TG-1: Portable Instrument for Transient Particulate Matter Measurements

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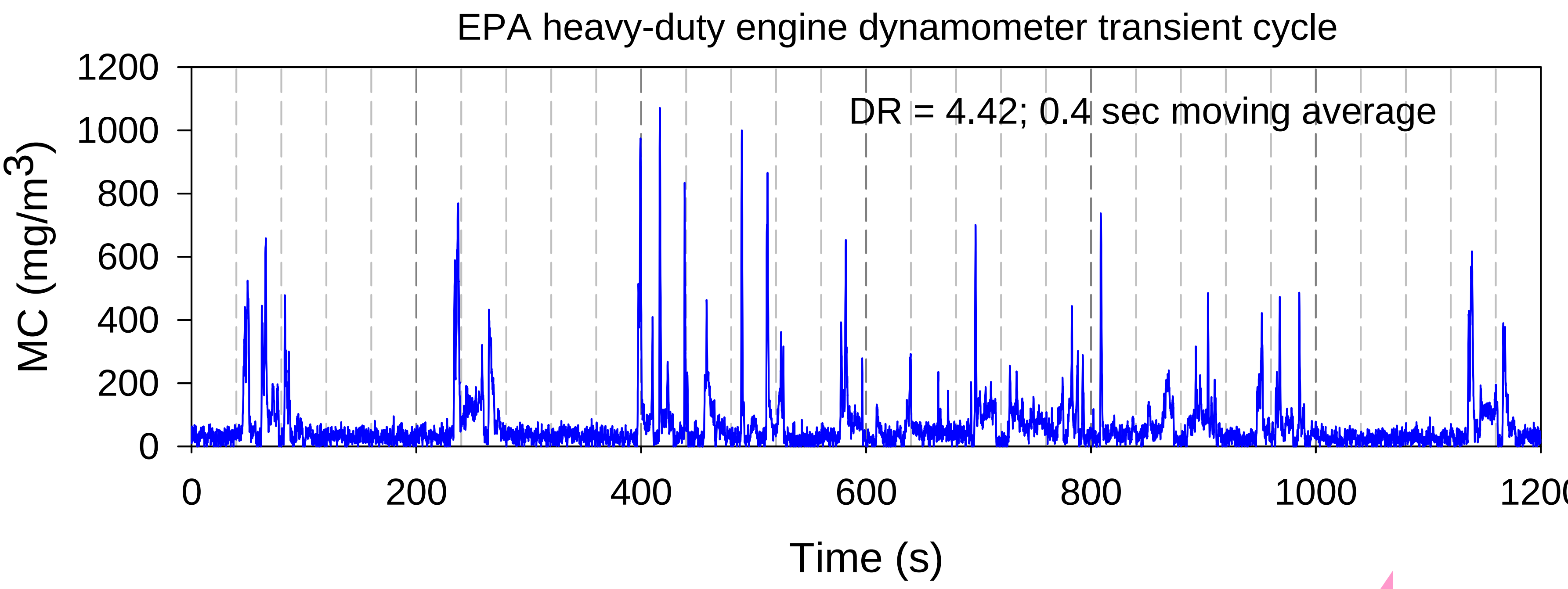
Overview

- Current particulate matter measurement issues
- Survey of commercially available instrumentation
- Laser-induced Incandescence
- Instrument development
- Future efforts

Emission Regulations Have Rendered PM Emissions So Low as to Be Comparable to Minimum Instrument Detectivity

Description	System Details	MC (mg/m^3)
N. J. Khatri, John Johnson (1978)	1973 Caterpillar 3150, V-8	27-84
Dave Hoefeldt (1993)	2 cyl Kubota generator set	2-25
Abdul Khalek (1998)	Perkins 4-cylinder	0.4-14
(2003)	Caterpillar's recommendation	0.1 ← target

Heavy-duty Truck Emissions Regulated Based on a Transient Cycle as Well as Steady-state Modes



Time response ≤ 0.5 sec

Dynamic range ~ 3-4 orders of magnitude

target

Health Effects Render Particle Size and Number Emissions Important

- Future (EU) regulations are likely to be based on particle number and size.
  - Aggregate particle size (D) and number density (N) measurement capability desirable

A Survey of Available Transient PM Measurement Instrumentation

Instrument	Issues	Cost (Thousands)
Smoke meters	Quantitative measurements not possible	~$100
TEOM 1105	Yields -ve measurements, vibration sensitive, and coarse resolution	$24
ELPI	Very coarse resolution	$70
DMS 500 (Cambustion)	Very expensive	$190
TG-1 (Argonne)	portable, cross-platform, real-time and modular	$30

target

Tapered Element Oscillating Microbalance (TEOM)

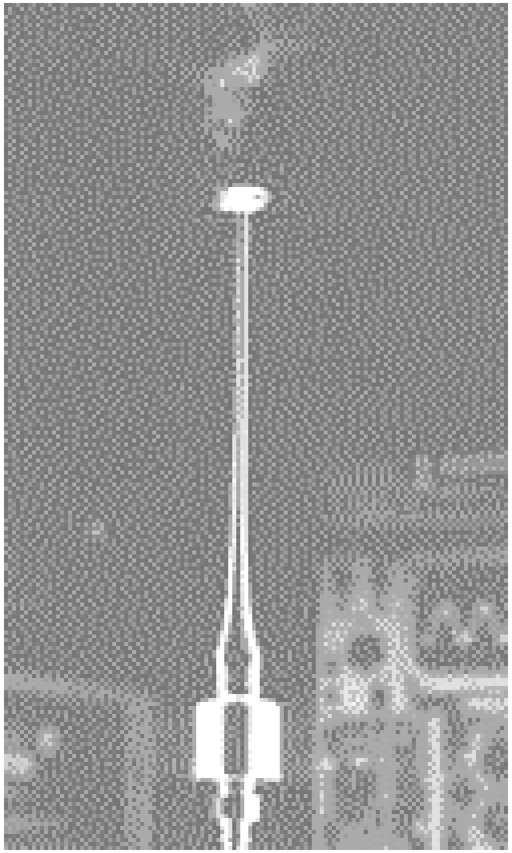
<u>Tapered Element Oscillating Microbalance</u>

Measures Mass Concentration, M (g/cc) in Diesel Exhausts

$$M = \frac{k_o}{f^2}$$

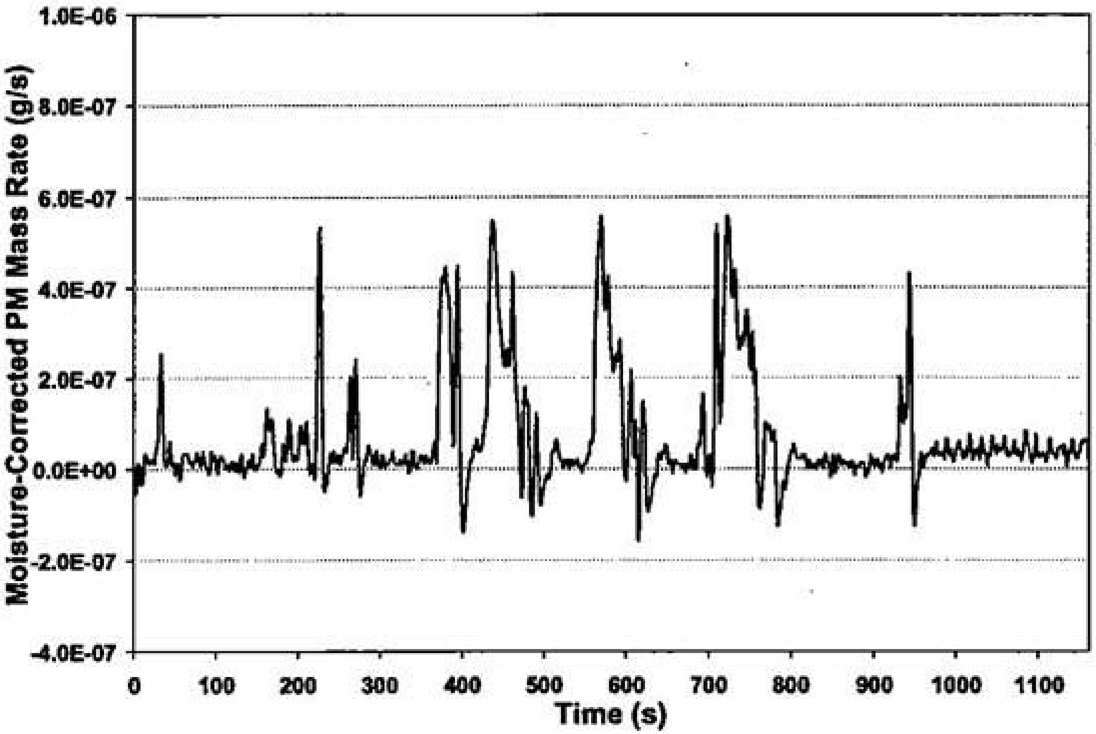
$$MC = \frac{1}{V}\frac{dM}{dt} = \frac{1}{V}\frac{-2k_o}{f^3}\left(\frac{df}{dt}\right)$$

$\therefore$ *f* as well as $\frac{df}{dt}$ need to be measured accurately.



