Gasoline Vehicle Exhaust Particle Sampling Study

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Why Study Gasoline PM?

- There is considerable uncertainty about the relative contributions of gasoline and Diesel engines to PM2.5 emissions
- There is even greater uncertainty about the relative contributions of gasoline and Diesel engines to nanoparticle emissions
- The U.S. consumes more than 3 times as much gasoline as distillate (Diesel) fuel in transportation

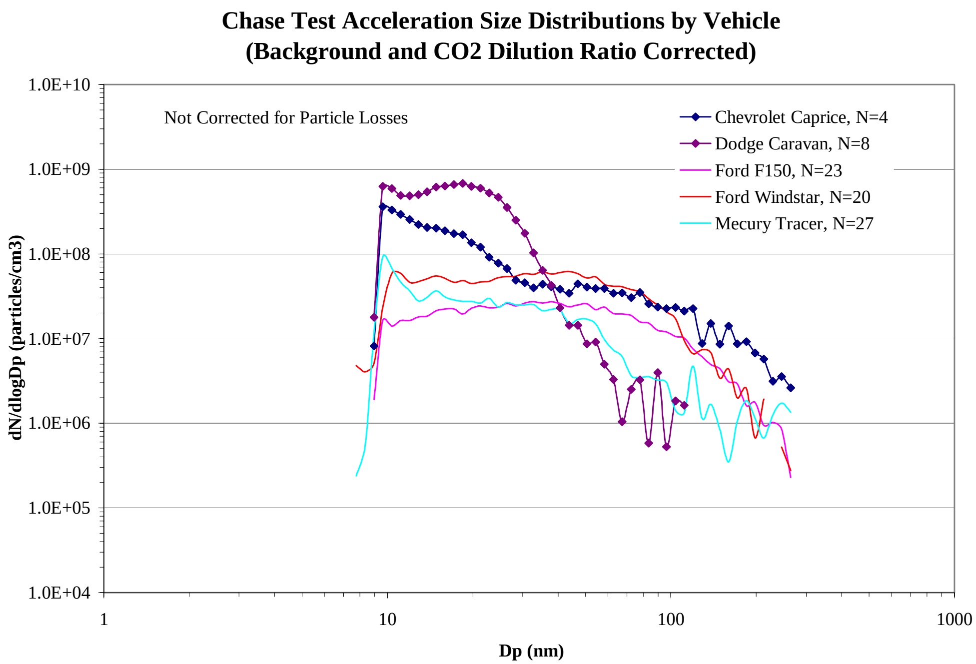
Outline – Spark Ignition PM emissions

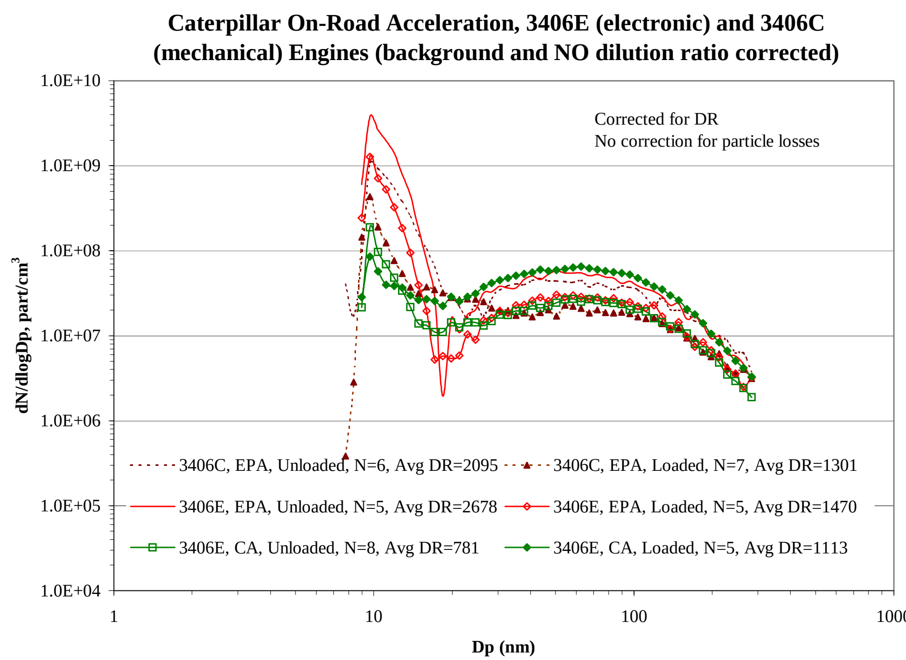
- On-road chase
- Chassis dynamometer
  - Physical measurements
  - Chemistry
- Simulated “smoker”
- Weekend vs. weekday
- Cold start and idle
- Conclusions

MEL Built During The CRC E-43 Project

- Instrumentation
  - SMPS to size particles in 9 to 300 nm size range
  - 3025A CPC to count all particles larger than 3 nm with leaky filter dilutor
  - Diffusion Charger to measure total submicron particle surface area
  - PAS to measure total submicron surface bound PAH equivalent
  - CO_2 , CO, and NO ambient gas analyzers
  - ECOM AC for exhaust gas analysis

On-Highway Chase Experiments - Comparison of Diesel and Gasoline Size Distributions during Hard Accelerations

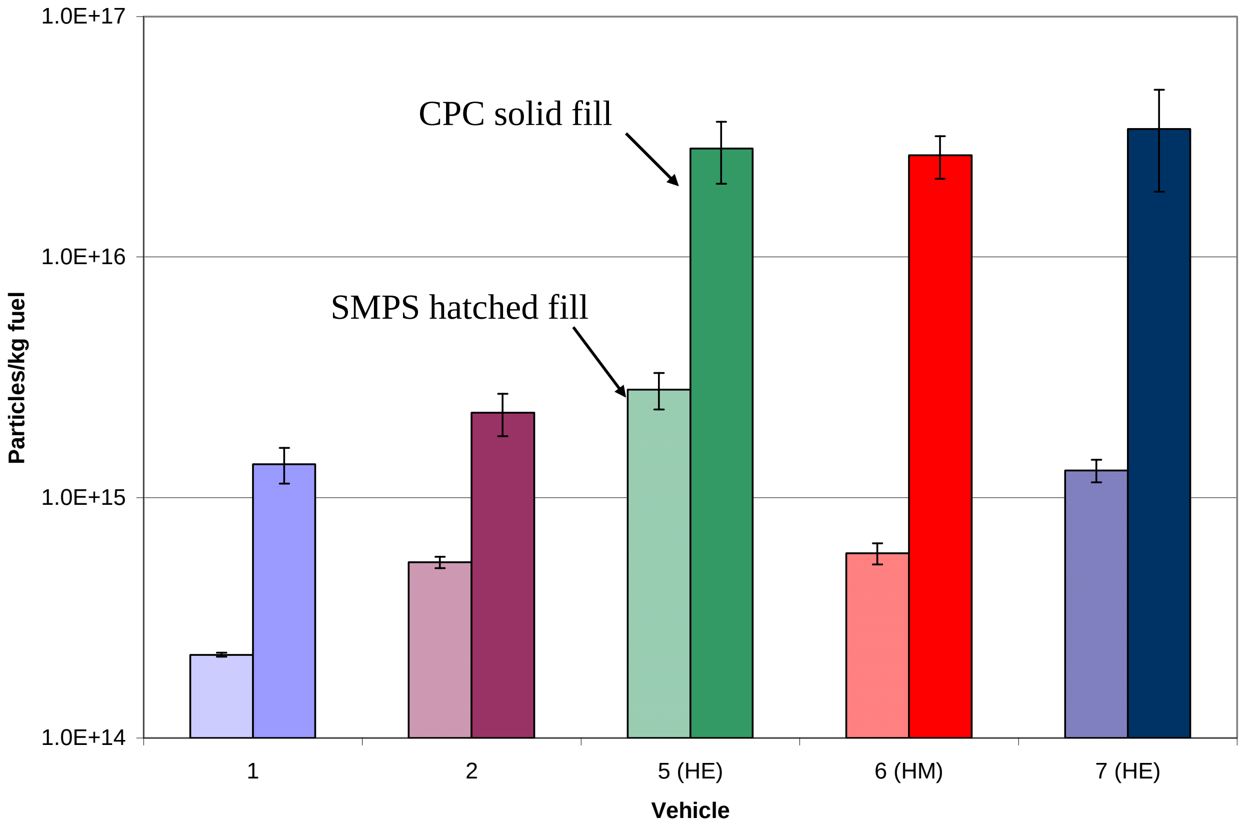




- Under steady highway cruise conditions we could not measure a significant particle signature above background for gasoline engines
- However, during hard accelerations, size distributions for gasoline light-duty vehicles were surprisingly similar to modern heavy-duty Diesel vehicles
- Generally gasoline engines have somewhat lower concentrations in the upper end of the accumulation mode were most of the particle mass is found, thus they have lower mass emissions

On-Road Chase Experiments - Number Emissions during 50 to 70 MPH Hard Accelerations

CPC number (D > 3nm), SMPS number (D > 10nm)



- Vehicles 1 and 2 were low mileage normal emitters, 5 and 7 were worn blue smokers, vehicle 6 was high mileage
- Fuel specific number emissions range from 2 x 10^{14} to 3 x 10^{16} particles/kg fuel
- Many particles below sizing range of conventional SMPS
- Emissions of extremely small particles, D > 3 < 10 nm, are often more than an order of magnitude higher than emissions of particles for D > 10 nm

