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CURRENT STATUS OF HEAVY DUTY IN-USE PM MEASUREMENT EQUIPMENT

October 2006

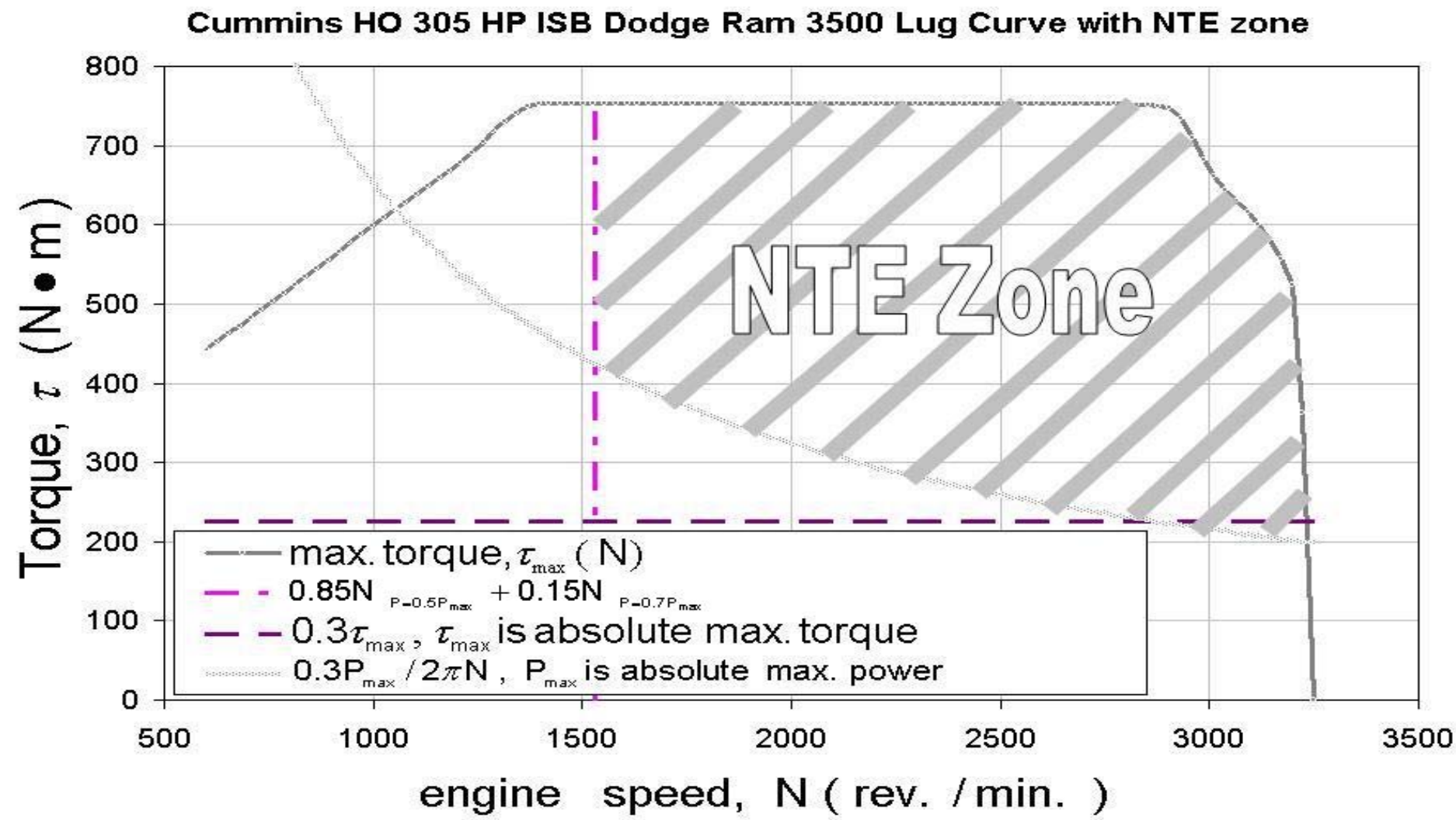
People :

EPA : Bob Giannelli, Matt Spears, Jingnan Hu, Bruce Cantrell (retired), Carl Fulper, Nick Beis, Bob Caldwell, Zuimdie Guerra, Ray Kondel, Toni Mentor, Joe McDonald, Joan Whinihan