Measurement Issues with TEOM

- Sensitive to typical test-cell vibration levels
- Can yield negative measurements due to water vapor desorption



SAE

2001-01-3575

Laser-Induced Incandescence (LII)

LII Has Many Desirable Characteristics

- Primarily measures volume fraction

  $f_v \times \rho$ = MC (grams/cc)

  Minimum detectivity = 0.001 (mg/m^3)

- Can measure in real-time

  Time response/ resolution = 1e-9 sec/ 0.1 sec

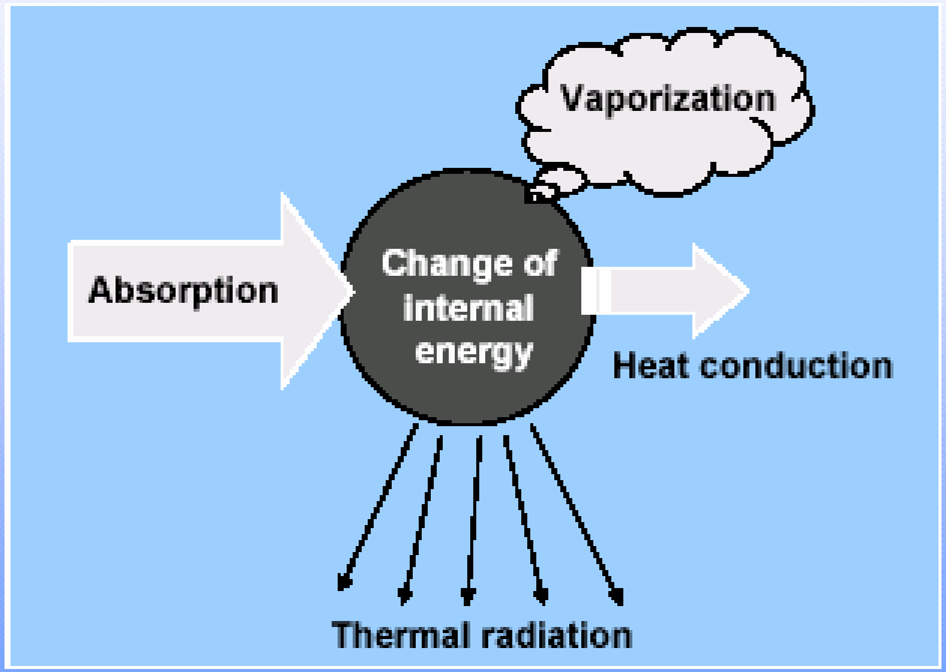
- In combination with Rayleigh scattering yields

  Mean particle size (nm) $$D = K_1 \cdot \left(\frac{Q_{vv}}{MC} \right)^{1/3}$$

  Number density (#/cc) $$N = K_2 \cdot \frac{MC}{D}$$

LII Phenomenon

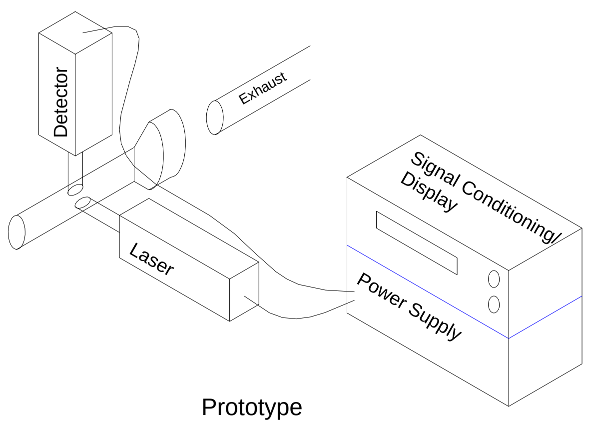
Particle heating by means of a highly energetic laser pulse → Detection of the enhanced thermal radiation



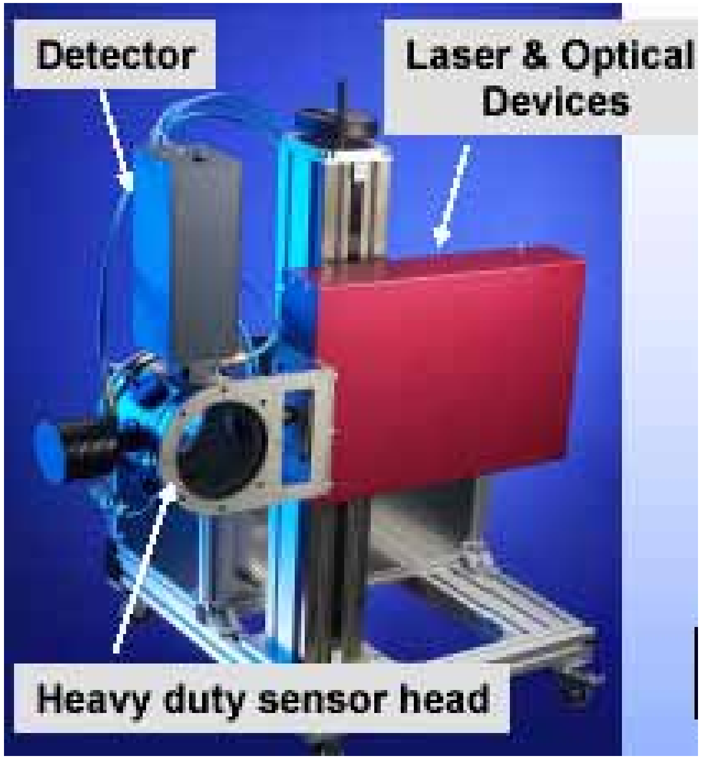
$$\underbrace{Q_{abs}\cdot\frac{\pi d_p^2}{4}\cdot E_i}_{\text{Absorption}} - \underbrace{\Lambda\cdot(T-T_0)\cdot\pi d_p^2}_{\text{Heat conduction}} + \underbrace{\frac{\Delta H_v}{M}\cdot\frac{dm}{dt}}_{\text{Vaporization}} - \underbrace{\pi d_p^2\int\varepsilon(d_p,\lambda)M_\lambda^b(T,\lambda)\cdot d\lambda}_{\text{Thermal radiation}} - \underbrace{\frac{\pi d_p^3}{6}\rho_s\cdot C_s\cdot\frac{dT}{dt}}_{\text{Change of internal energy}} = 0$$