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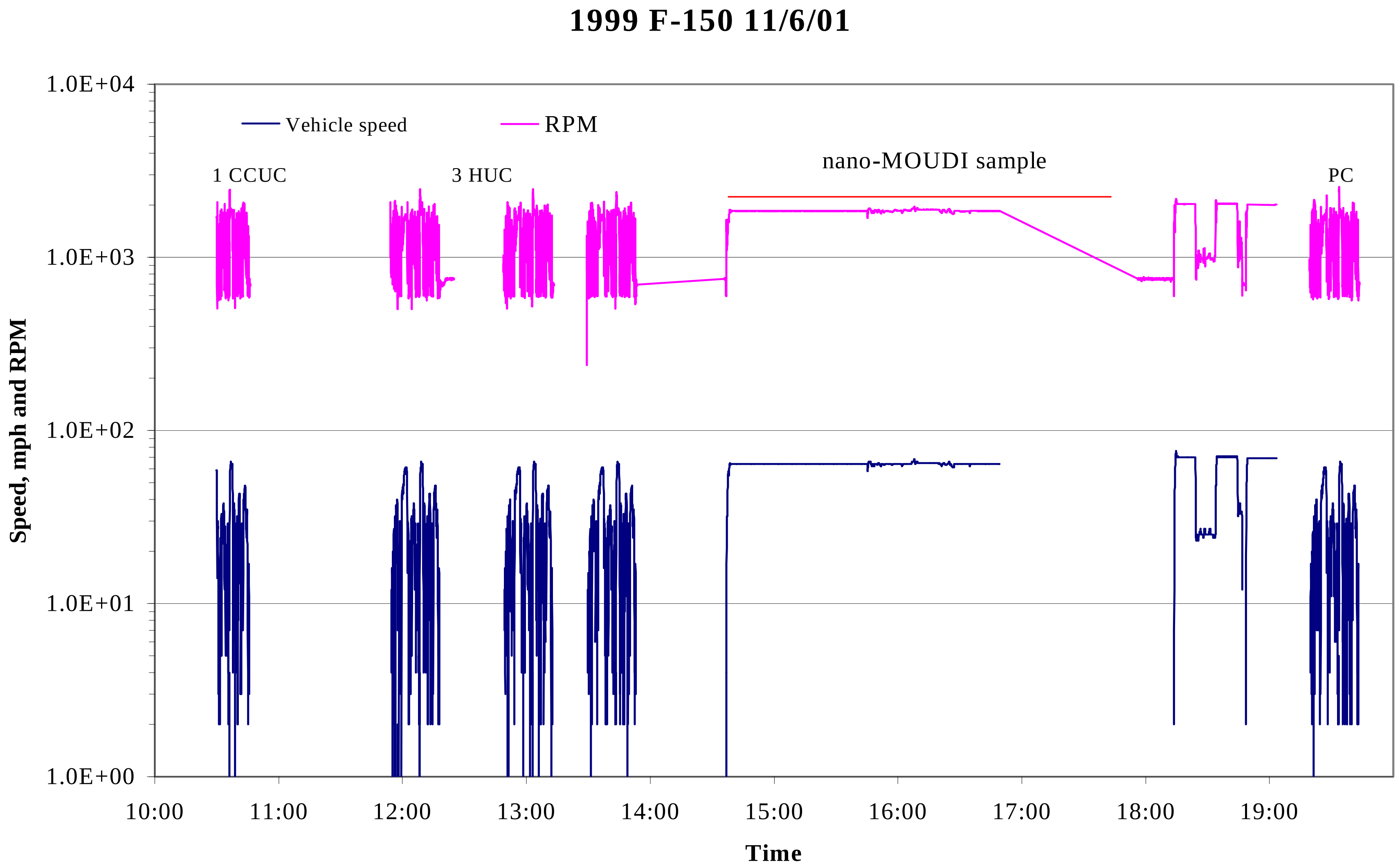
Chassis dynamometer tests

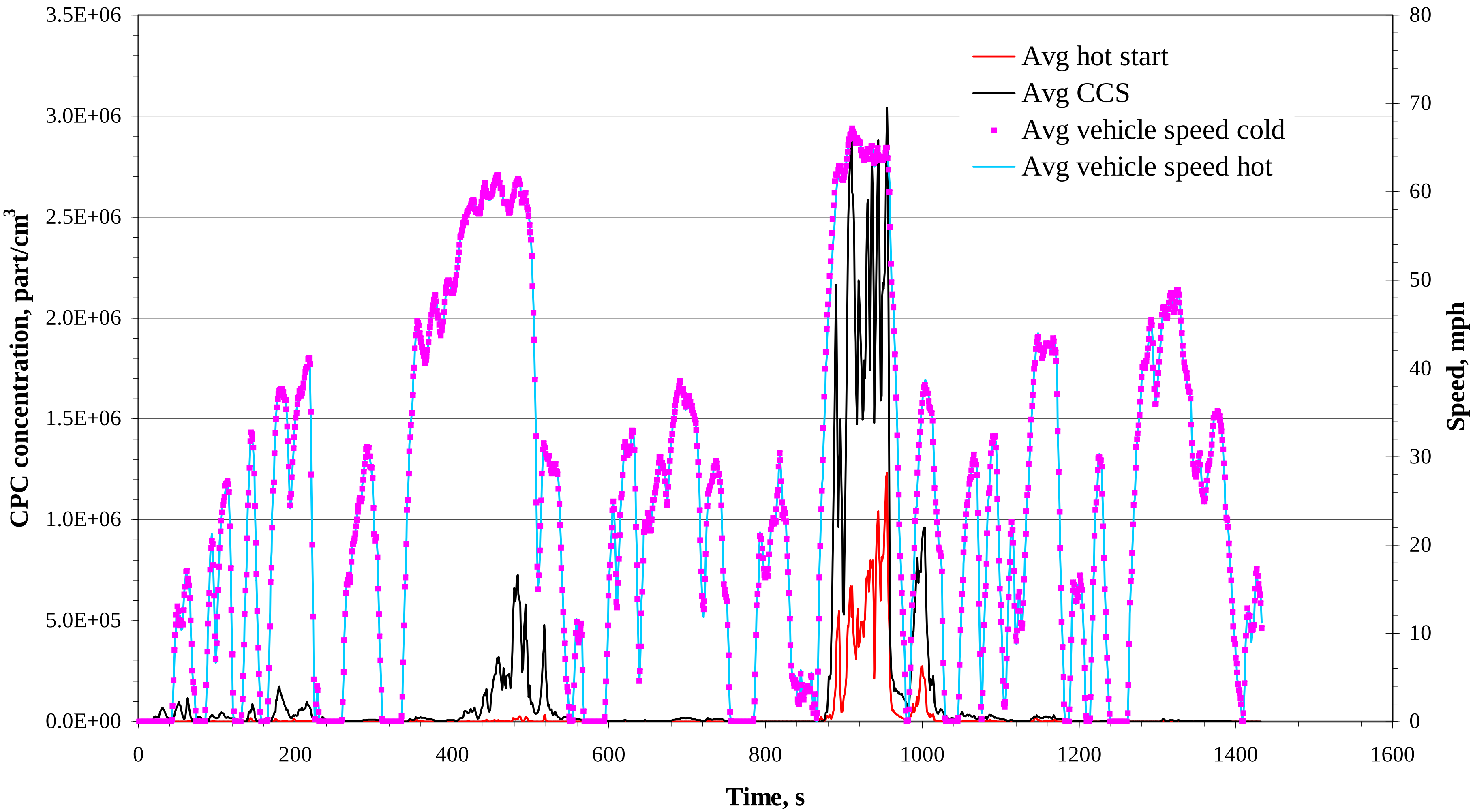
- Compare the information obtained from on-road tests to a small subset of light-duty gasoline vehicles tested on a chassis dynamometer with a dilution tunnel using the Unified Drive Cycle, at both room temperature and 30° F.
- Hot and cold cold start UDCs and steady state conditions evaluated
- Use instruments from MEL plus filter and impactor samples for PM2.5 and chemistry
- Specially designed dilution system, CVS with dilution at tailpipe

