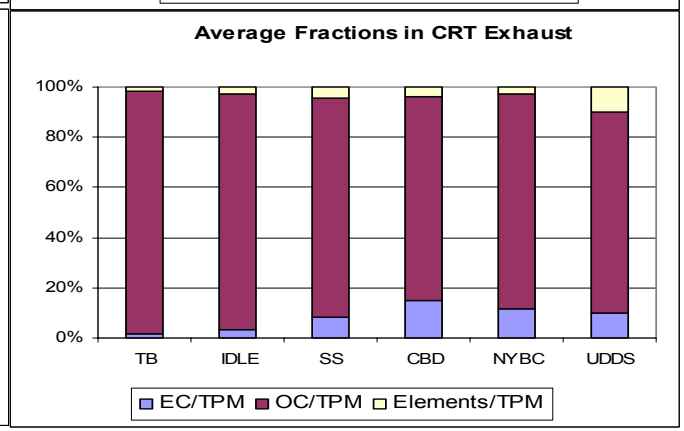


Average Composition of PM









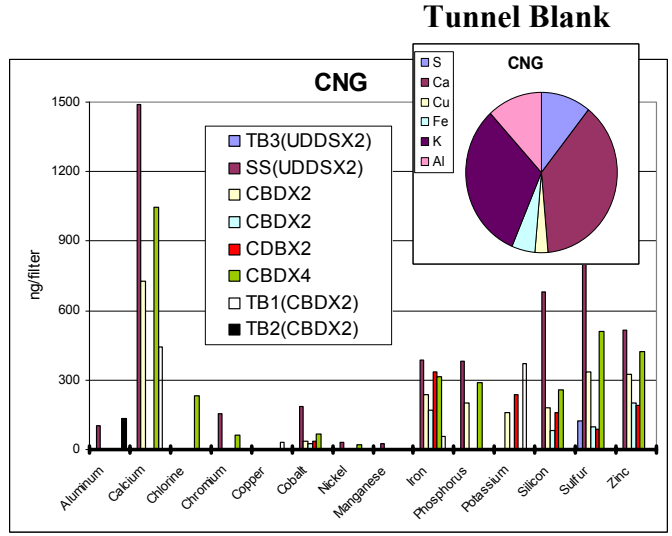
- OC dominates CNG PM composition across all cycles
- Similar tunnel blank composition
- EC/OC fraction in Diesel (OEM) PM shows strong cycle dependence
- OC dominates CRT PM composition across all cycles

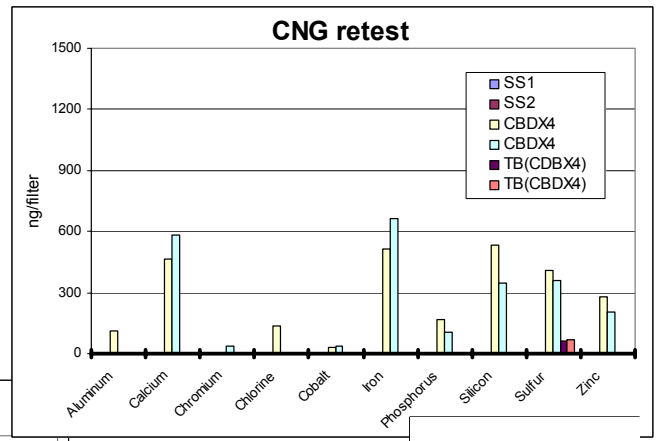
NOTE: TPM=Total PM= EC+OC+Elements

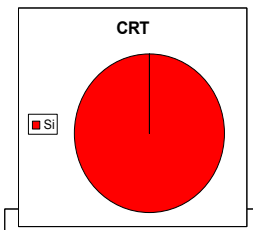
Elemental Analysis Results

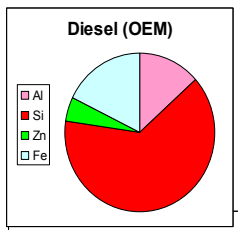
- Ca, Cl, P, Zn, S are oil components
- Fe from engine wear
- Si source unknown
- Si emissions: Diesel (OEM) >> CNG ~ CRT
- In general, TB << SS and CBD