Development of an LII-Based Instrument

Many Possible Arrangements Were Evaluated…



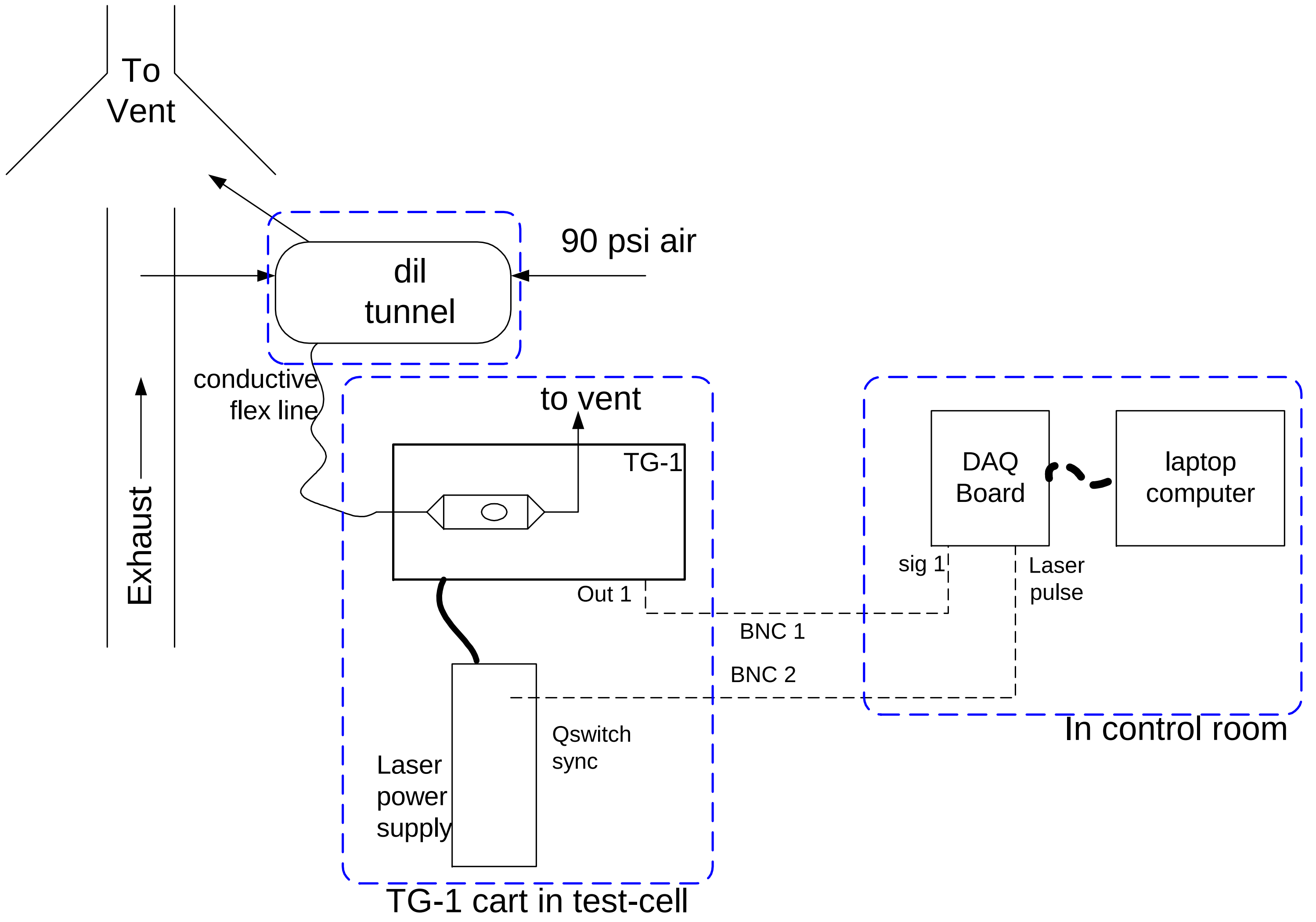
Argonne's Schematic 1997



www.esytec.de 2001

- Sensor head design dependent on engine size
- Potential operator (laser) safety hazard

...to Reach an Optimal Design



A Portable Instrument Was Integrated

Component cost: $40 K

Size: 24” x 15” x 8.5”