Windstar at Chassis Dynamometer

Sequence of Testing First Day for Each Car

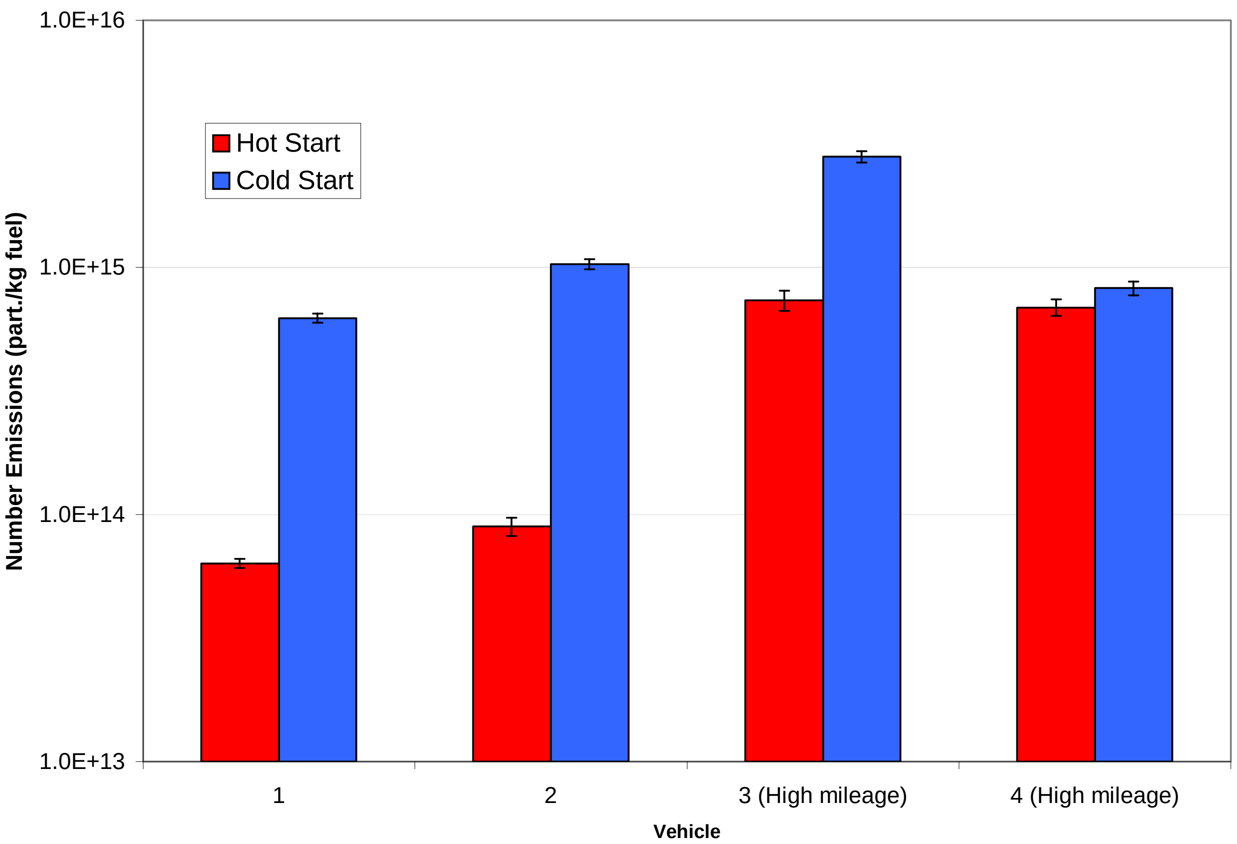


Average Hot and Cold UDCs for the Escort



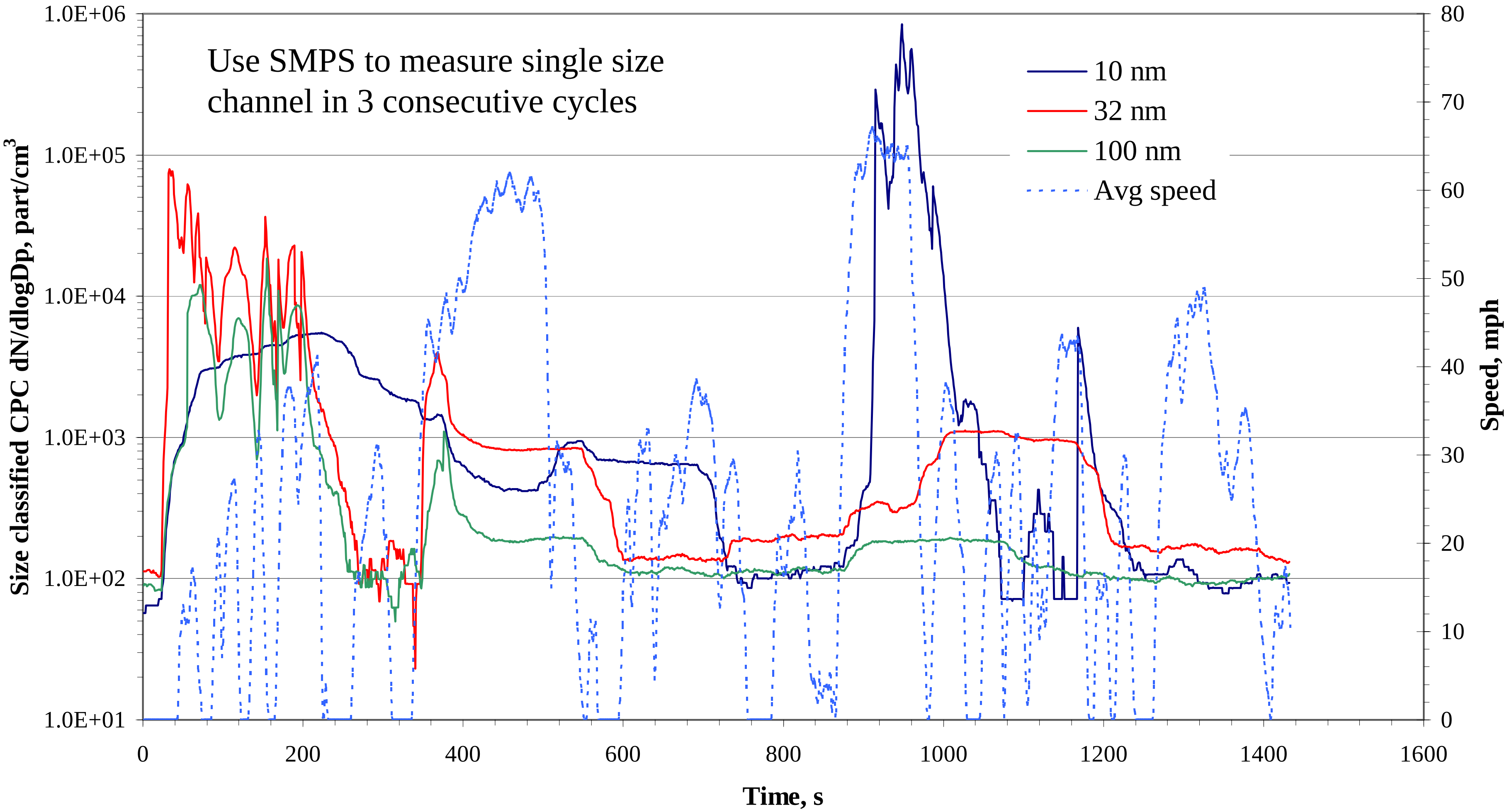
Note: Peak CPC concentrations are underestimates because the CPC over ranged.

Chassis Dynamometer Tests – Unified Cycle CPC Number Emissions (Dp > 3 nm)

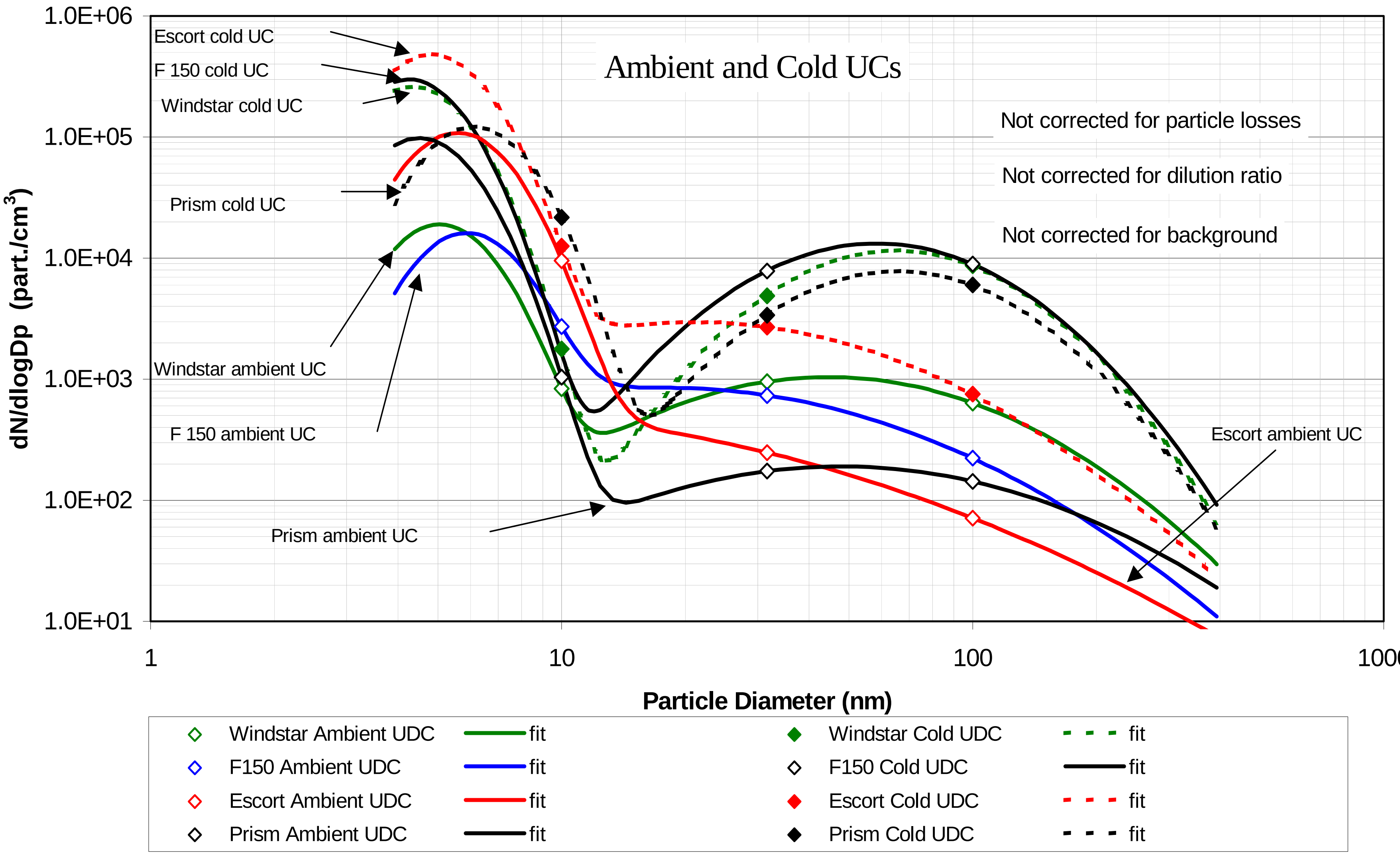


- Number emissions much higher in cold start cycle, particularly with low mileage vehicles
- Fuel specific emissions range from $6x10^{13}$ to $3x10^{15}$ part/(kg fuel)

Cold Cold Start Size Classified UDCs - Escort



Unified Cycle Test Size Distributions



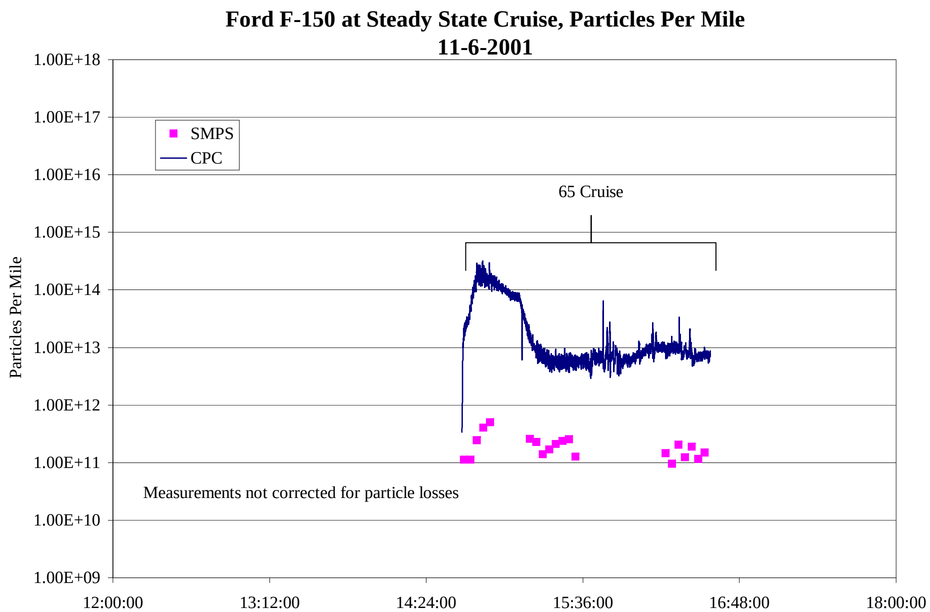
Summary UDC Test Trends

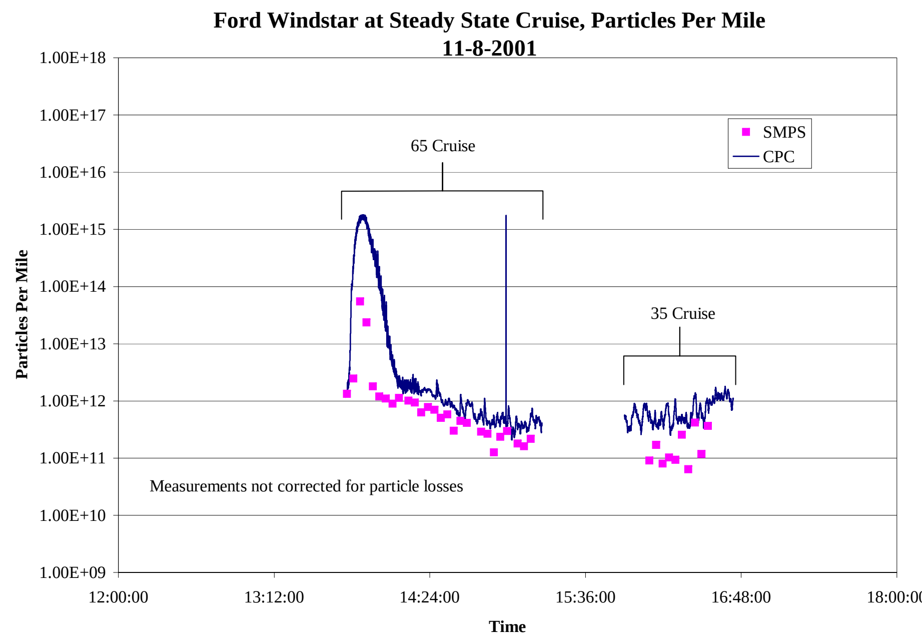
- Gasoline particle emissions are very condition dependent
- Highest number concentrations measured at peak vehicle speed (70 mph)
- Cold cold start emissions were consistent from test to test
  - During the cold cold start test larger particles are emitted early in the cycle when the vehicle is warming up at low speeds
  - Larger concentration in accumulation mode consistent with higher mass emissions
- Hot start emissions were much lower than cold and decreased (CPC) from test to test
  - The vehicle would be warmer for each hot start test.
  - The order of the sampling was always the same during the hot start tests (10, 32, and 100 nm). This may have introduced a bias into the reconstructed size distributions.