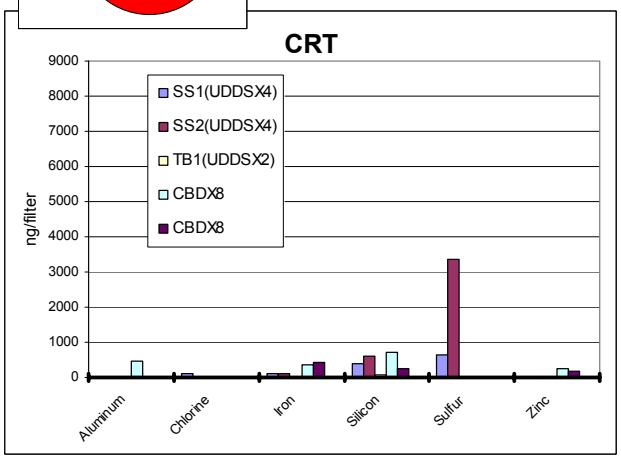
NOTE: Cumulative results per test sequence, not per cycle

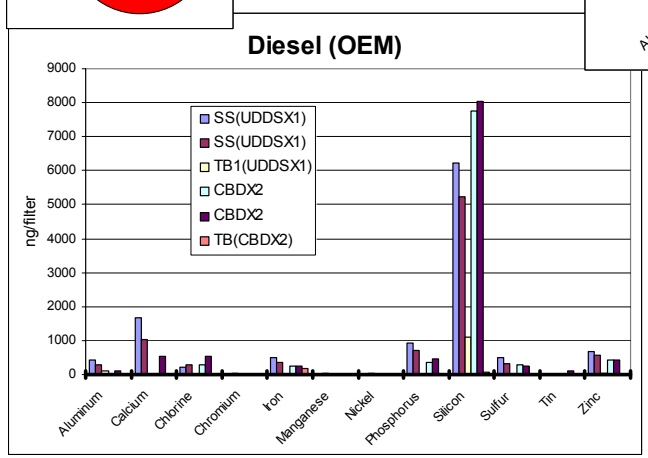