Weight: Approx 40 lbs

Specifications

10 Hz sampling

Utility requirements

110 VAC, 13 Amps

Patent pending

Performance Tests on a Light-Duty Diesel Engine

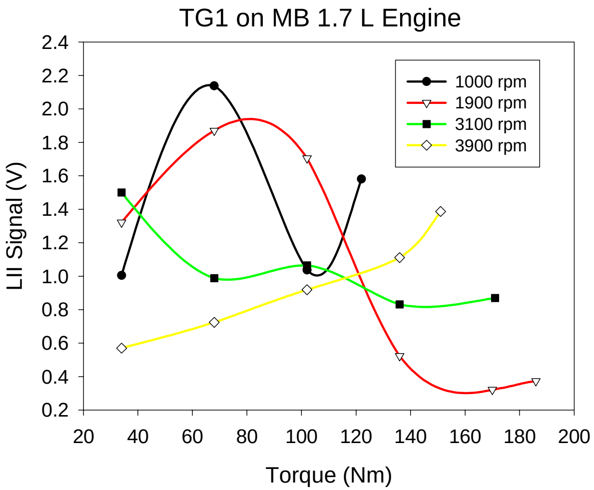
Mercedes Benz

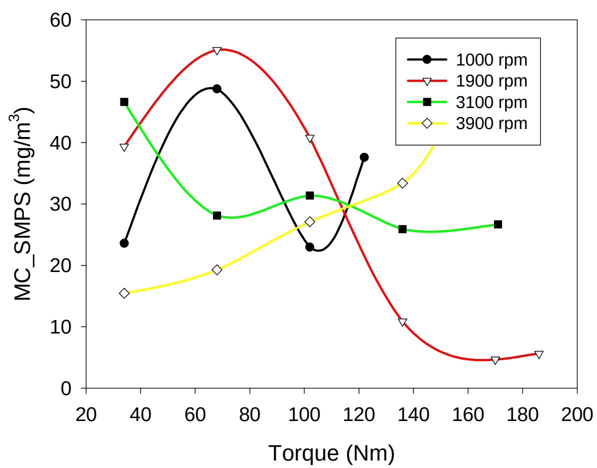
1.7 L

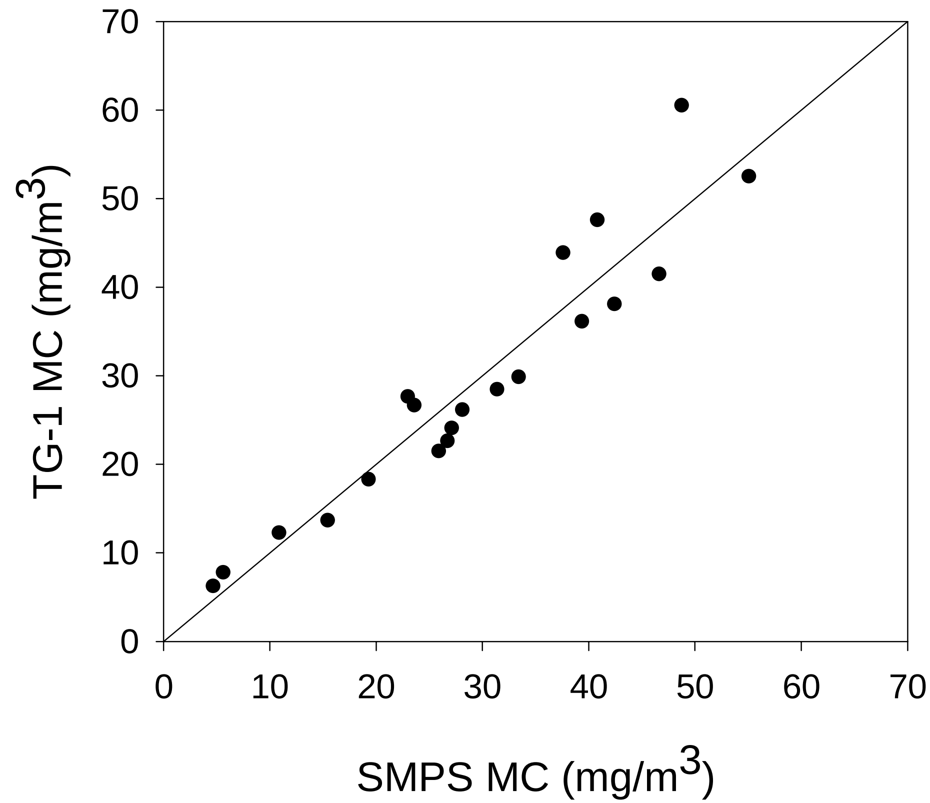
4 cyl

Low-inertia Dynamometer

Excellent Performance over Typical Diesel Engine Steady-State Operation



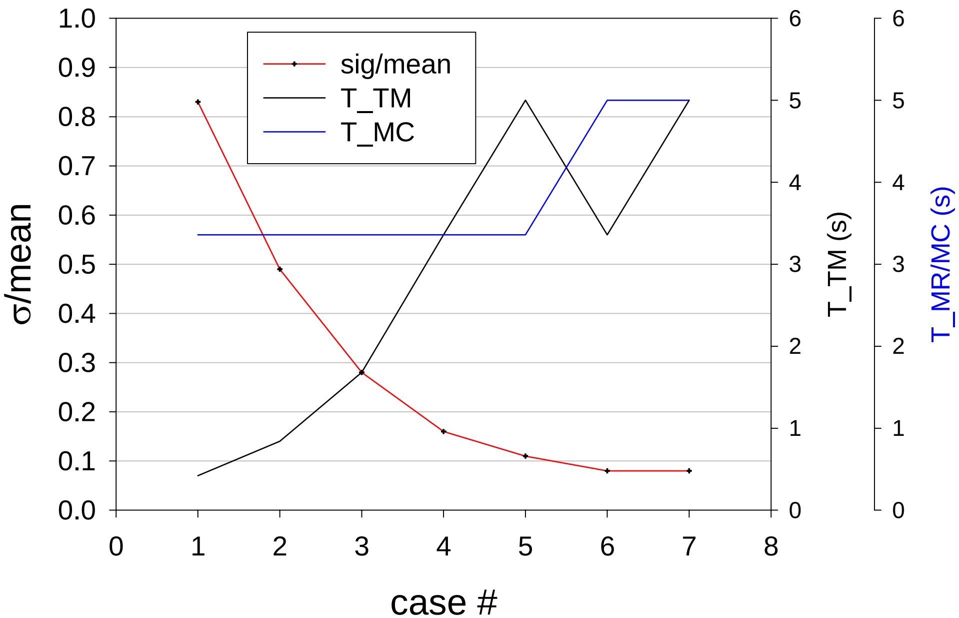




S. Gupta et al.; 6th ETH Conference on Nanoparticle Measurement

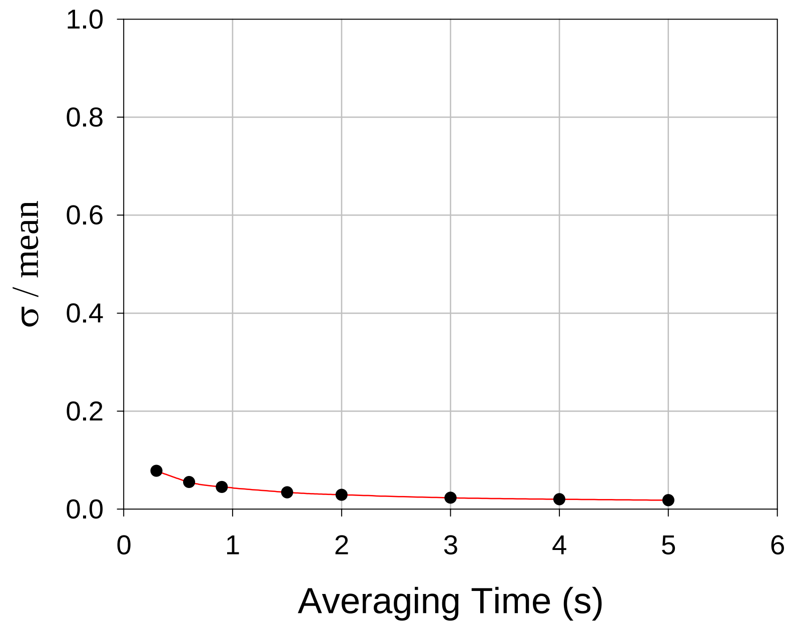
TG-1 Has Better Time Resolution than a TEOM 1105