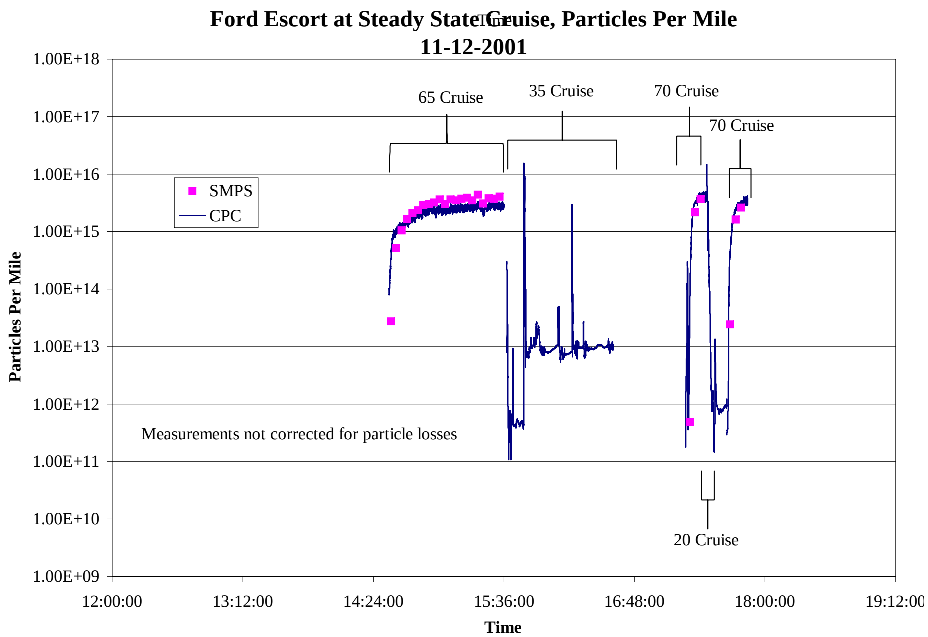
Chassis Dynamometer Steady-State Data Conditions

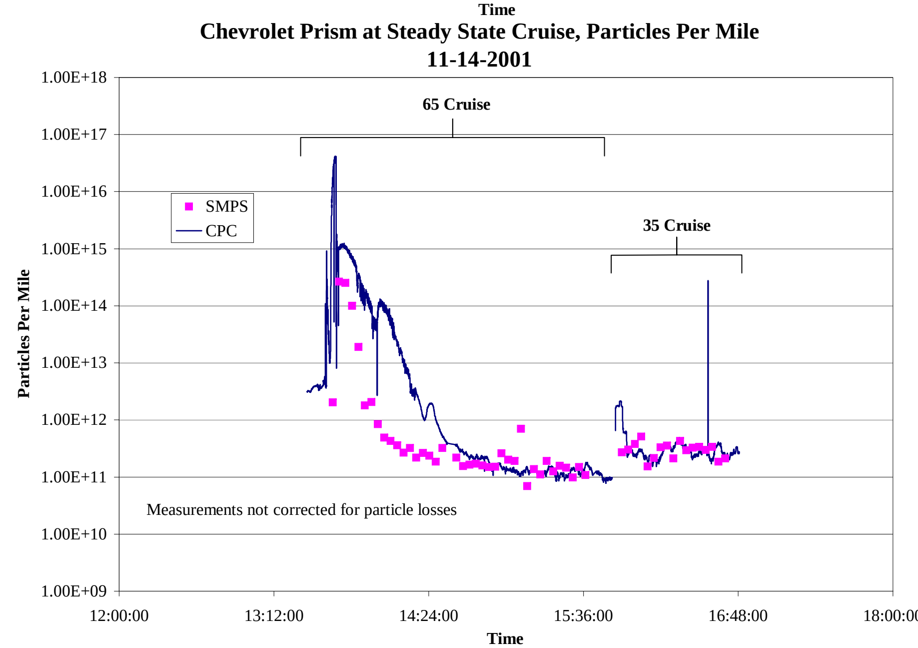
- The steady-state operating condition included
  - 2 hrs at 65 mph
  - 1 hr at 35 mph
  - nano-MOUDI and filter samples collected during entire 3 hrs
- Approximately one hour composed of four 10-15 min periods
  - Idle
  - 70 mph
  - 20 mph
  - 70 mph

Total Number Concentrations, Storage and Release With Decaying (Except for Unusual Emitters) Emissions of Sub 10 nm Particles