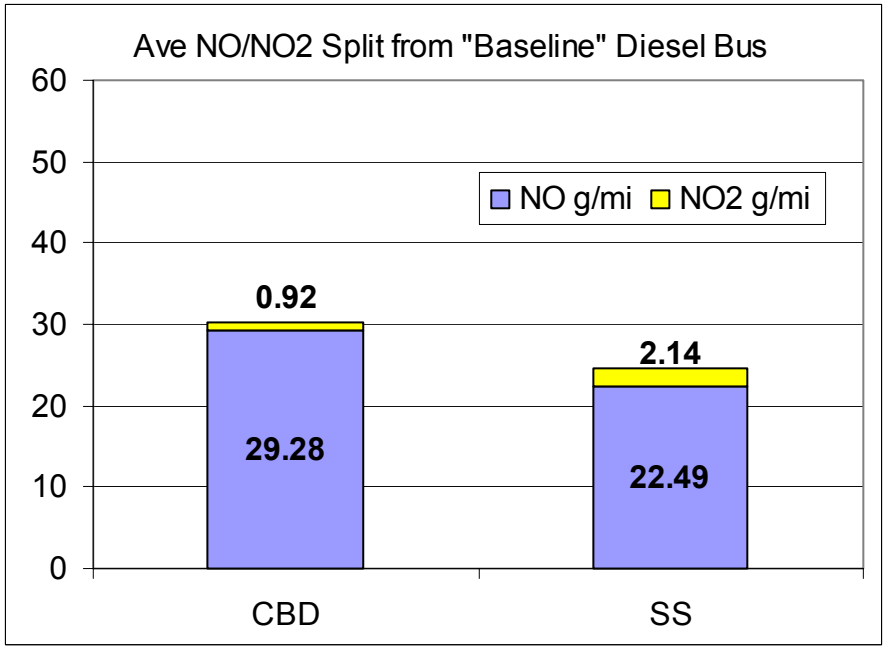




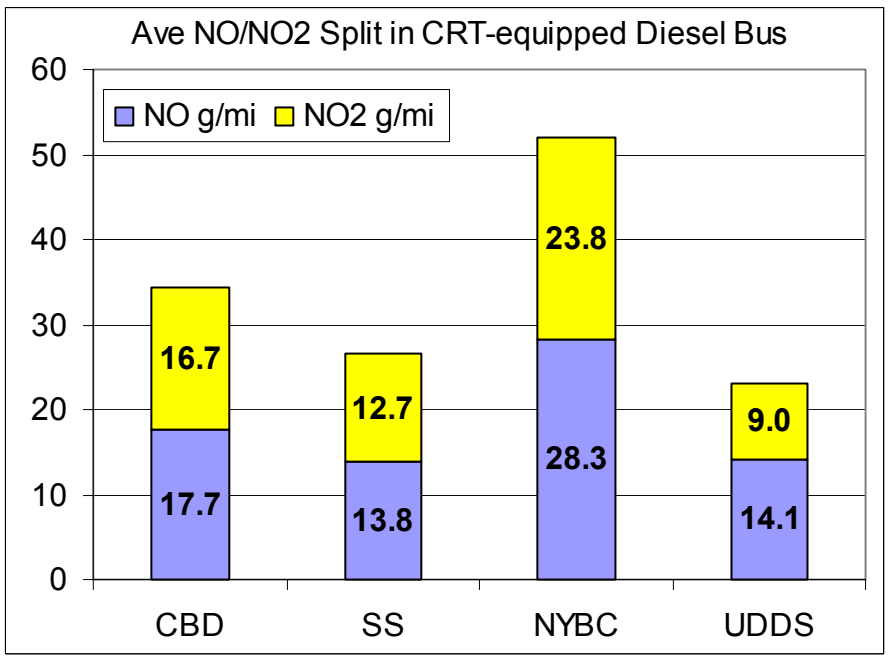


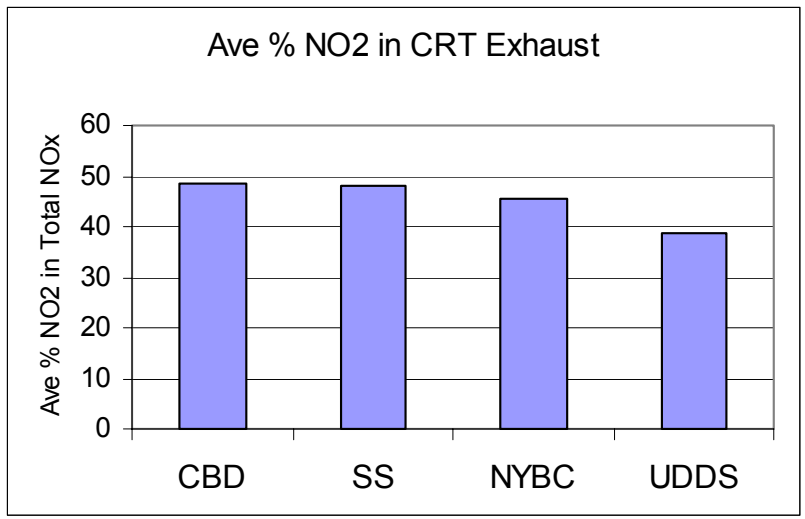