TEOM 1105



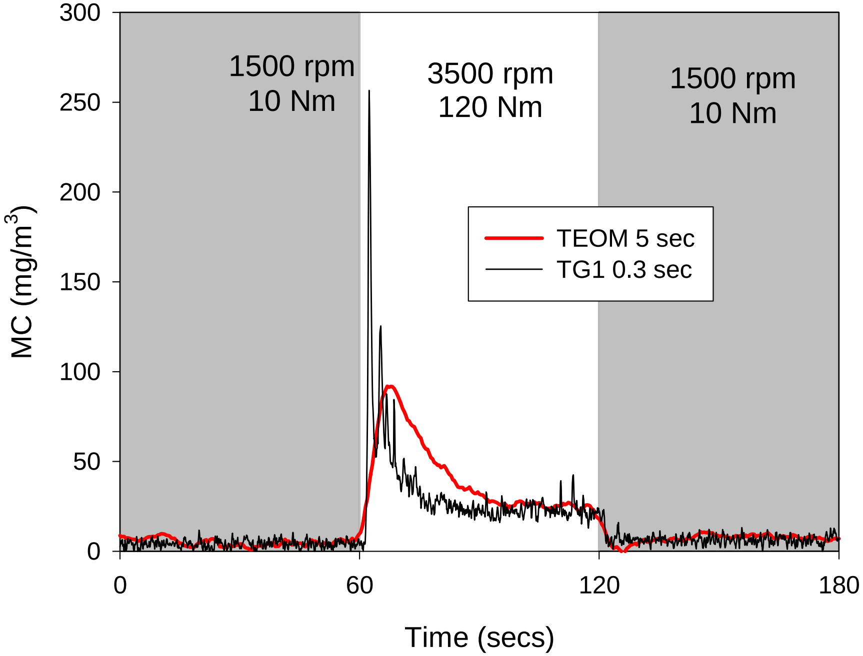
5 sec mvg. average

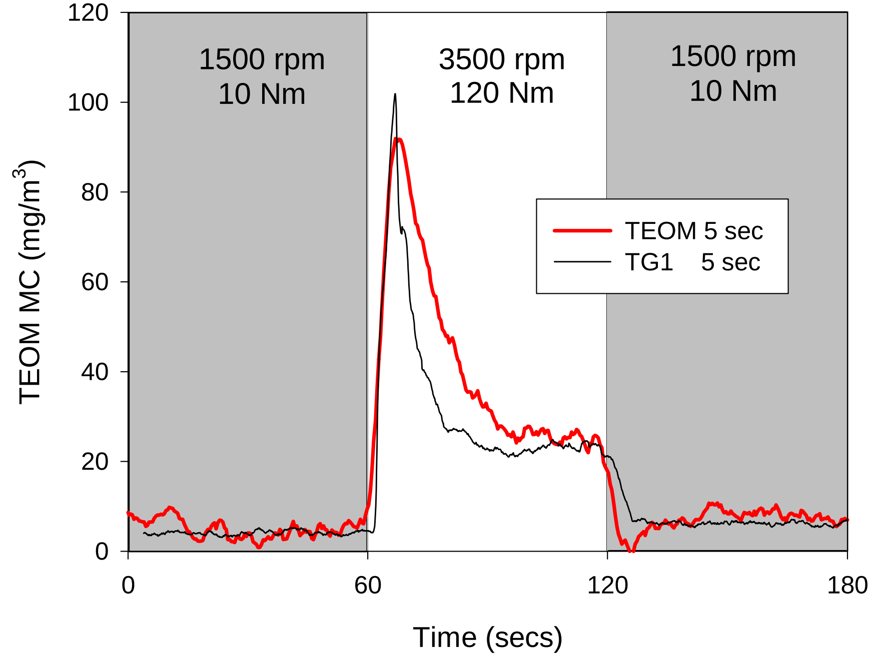
TG-1



0.3 sec mvg. average

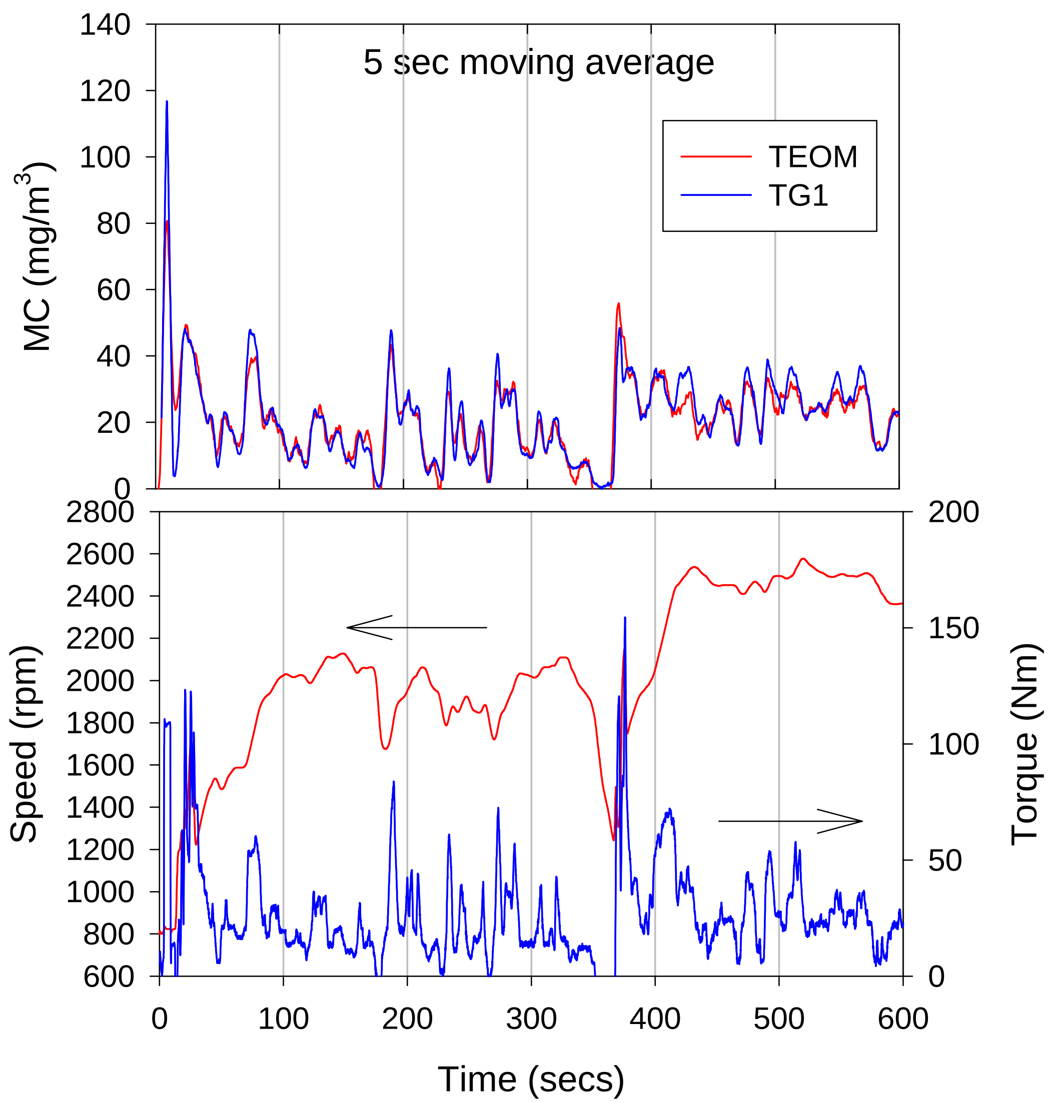
TG-1 Performs Better than a TEOM 1105 for Step Changes in Engine Modes





Transient measurements performed on a Mercedes Benz 1.7 L engine coupled to a low-inertia dynamometer

TG-1 Performance over the Urban Driving Cycle



Performance Tests on a Heavy-Duty Diesel Engine

CAT C-10

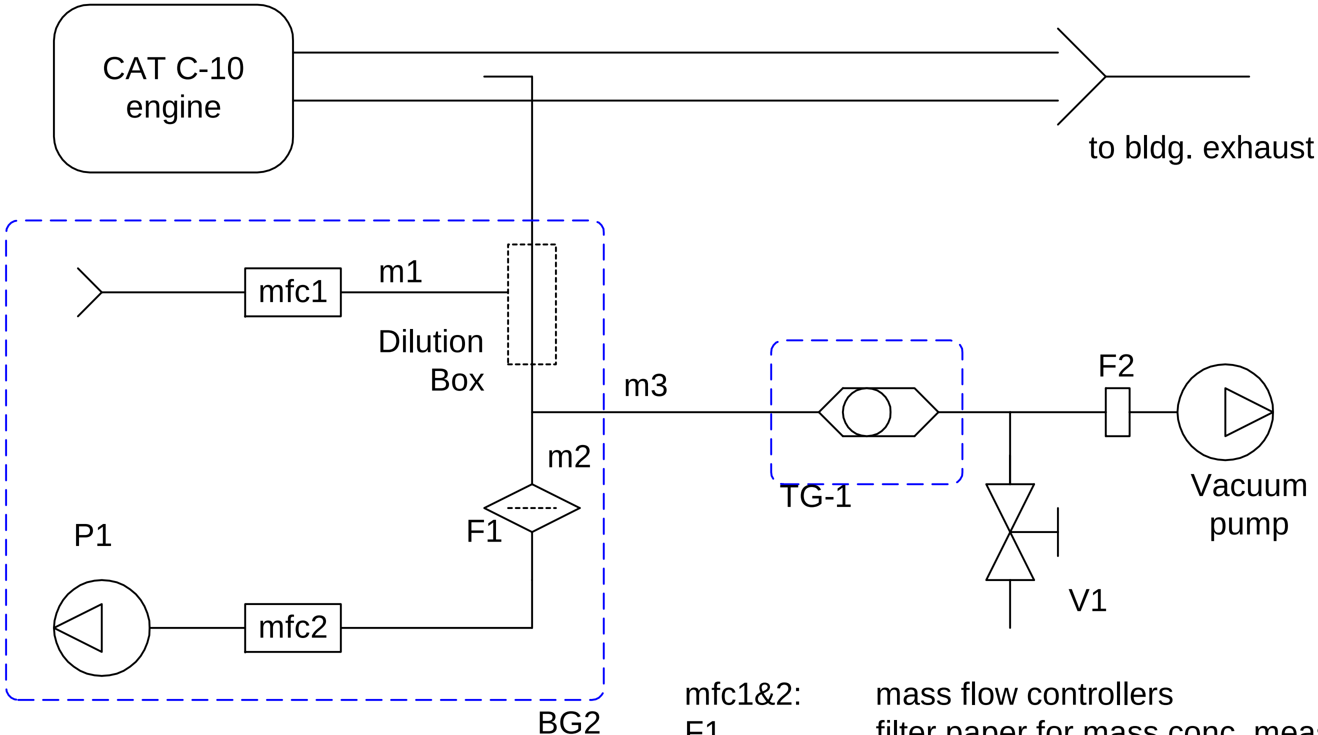
6 cyl

10 L

1800 rpm

1460 Nm@
1200 rpm

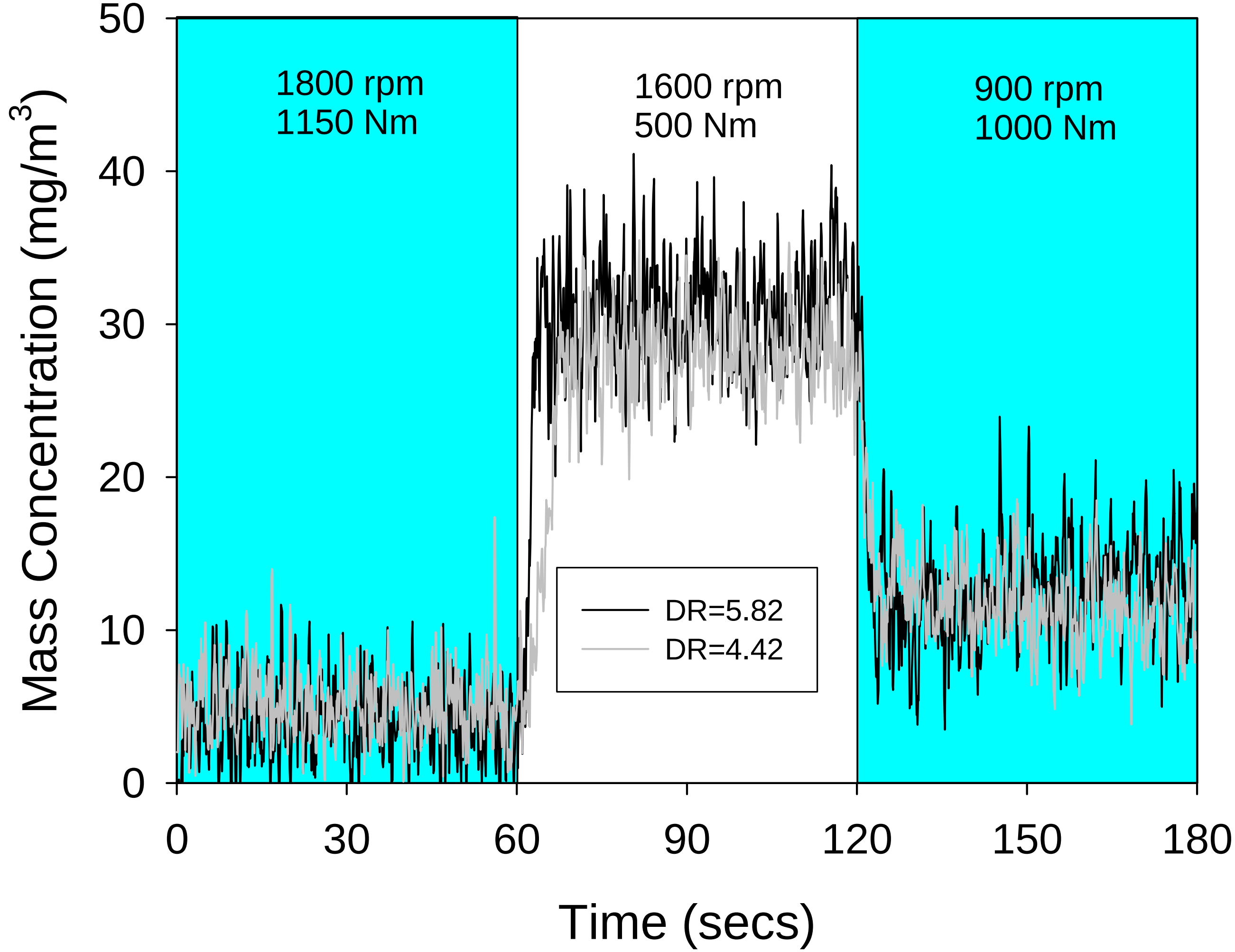
Validation Using Sierra's BG2 Dilution System