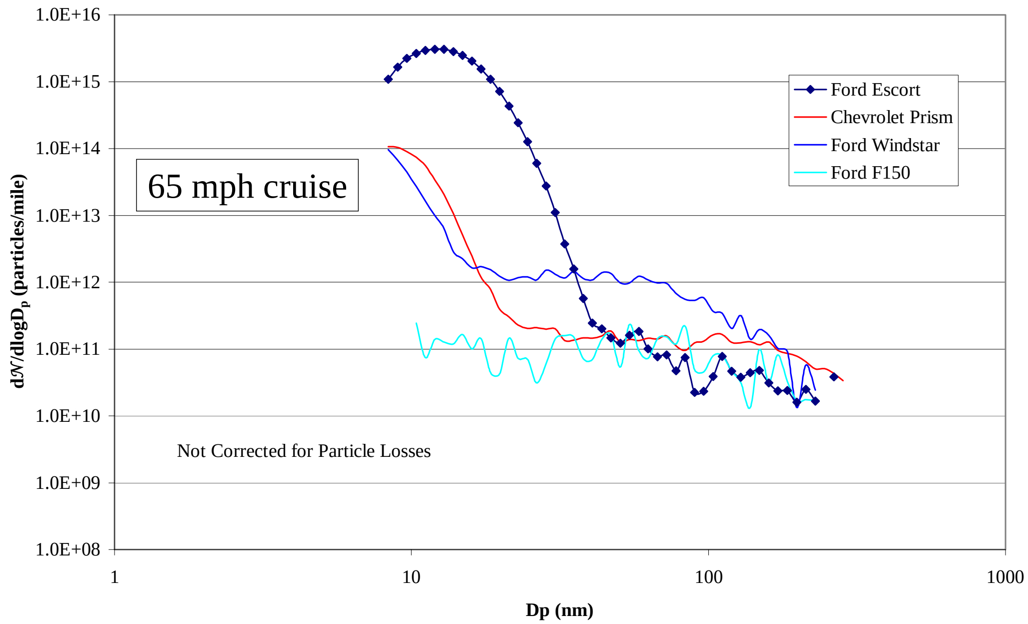


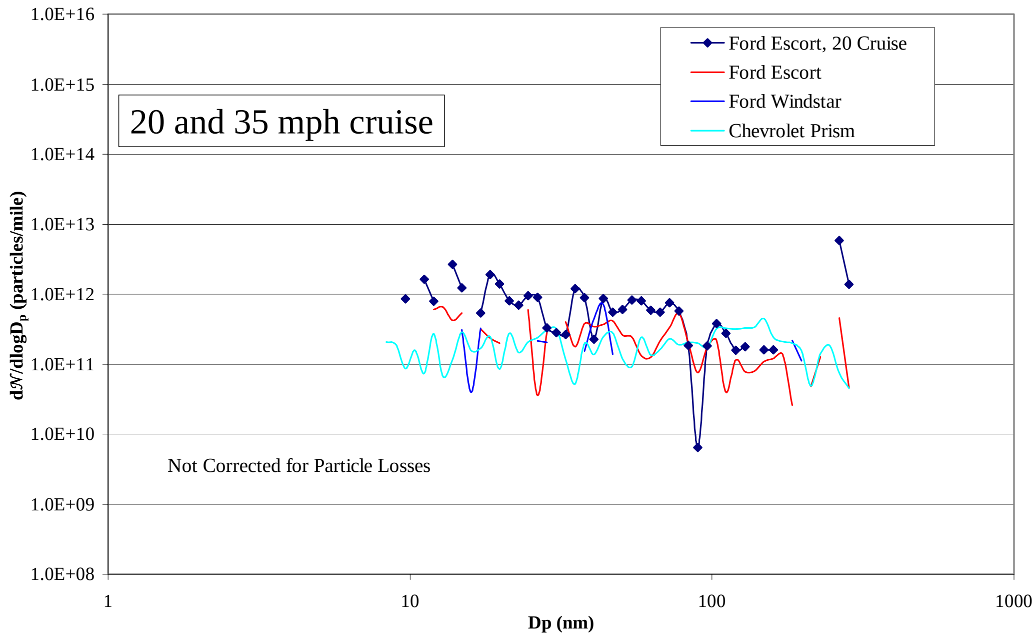






Chassis Dynamometer Tests – SMPS Measurements during Steady-State Tests

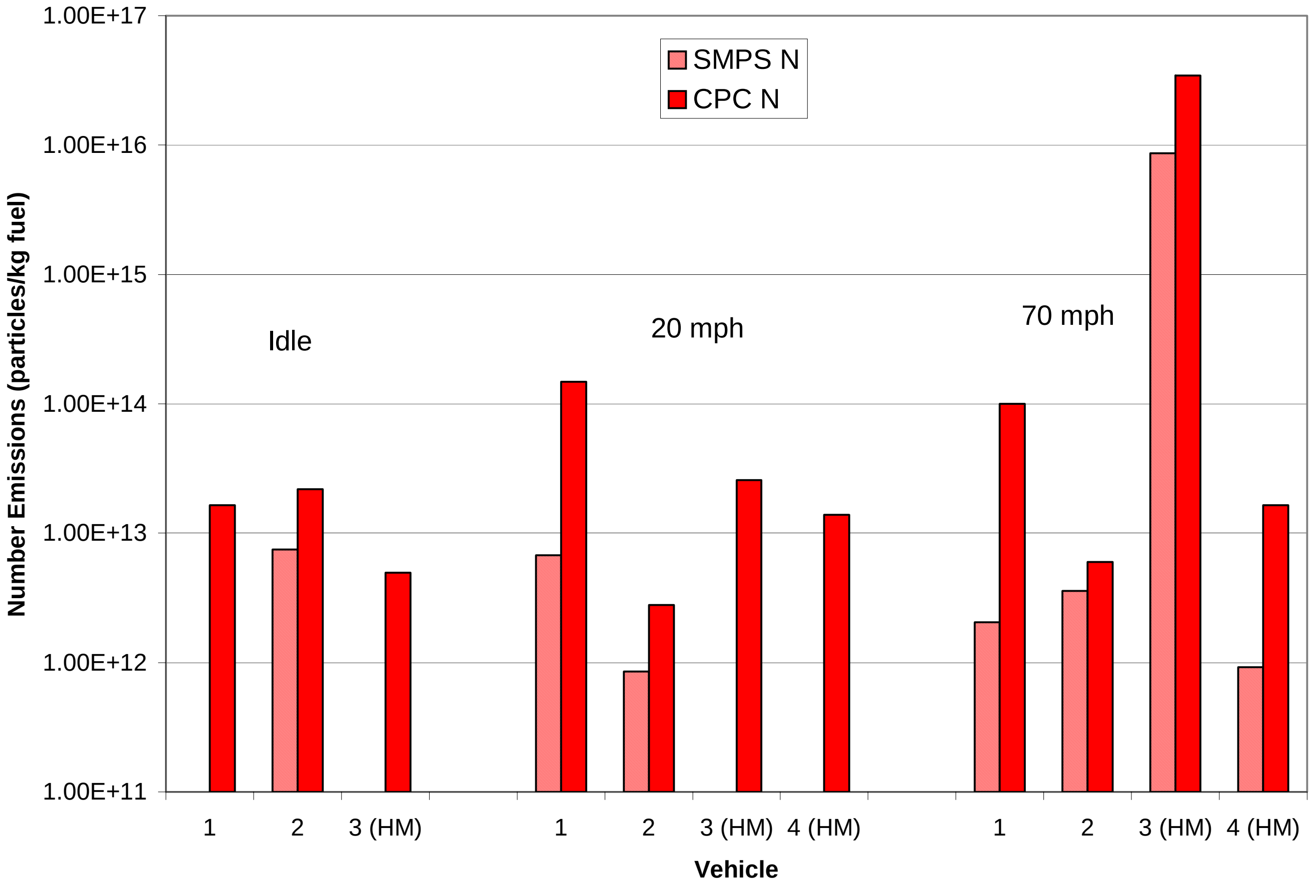




- Number emissions above 10 nm are very low at low speed cruise
- High speed cruise leads to much higher emissions in this size range
  - Most of these emissions occur in the first few minutes after accelerating to high speed for 3 of the 4 vehicles tested. This is apparently due to storage and release effects
  - One unusual emitter showed the opposite trend with emissions growing with time
- Simultaneous CPC measurements show that for most of these vehicles there are many particles below 10 nm

Chassis Dynamometer Tests - State Number Emissions

CPC number (D > 3nm), SMPS number (D > 10nm)

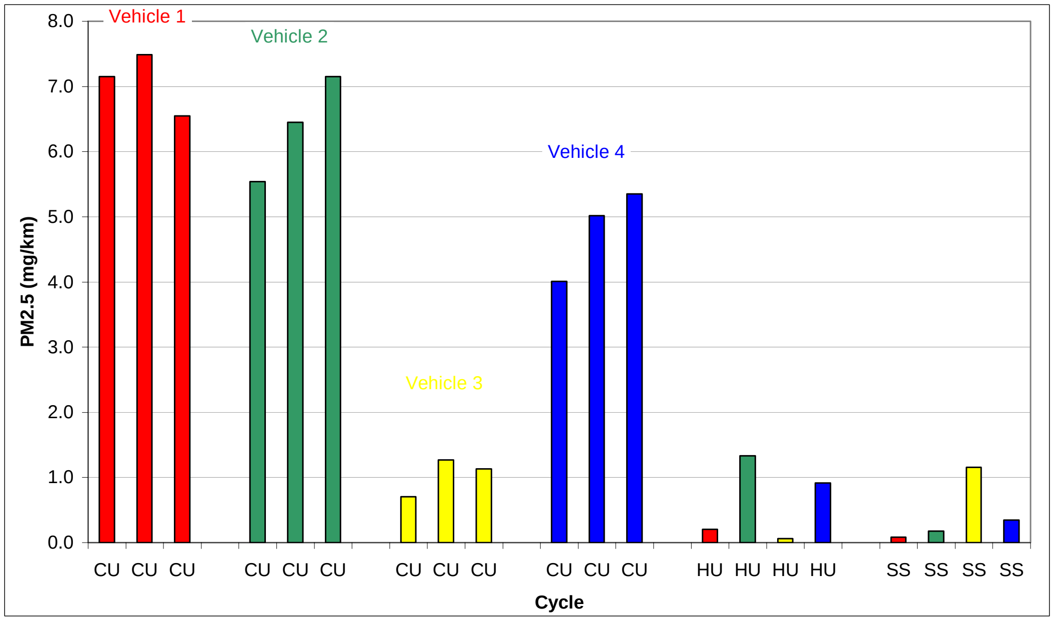


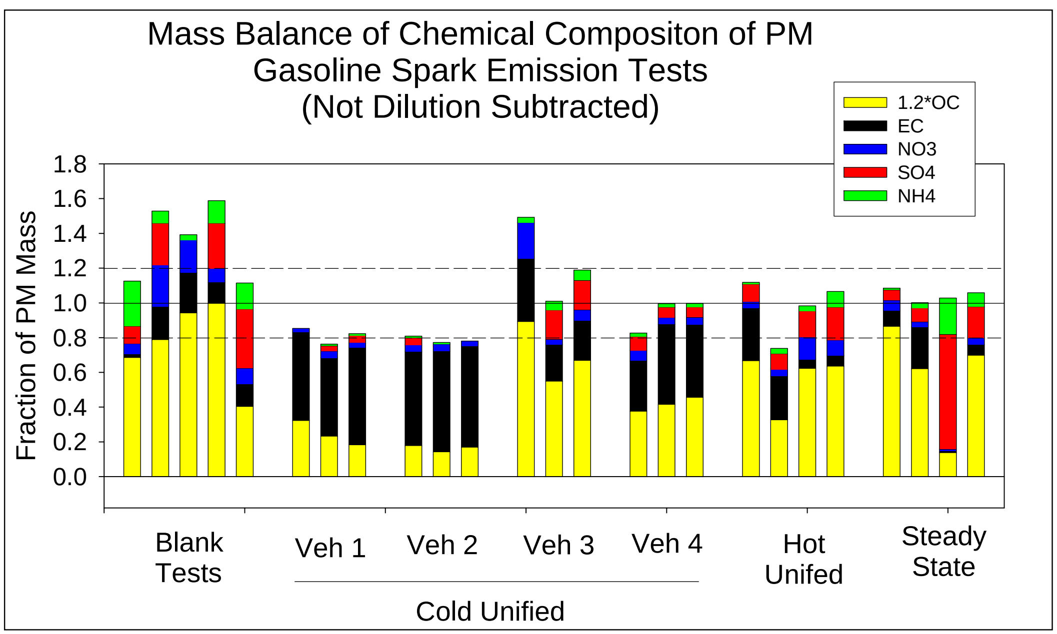
- Number emissions are much higher at high speed, mainly in transient storage and release mode
- Fuel specific number emissions range from 10^{12} to 3×10^{16} particles/kg fuel
- Many particles below sizing range of conventional SMPS
- Emissions of extremely small particles, D > 3 < 10 nm, are often more than an order of magnitude higher than emissions of particles for D > 10 nm
- There does not seem to be a simple relationship between number and mass emissions

Sample Collection and Chemical Analysis

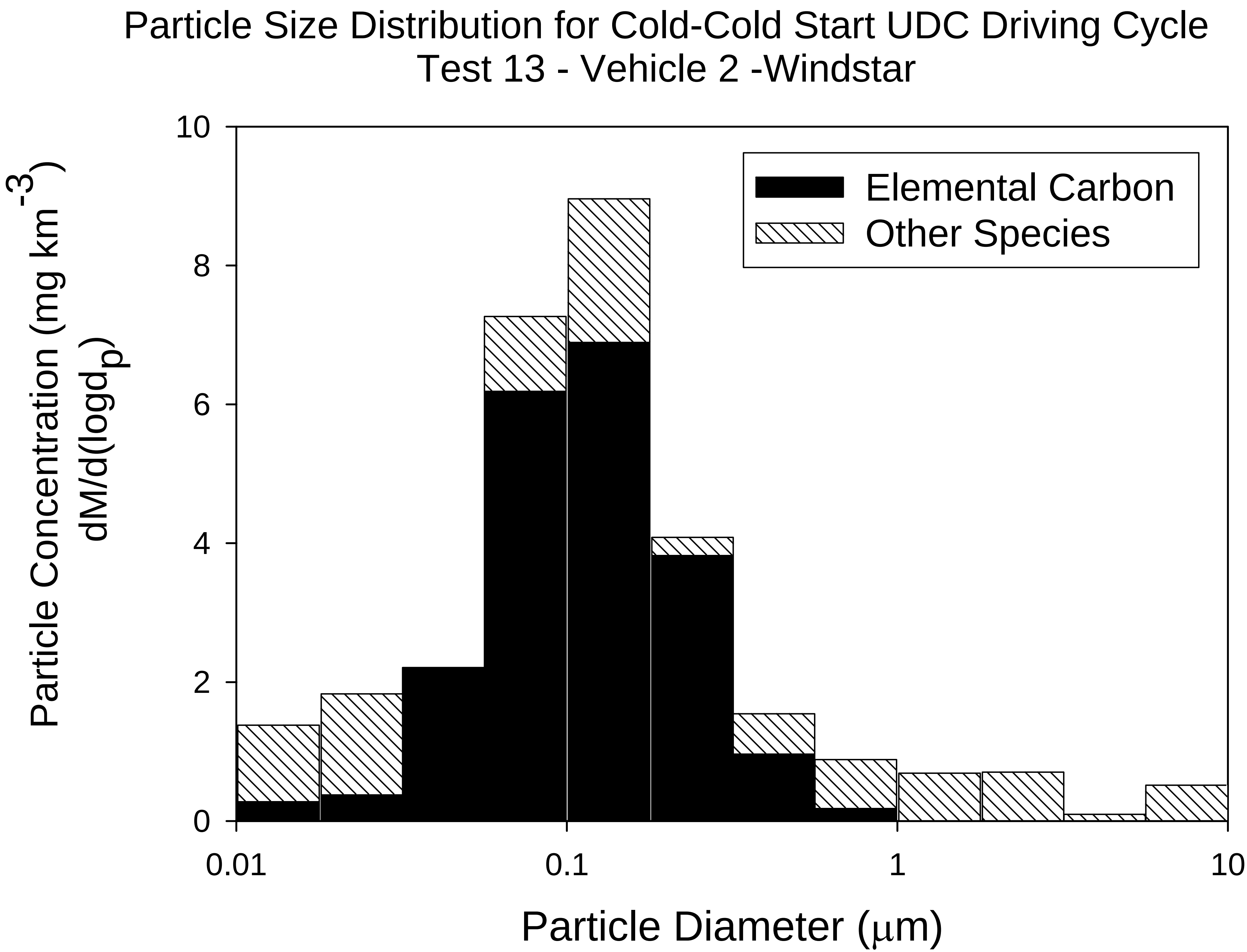
- Filter and Chemistry by Jamie Schauer, U of Wisconsin
- Characterize bulk and size segregated chemical composition of the particulate matter (PM) emitted in the exhaust from the gasoline vehicles.