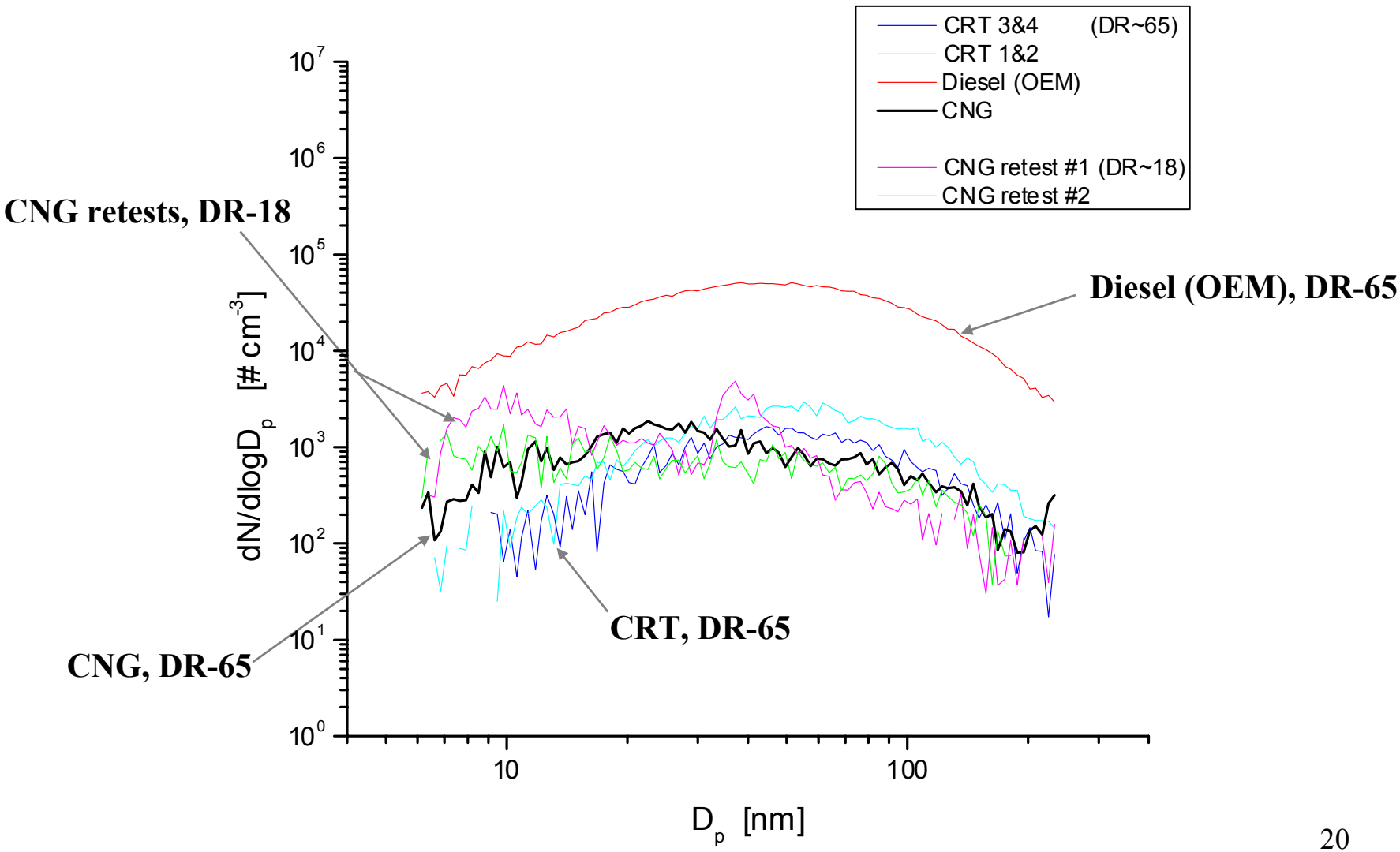


CRT Effect on Diesel Bus NO_X Emissions





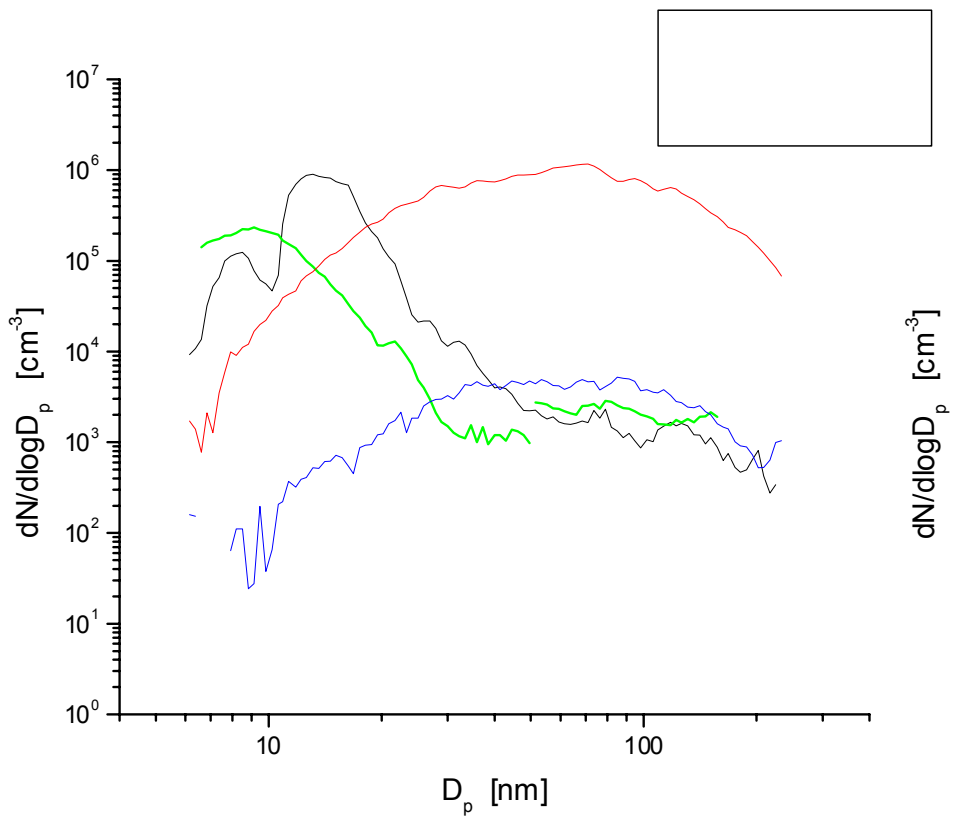
Average of Individual Scans - Mini-diluter- SS Tests