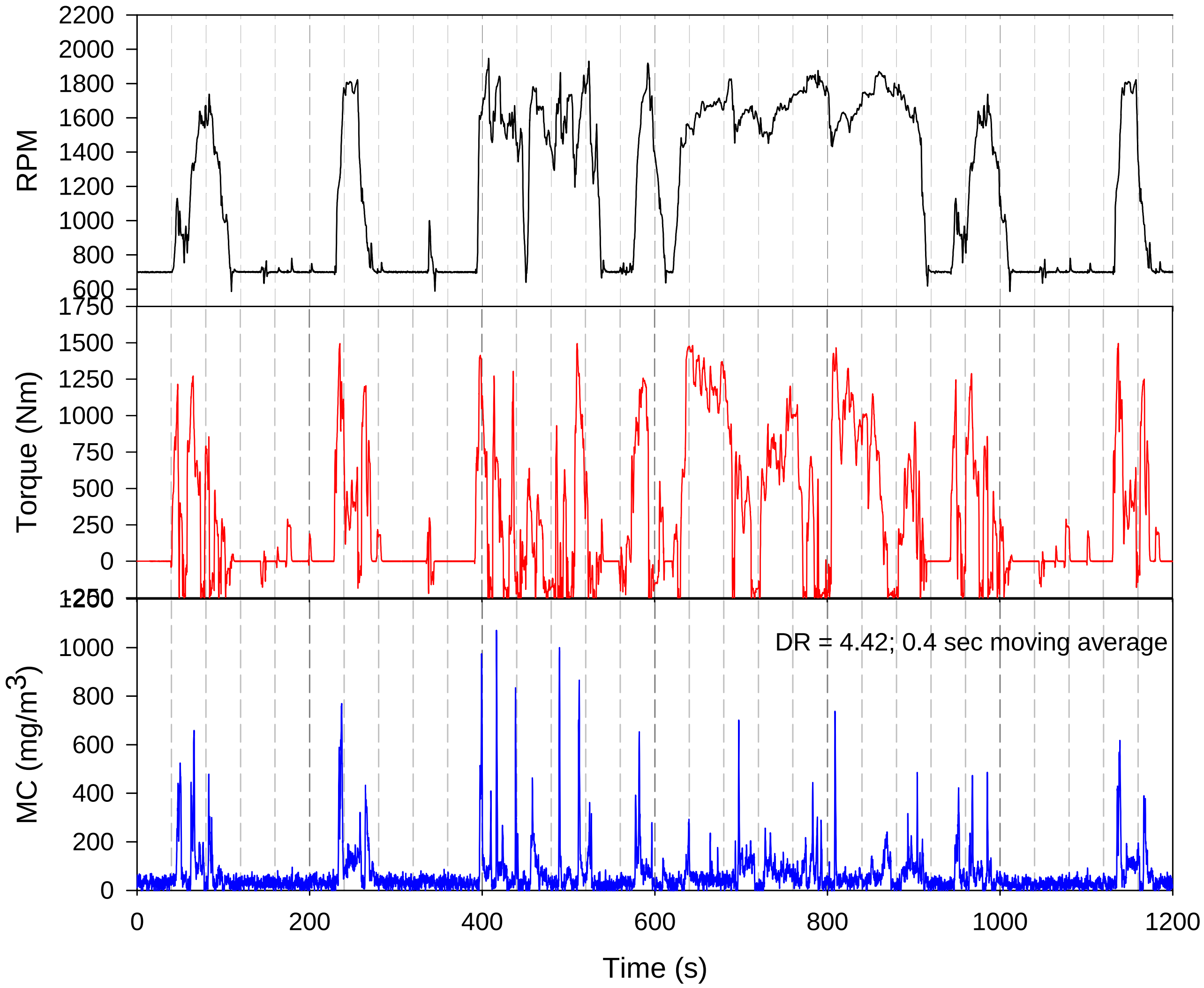
mfc1&2:	mass flow controllers
F1	filter paper for mass conc. measurements
P1	vacuum pump inside BG2
V1	valve to control TG-1 sample flow rate
F2	prefilter for vacuum pump