Chemistry and mass emissions

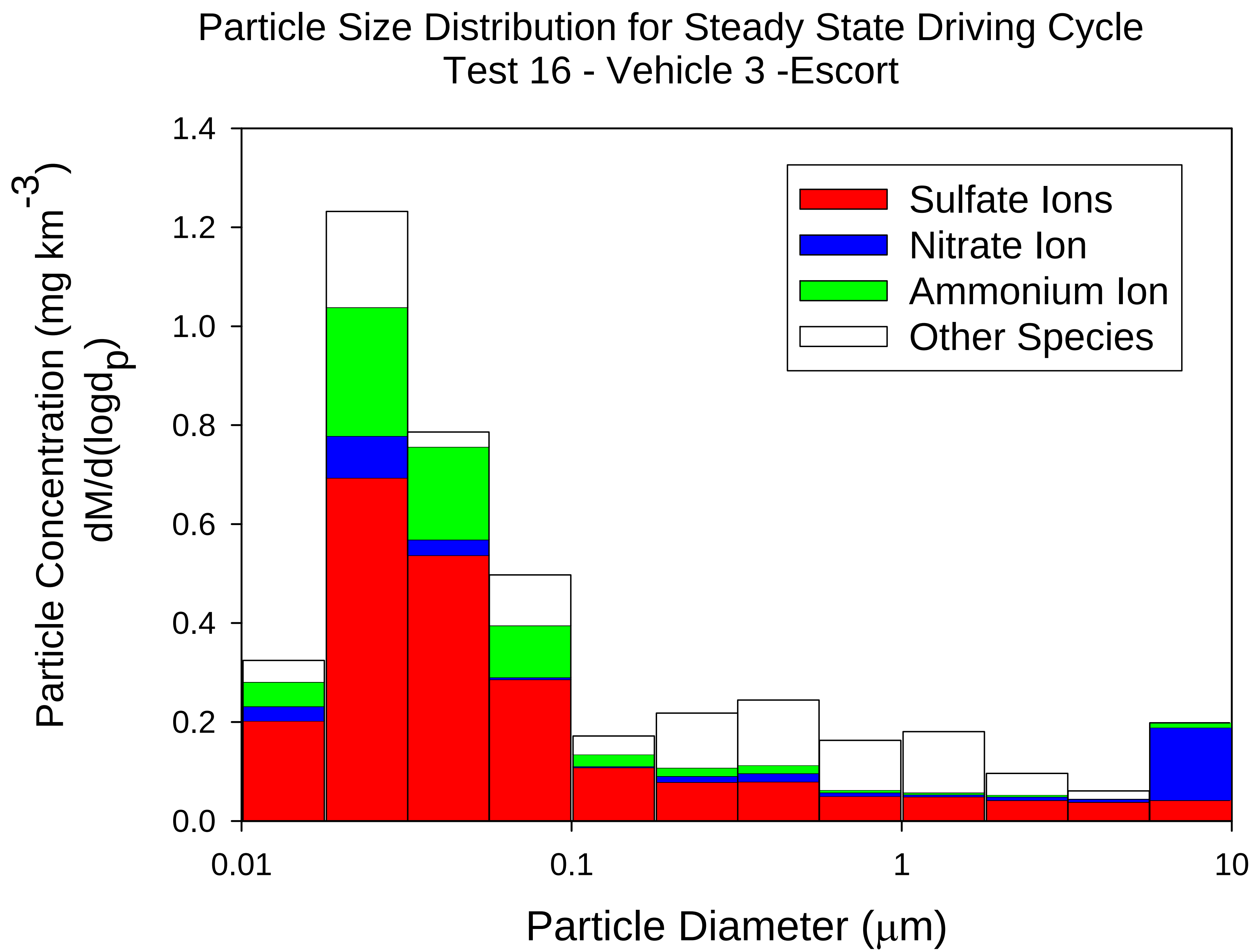




- DOE Chassis dynamometer tests - PM2.5 filter measurements
  - Optimized sampling and dilution system
  - CU – Cold Unified Cycle (0°C start)
  - HU – Hot Unified Cycle
  - SS – Steady State
- Mass emissions from modern gasoline vehicles on cold unified cycles are relatively high, 1 – 7 mg/km
- EC fraction in cold unified cycles 30 to 60%
- Vehicle 3 was an unusual emitter, low mass emissions on cycles, higher mass and number emissions on SS, sulfates
- There does not seem to be a simple relationship between number and mass emissions



Particle Size Distribution for Cold-Cold Start UDC Driving Cycle
Test 13 - Vehicle 2 -Windstar
Particle Concentration (mg km-3)
dM/d(logdp)
Particle Diameter (μm)
Elemental Carbon
Other Species
0
2
4
6
8
10
0.01
0.1
1
10


Particle Size Distribution for Steady State Driving Cycle
Test 16 - Vehicle 3 -Escort
Particle Concentration (mg km-3)
dM/d(logdp)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.01
0.1
1
10
Particle Diameter (μm)
Sulfate Ions
Nitrate Ion
Ammonium Ion
Other Species

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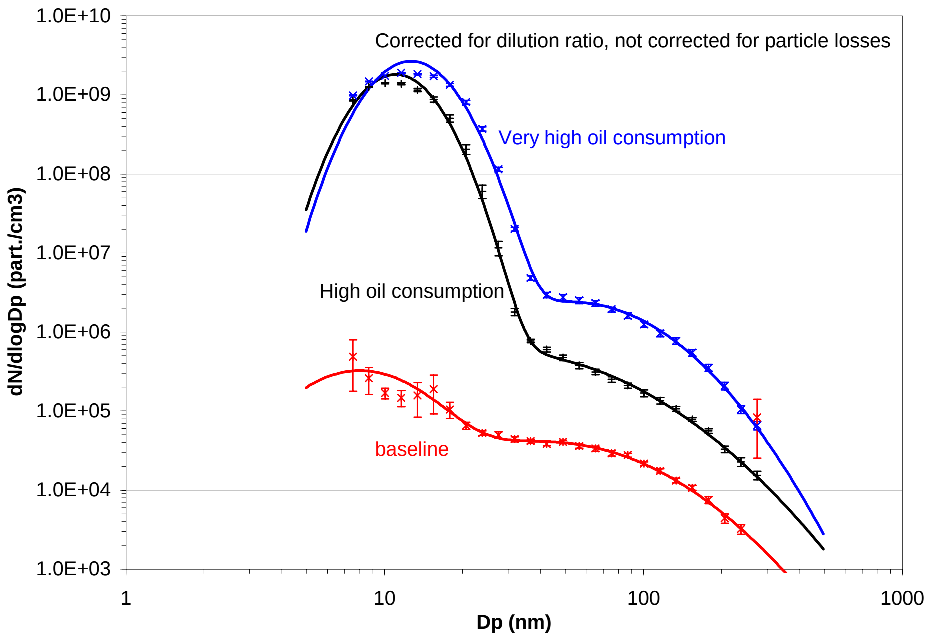
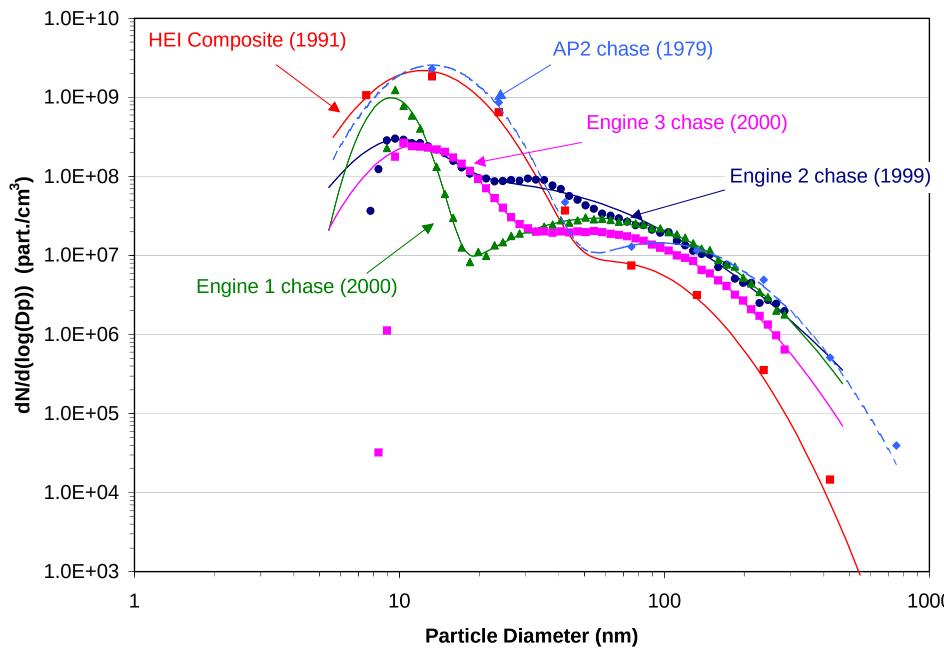
Simulation of a High Emitter – "Smoker"

- The objective of this experiment was to simulate the behavior of a worn SI engine with high oil consumption under controlled conditions and measure its emissions
- A worn engine was simulated by the introduction of used lube oil onto the intake valve stems under controlled laboratory conditions. Leaky valve seals are a common cause for high oil consumption
- Properties and characteristics of the exhaust aerosol that were characterized included particle number and length concentrations, and the aerosol number and mass size distributions.