Sensors, Inc. : David Booker, …

HDIU Rule and Testing (my understanding)

- EPA's interest in performing in-use, on-road emissions testing resulted in the HD vehicle in-use testing provisions contained in CFR 1065 (gaseous and PM both included in 1065)
- This in turn requires development of in-use testing equipment for both gaseous and PM emissions
- In-use emissions measurements limited to particular vehicle operational "zones" or Not-To-Exceed (NTE) zones which are dependent on engine characteristics


Cummins HO 305 HP ISB Dodge Ram 3500 Lug Curve with NTE zone
NTE Zone
Torque, τ (N • m)
engine speed, N (rev. / min.)
max. torque, τmax (N)
0.85N P=0.5Pmax + 0.15N P=0.7Pmax
0.3τmax , τmax is absolute max. torque
0.3Pmax / 2πN , Pmax is absolute max. power
800
700
600
500
400
300
200
100
0
500
1000
1500
2000
2500
3000
3500

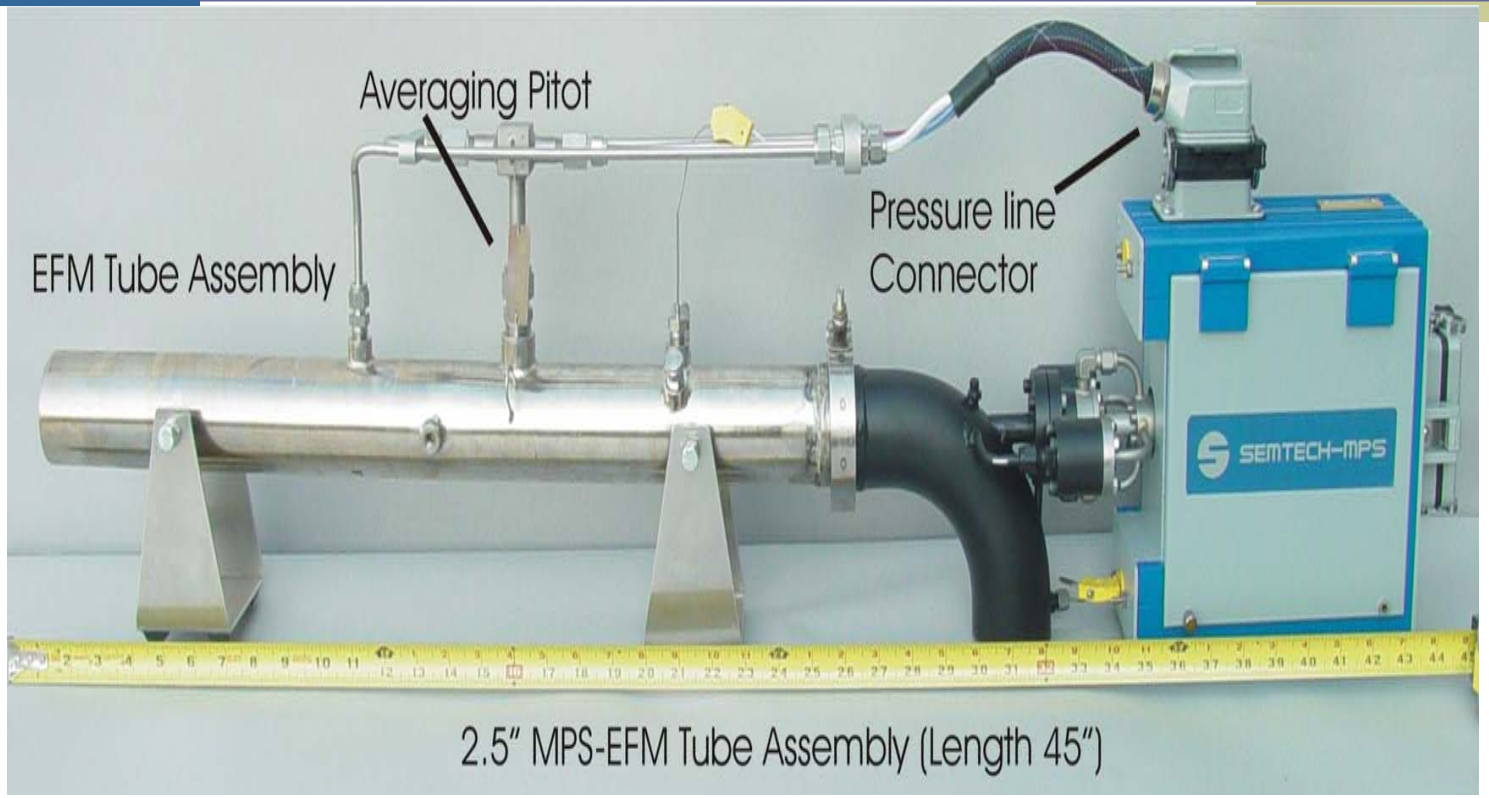
ISO 16183 and CFR-1065 Standards

Standard	*Minimun Requirement*	*Permissible Deviation*
ISO 16183	Exhaust Gas Flow	2.5% of reading or 1.5% of engines max. value, whichever is greater
	Exhaust Temp < 600K	2K absolute
	Exhaust Temp >600K	1% of Reading