- Such a setup necessitated the use of dilution ratios ~ 4 – 8

TG-1 Has Excellent Day-to-day Repeatability

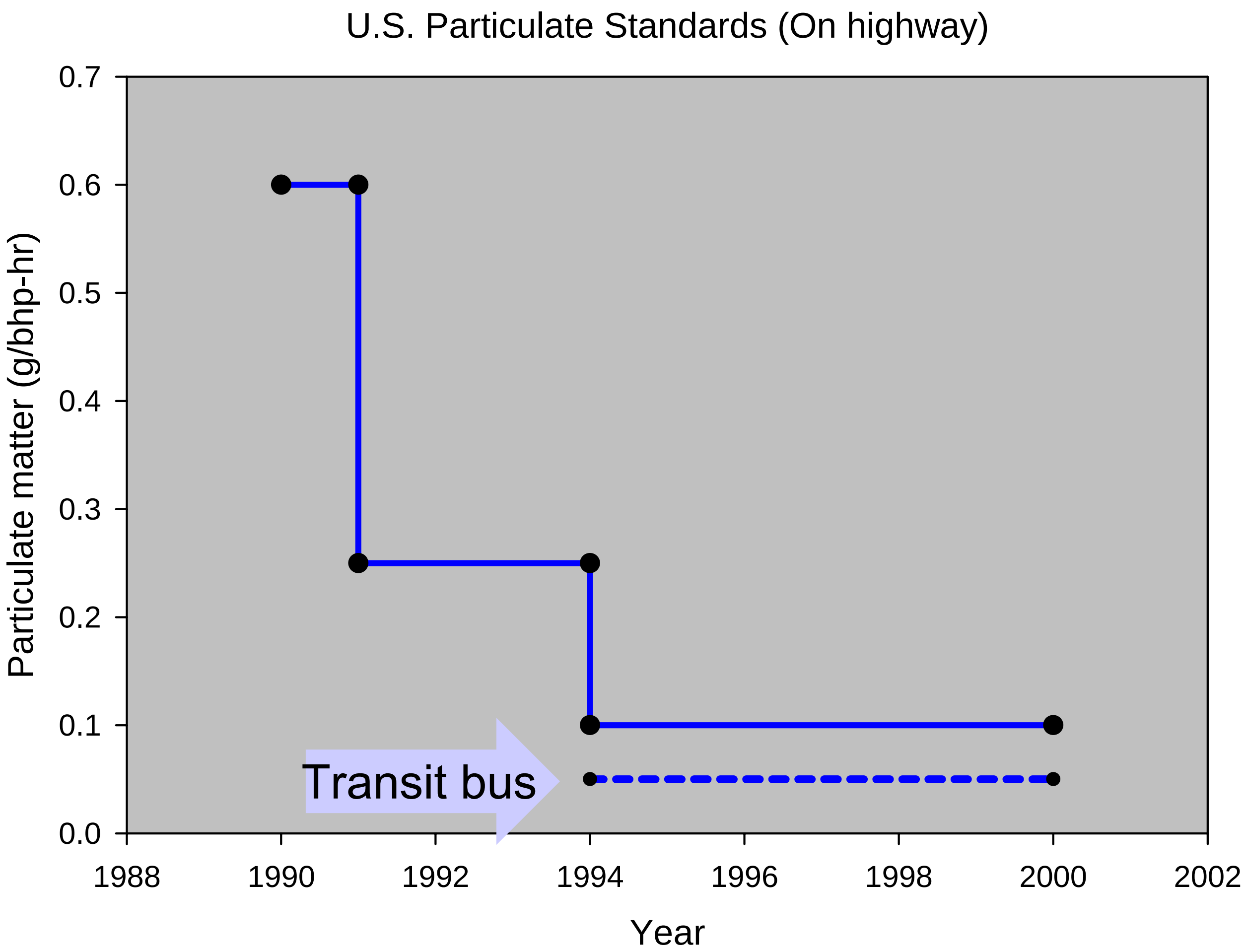


EPA Heavy-Duty Engine Dynamometer Transient Cycle

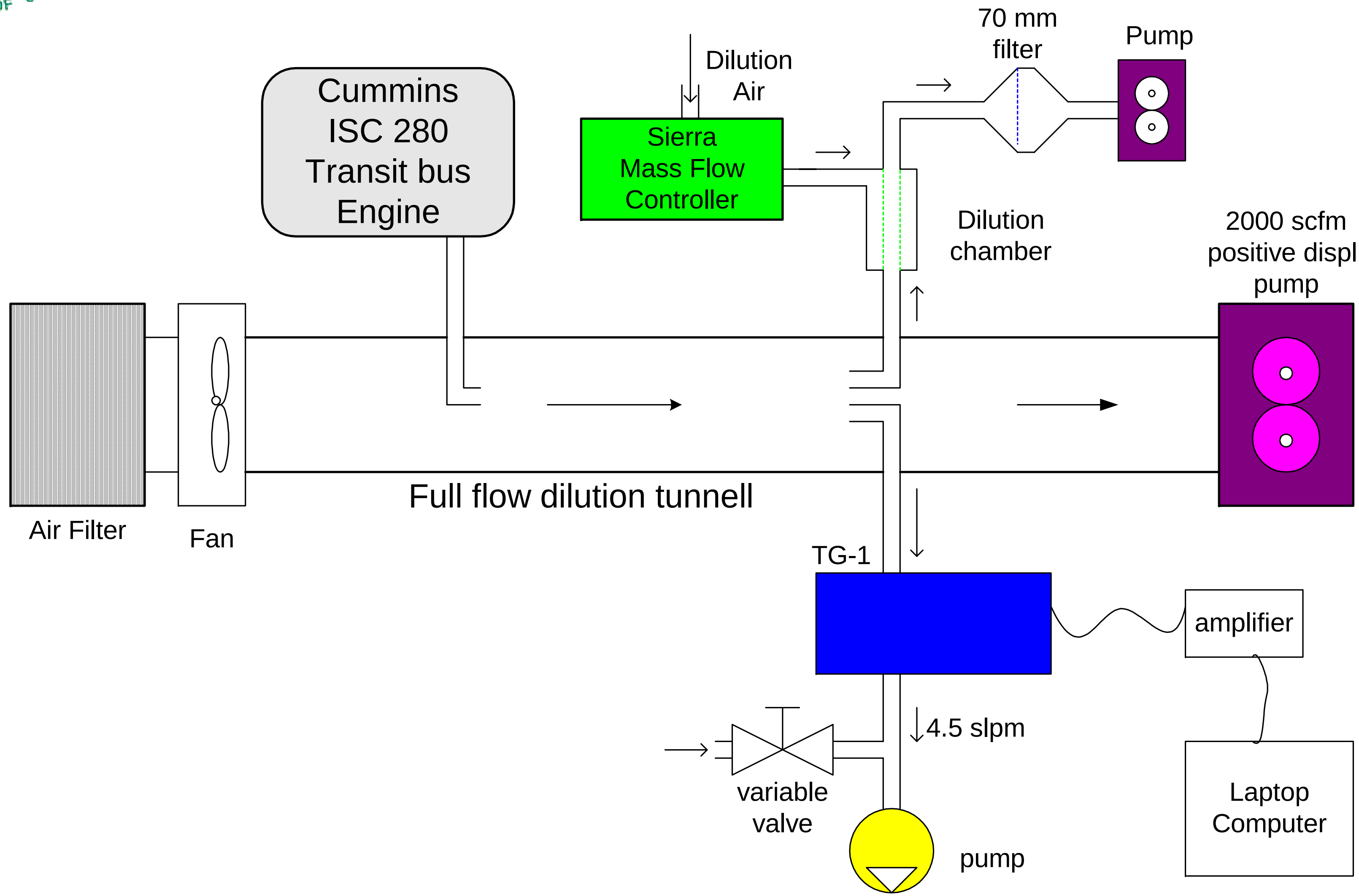


Tests on Cummins Full-Flow Dilution Tunnel

The Engine Tested Had to Satisfy the Most Stringent of PM Emission Standards

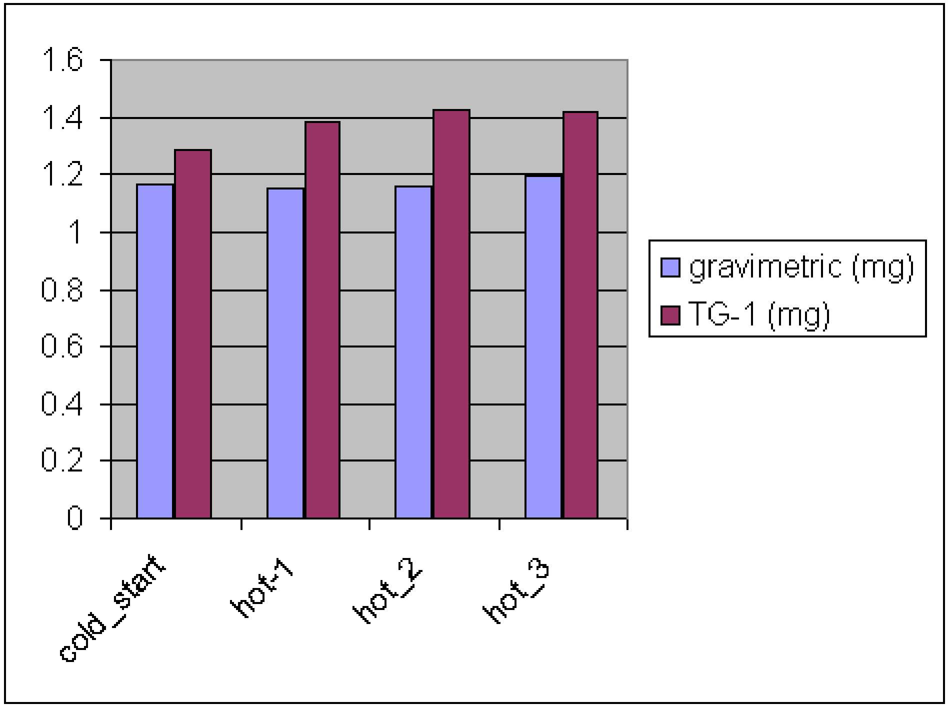


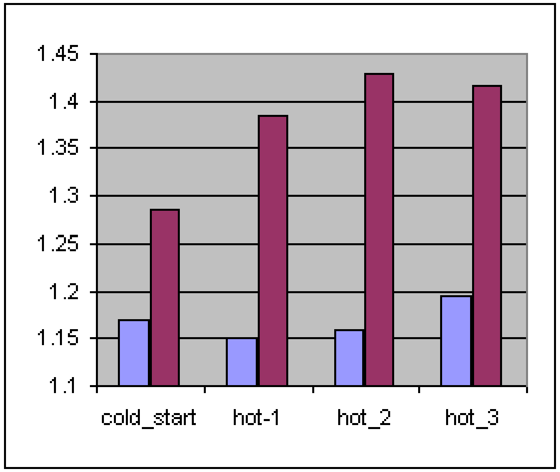
Cummins' Full-Flow Dilution Set-Up



Gravimetric vs. TG-1 over the Transient Cycle

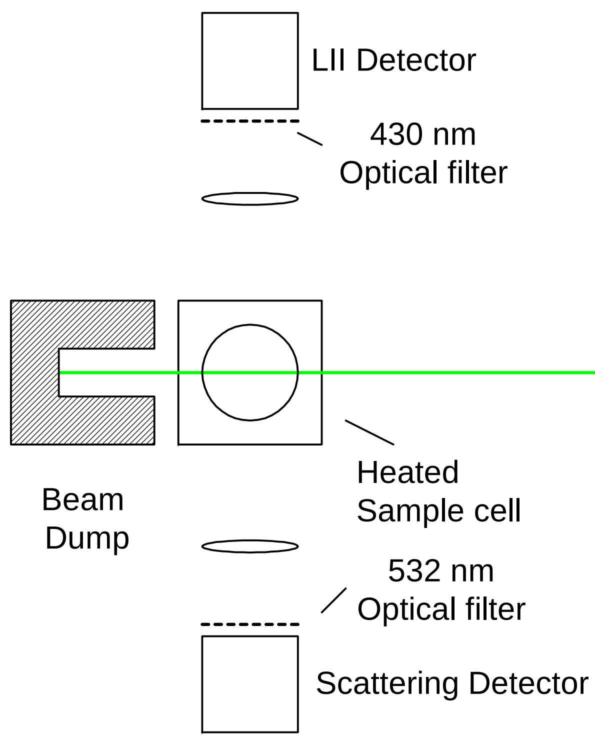
	Total flow (m3)	Gravimetric (mg)	TG-1 (mg)
Cold start	1.1646	1.17	1.285
Hot start 1	1.1684	1.15	1.385
Hot start 2	1.16294	1.158	1.428
Hot start 3	1.16334	1.194	1.416