Simulation of a gasoline high emitter by increasing oil flow on intake valve stems





- Figure on upper left shows results of tests of contemporary gasoline engine, baseline and high oil consumption due to leaky valve seals
- Oil and fuel were not premixed, oil added at valve stem
  - Baseline
  - Oil/Fuel 2%
  - Oil/Fuel 4%
- Figure on upper right is comparison Diesel figure from the CRC E-43 program on same scale – the nuclei mode of the high emitter approaches levels of older Diesels

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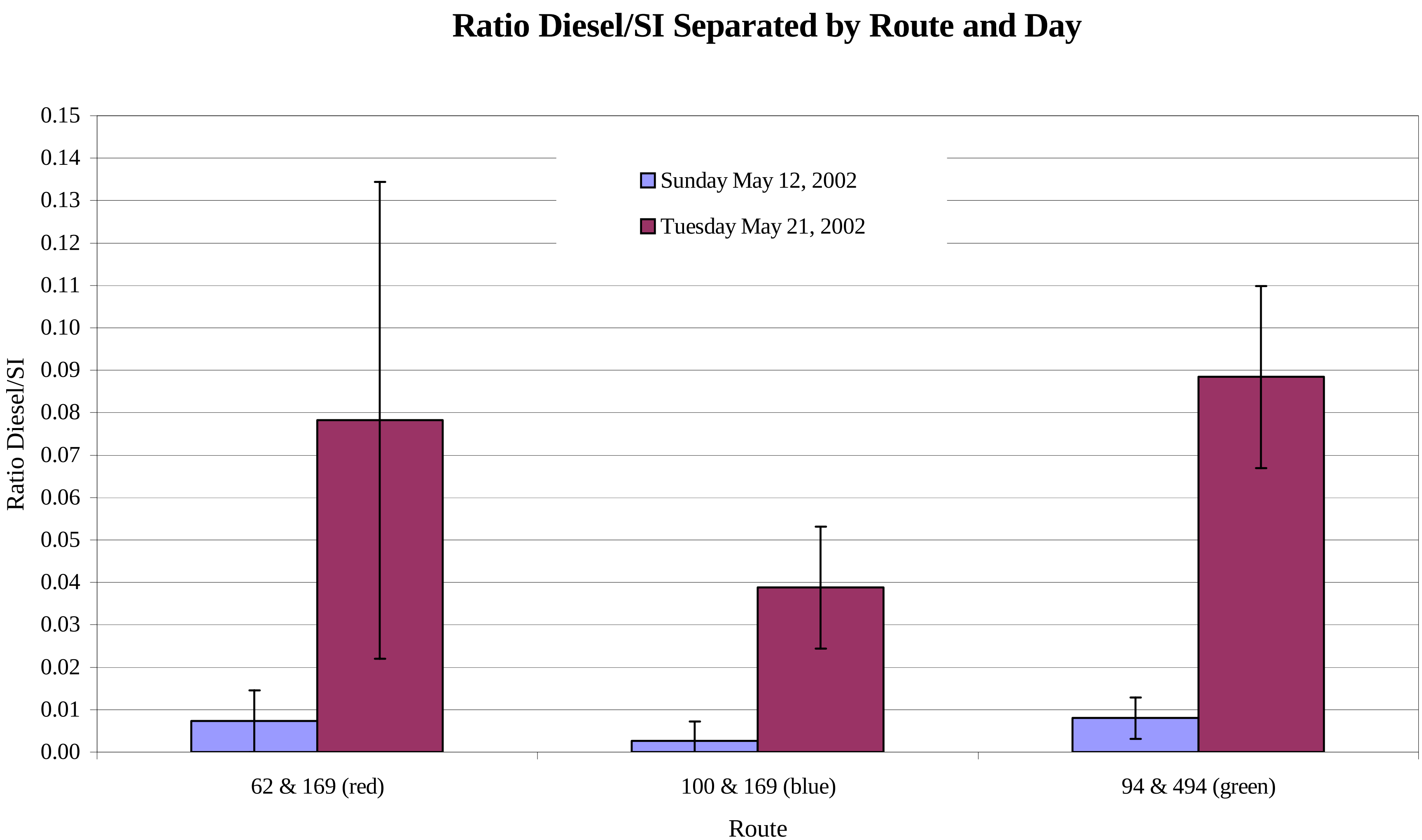
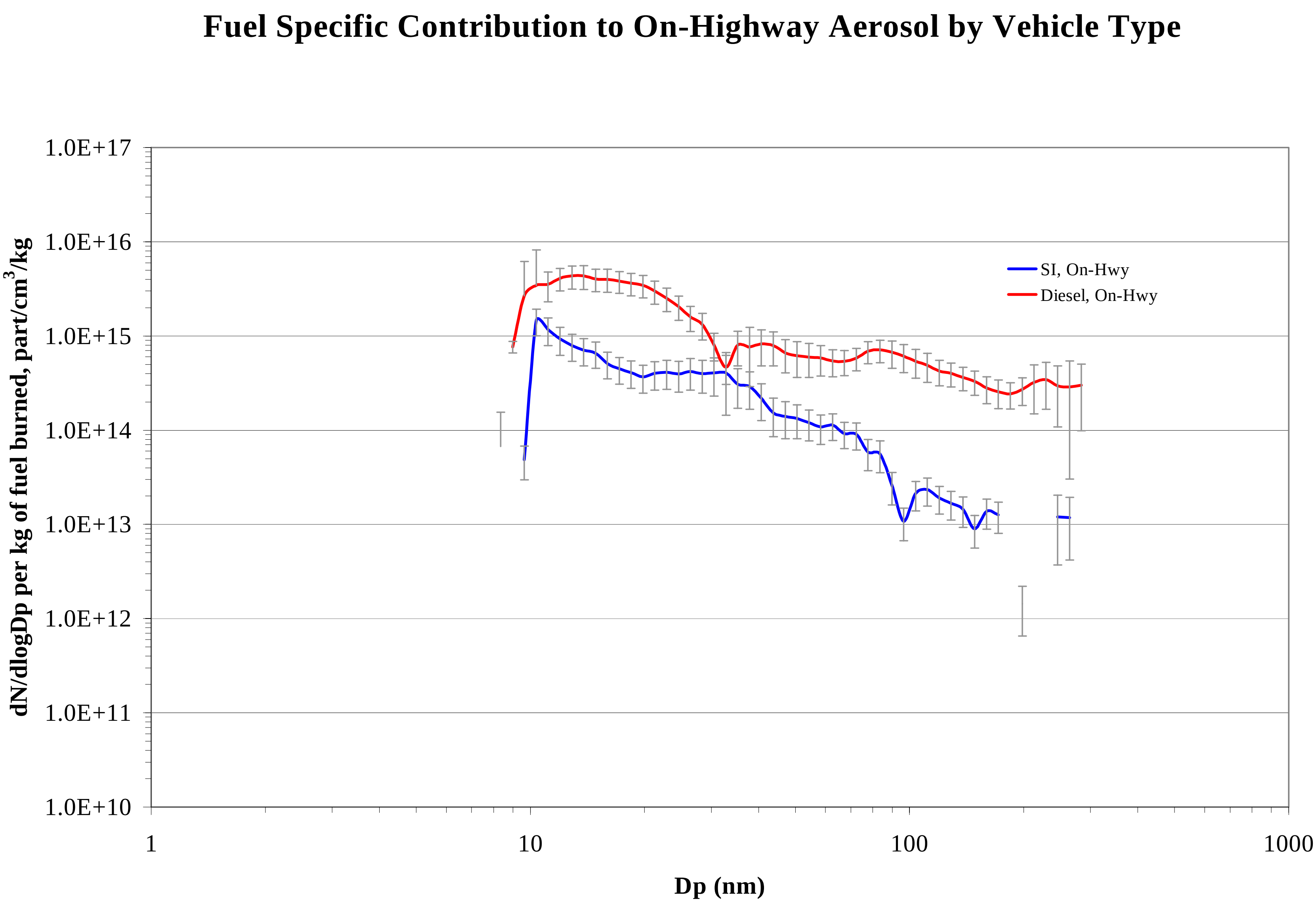
On-Road Characterization of Real World Fleets: Weekday / Weekend On-Highway Apportionment Experiments

- Summertime urban freeway measurements
- Over-the-road aerosol, corrected for the background is contributed by vehicles in proportion to their traffic volume.
- Measuring traffic volumes and aerosol concentrations on days with differing SI to Diesel ratios gives a system of equations that can be solved for average Diesel and SI contribution on a per unit traffic volume basis
- Presented on a fuel specific (per kg of fuel) basis
- Principal uncertainties are in traffic counts and background corrections