	Exhaust Gas Pressure	0.2 kPa absolute
	Atmospheric Pressure	0.1 kPa absolute
	Other Pressures	0.1 kPa absolute
	Absolute Humidity	5% of reading
	Dilution Air Flow	2% or reading
	Diluted Exhaust Gas Flow	2% of reading
	Response Time	<300 ms
	Proportionality	Correlation Coefficient > 0.95
	Standard Error / Max. Sample flow Rate	< 5%
USEPA in the CFR §1065.545	Response Time	<250 ms
	Standard Error / Mean Sample Flow Rate (SEE)	< 3.5%

PM Mass Measurement

- Proportional sampling system
- PM time-resolved mass scale
- Scale must be for on-board measurement (power and size limitations)

Proportional Sampling System

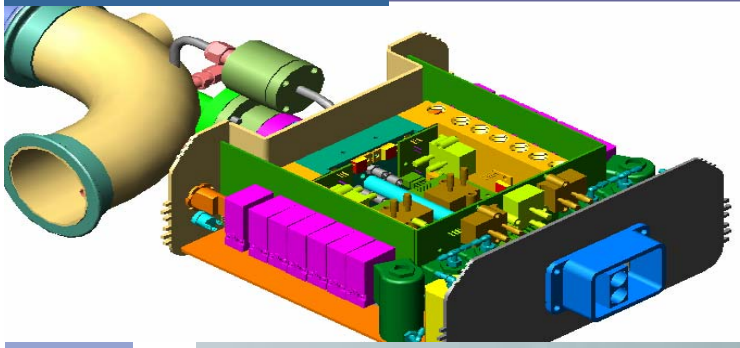


Fall 2005 version of Micro proportional Sampling system (MPS) with exhaust flow meter

Proportional Sampling System (cont.)

- Developed by David Booker of Sensors, Inc. along with Bruce Cantrell while at USEPA
- Fast (10's of milliseconds, 20Hz), solenoid controlled needle valve dilution air supply along with constant volume, venturi type mixing system (e.g., Brockmann, et al. , 1984)

Proportional Sampling System (cont.)



Proportional Sampling System (cont.)