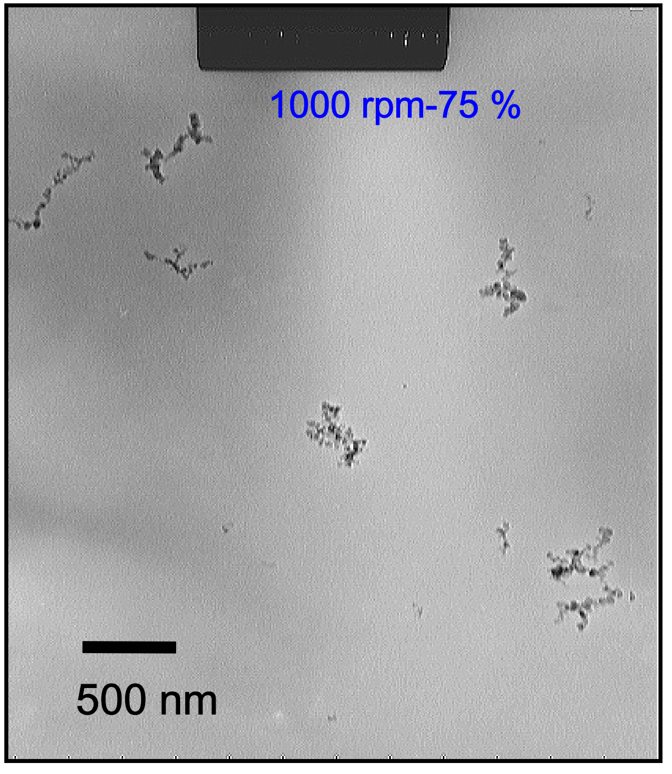
- In these limited set of tests, the agreement is encouraging.
- Cummins desires agreement within 0.01 mg

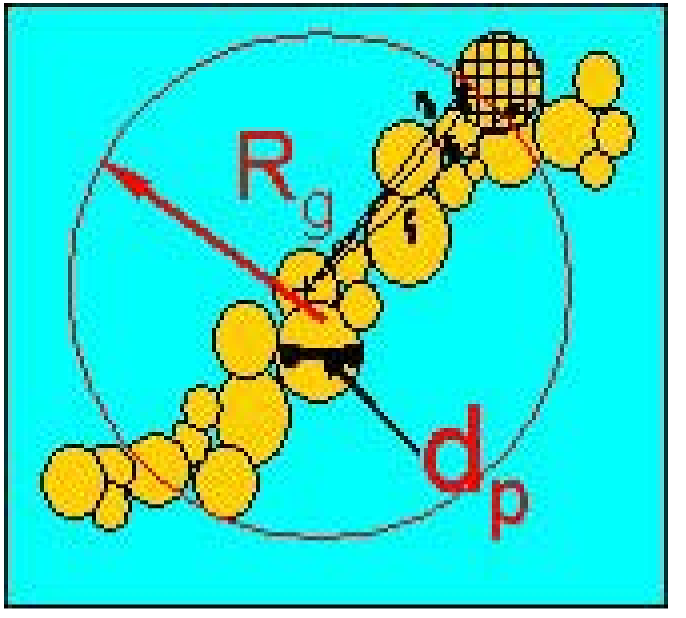
Ongoing Effort: Develop Capability to Measure Particle Number Density and Aggregate Size



Rayleigh scattering signal in combination with LII signal provides aggregate particle size and number information

Particle Size to be Validated with TEM Morphology Studies

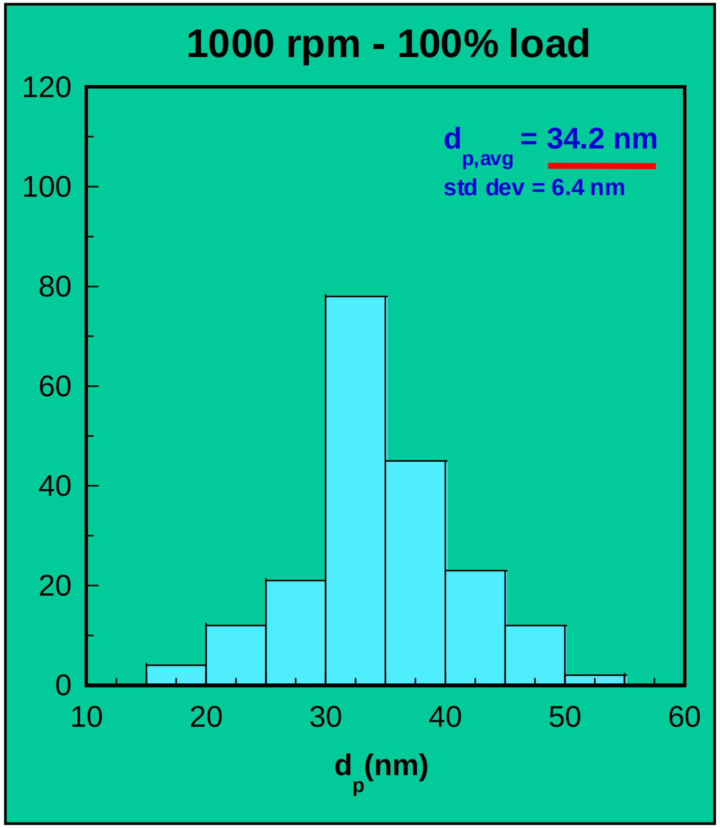


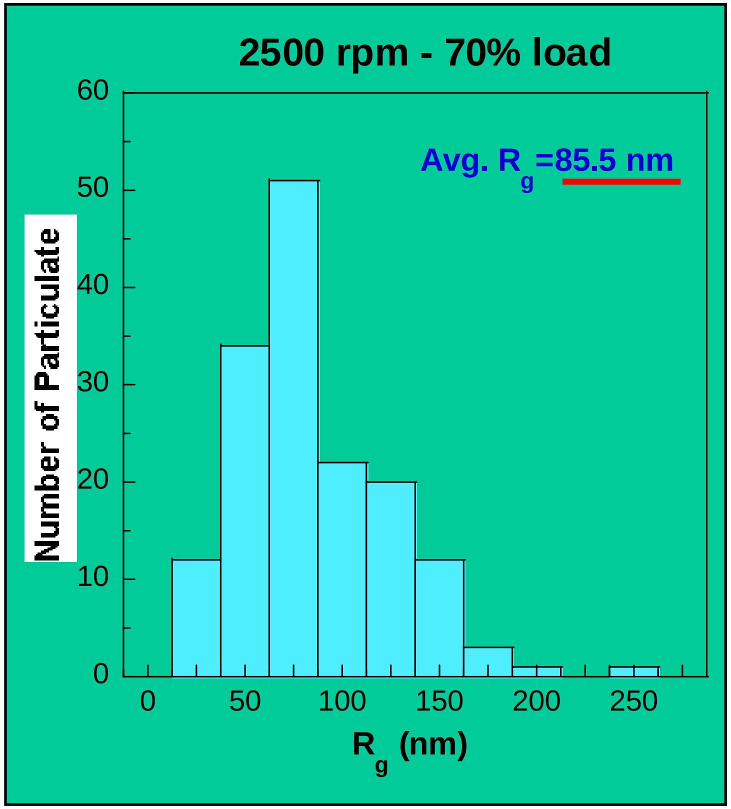


- Stretched chain-like particles
- 17,000 magnification

K. O. Lee, poster session

Such Studies Yield Very Accurate Particle Size Information





Primary particle size

Aggregate particle size

K. O. Lee, Poster session and Session 9

TG-1 May Help Develop Control Strategies to Lower the NOx–Soot Trade-Off