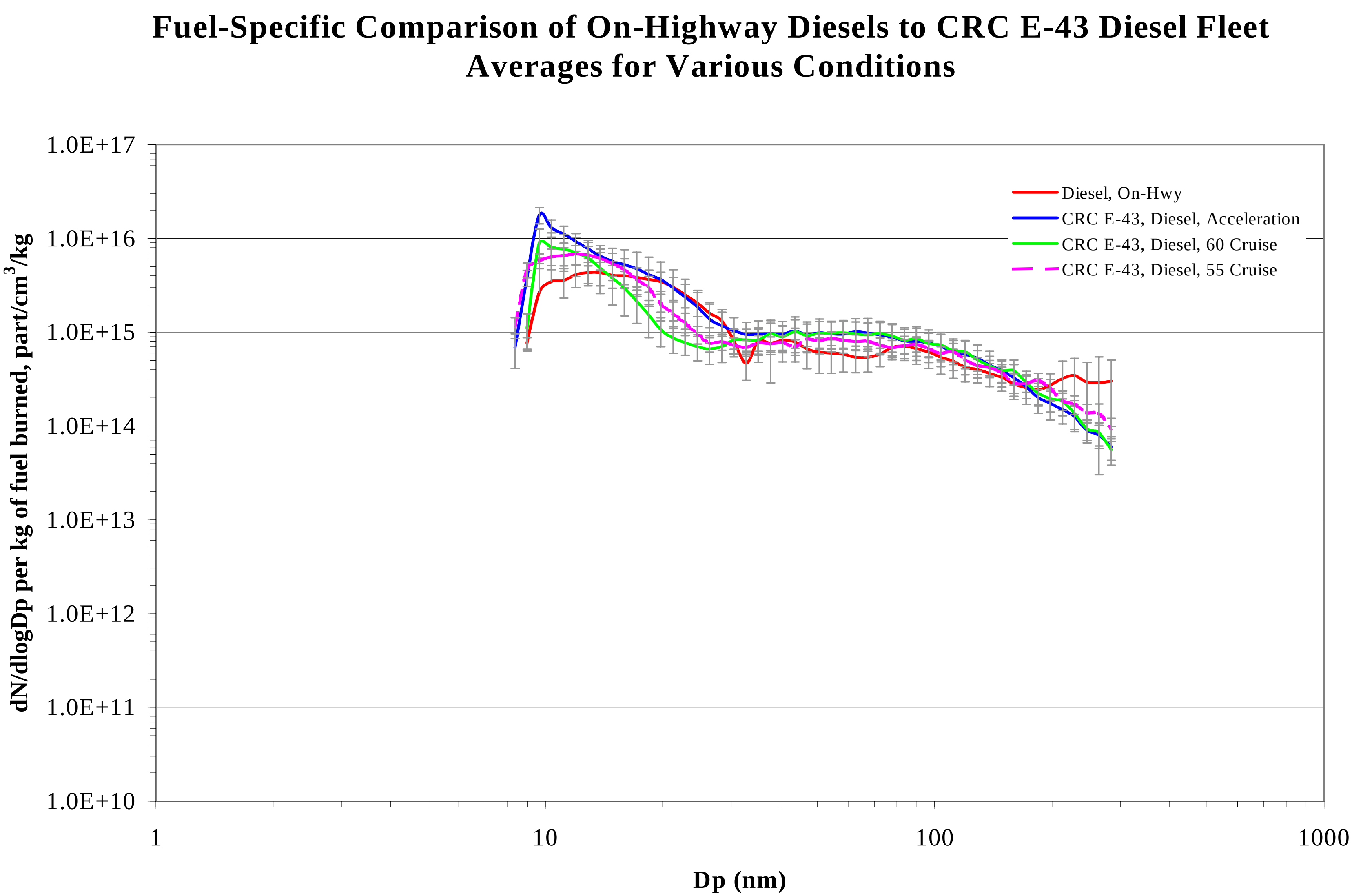
Diesel/SI Ratio By Route And Day



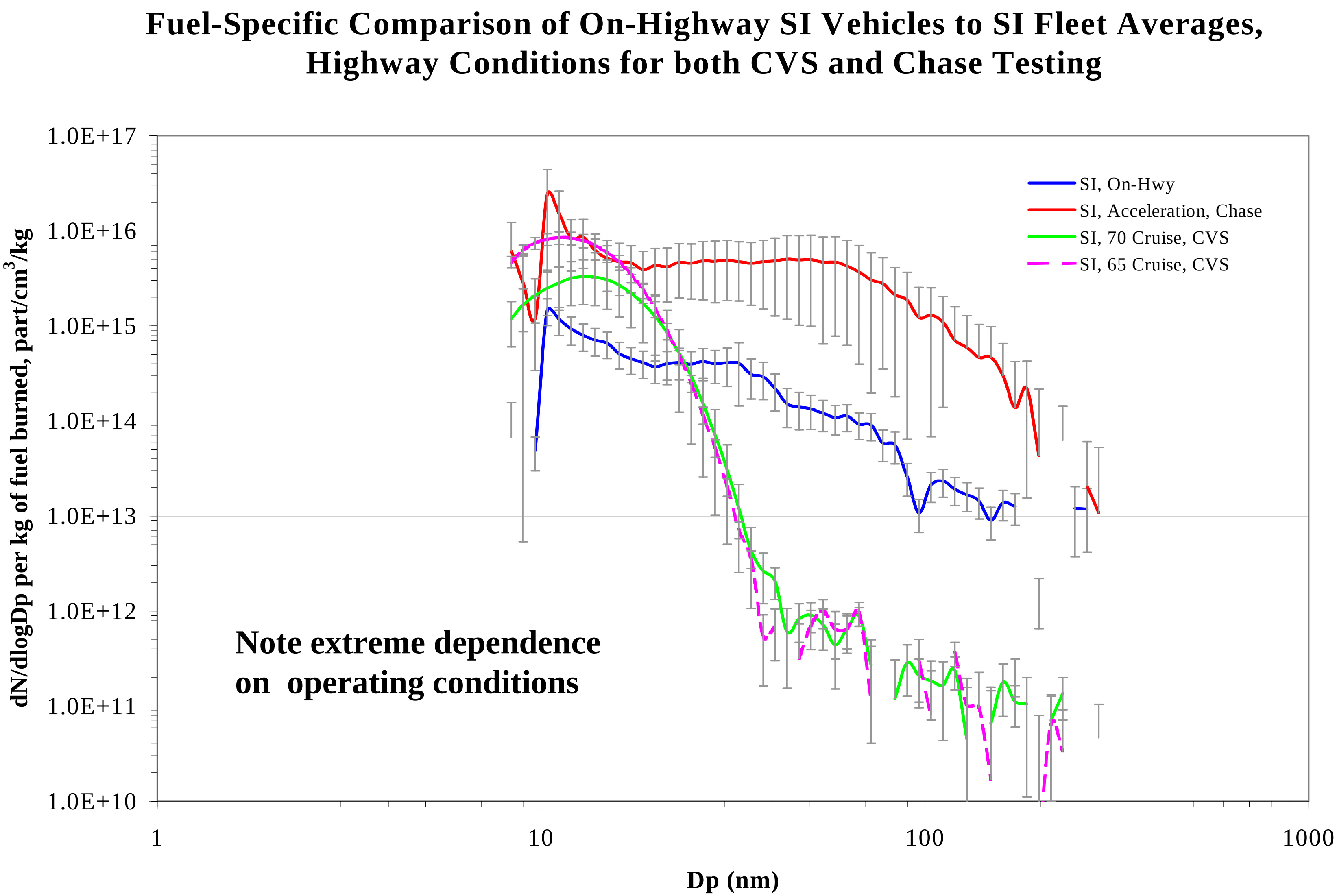
Diesel and SI Apportioned Size Distributions on a Fuel Specific Basis



Diesel On-Highway Compared to CRC E-43 Fleet Average On a Fuel Specific Basis



SI On-Highway Compared to Fleet Average On a Fuel Specific Basis



Fuel Specific Emissions – Diesel and SI Summertime Highway Cruise

Dp > 3 nm　　Dp > 10 nm

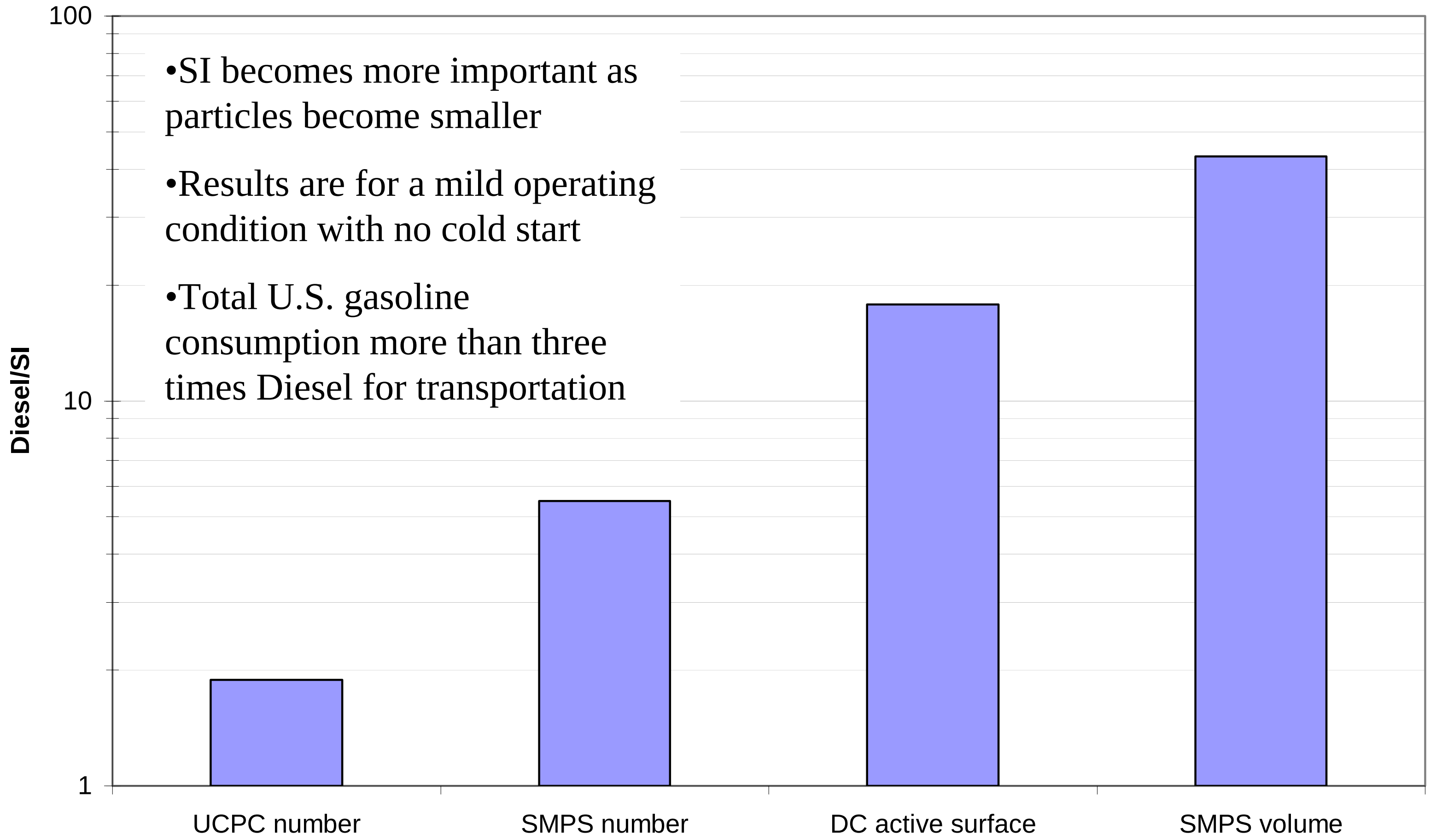
Apportioned Source	CPC (part/kg)		SMPS Number (part/kg)		DC (μm^2/kg)		SMPS Active Surface (μm^2/kg)	
	Mean	SDOM	Mean	SDOM	Mean	SDOM	Mean	SDOM
Diesel	1.34E+16	1.86E+15	2.13E+15	3.04E+14	3.15E+12	6.15E+11	1.45E+13	2.15E+12
SI	7.10E+15	1.55E+15	3.88E+14	6.11E+13	1.77E+11	3.91E+10	9.41E+11	1.52E+11

Apportioned Source	PAS (fA/kg)		SMPS Volume (μm^3/kg)		DGN (nm)		DGV (nm)	
	Mean	SDOM	Mean	SDOM	Mean	SDOM	Mean	SDOM
Diesel	2.91E+12	4.04E+11	6.21E+11	1.40E+11	22.7	1.7	195.7	12.1
SI	5.69E+11	1.26E+11	1.44E+10	4.44E+09	19.3	0.7	104.0	24.3

Apportioned Source	N/V Ratio		N_{30}/N Ratio		V_{30}/V Ratio	
	Mean	SDOM	Mean	SDOM	Mean	SDOM
Diesel	3.44E+03	7.76E+02	0.76	0.13	0.008	0.002
SI	2.70E+04	7.69E+03	0.77	0.09	0.059	0.017

Fuel Specific Emissions – Diesel and SI Summertime Highway Cruise

Ratio of fuel specific emissions



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Conclusions - Number Emissions from Gasoline Engines

- Modern in-use SI vehicles have significant mass emissions (1-7 mg/km) in Cold (0 C) Unified cycles.
- EC emissions in these test cycles were surprisingly high, typically 30-60% of PM2.5 mass
- Emissions of extremely small particles (Dp < 10 nm) at high road speed may be very high (10^{14} - 10^{16} part./kg fuel) even for nominal low emitters. Storage and release play an important role in the formation of these particles.
- Number emissions from two classes of SI engines may equal or exceed Diesel levels
  - Normal emitters at high speed and load
  - Worn engines with high oil consumption
- The Swiss EPA has proposed that Europe adopt a **solid** particle emission standard of 10^{11} part./km
  - This corresponds to roughly 10^{12} part./kg fuel
  - It is unlikely that our current on-road gasoline fleet meets this standard
  - Will gasoline engines need exhaust filters?