SIZE-SCAN MODE



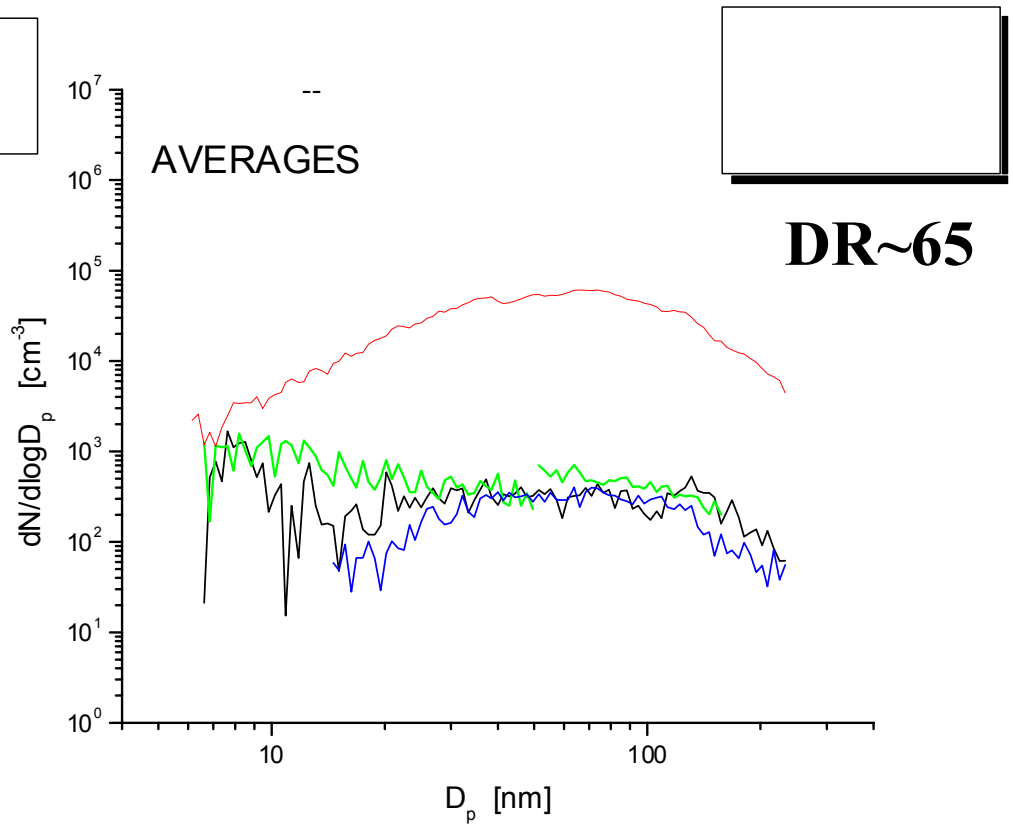
Note: CNG retest#1 = 55mph, 0% gradient, CNG retest#2=55mph,0.6% gradient

Average of Individual Scans - Dilution Comparison - CBD Tests
SIZE-SCAN MODE

CVS



Mini-diluter



Final Remarks

Regulated and NO_2 Emissions

•CRT showed reductions in CO (87%), THC (100%), and uncorrected PM (88%) relative to Diesel (OEM)

• CRT and Diesel OEM NO_x not significantly different

• Significantly different NO_2/NO_x ratios in CRT (50%) and Diesel OEM (3%)

• CNG NO_x exhibited high variability. CNG re-test NO_x was 75% of Diesel (OEM) NO_x

Ultrafine Number Emissions

•CRT showed reduction in size distribution across entire size range compared to Diesel OEM

• Only accumulation mode was evident in diesel

• For SS, modes in CNG size distributions were not distinct, but nanoparticle (<50nm) concentrations were higher than for CRT

• For SS, total particle numbers were always lower for CNG and CRT compared to Diesel OEM

Final Remarks (cont'd)

Toxic Hydrocarbons and Carbonyl Compounds

- Butadiene was only detected in CNG vehicle exhaust (with 1 exception: Diesel without trap idle test).
- Generally, BTEX concentrations in CVS exhaust samples were close to ambient levels
- Generally, BTEX emission follows the order: CNG > Diesel (OEM) > CRT
- Carbonyl emissions from CNG vehicle were much higher than from CRT-equipped vehicle
- Total carbonyl emissions (by mass) from CNG vehicles are two orders of magnitude higher than BTEX and 1,3 Butadiene emissions
- CNG vehicle carbonyl emissions are dominated (>80%) by formaldehyde

Composition of PM

- OC dominates CNG PM composition across all cycles
- Similar tunnel blank composition
- EC/OC fraction in Diesel (EOM) PM shows strong cycle dependence
- OC dominates CRT PM composition across all cycles
- Ca, Cl, P, Zn, S are oil components
- Fe from engine wear
- Si source unknown. Emissions: Diesel (OEM) >> CNG ~ CRT

PAH's and Bioassay

- Emission rates (ug/mi) for most PAH's were higher in the CBD than SS
- Emission rates for CNG retest were generally higher than CNG
- Differences were observed in the properties of PM from CNG, Diesel (OEM), and CRT
- CRT PAH levels are similar levels to TB's
- Generally, CNG and Diesel (OEM) are higher than TB's
- Emissions of mutagenic compounds showed cycle dependence
- For CBD, bioassay follows: CNG > Diesel (OEM) > CRT
- For SS, bioassay follows: CNG > CRT > Diesel (OEM)