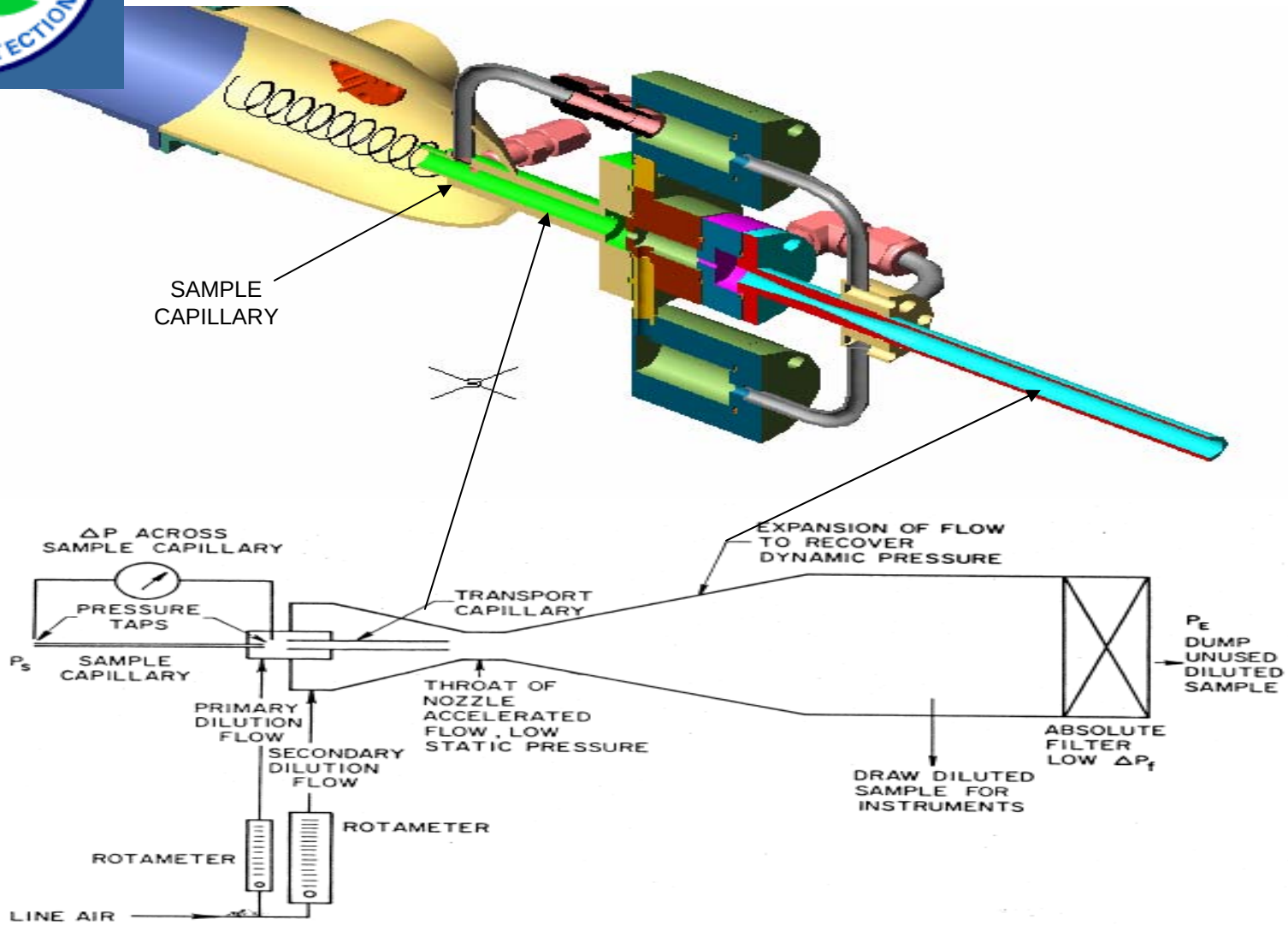


FIGURE 1. A schematic diagram of the sample extraction diluter.

PM Mass Measurement

- Final design is an eight head quartz crystal microbalance

PM Mass Measurement (cont.)

- QCM for needed mass sensitivity and time resolved measurements of PM mass at 2007 emissions levels of heavy duty diesel and light duty vehicles
- In contrast to other mass measurement techniques, it determines the PM mass directly from a frequency measurement
- Mass deposition/increase on an oscillating piezoelectric crystal is directly proportional to the frequency change of the crystal
- It has been used as a highly sensitive mass (ng) measurement technique in many disciplines and over many decades
- Other methods are based on particle size measurements, either light scattering or aerodynamic properties, of the aerosol; these methods depend on an assumed particle mass density function

QCM and MPS Procurement

- Contract awarded to Sensors, Inc. to develop both gaseous and PM measurement equipment
- Currently, a small contract to finish the development of the eight head QCM and the MPS is in effect (ends in September with the delivery of an eight head QCM; the MPS has already been delivered and is under evaluation)
- Commercial versions of MPS and 8 head QCM have been delivered in September (Matt Spears)
- Procurement of a PM standard or source (Matt Spears)

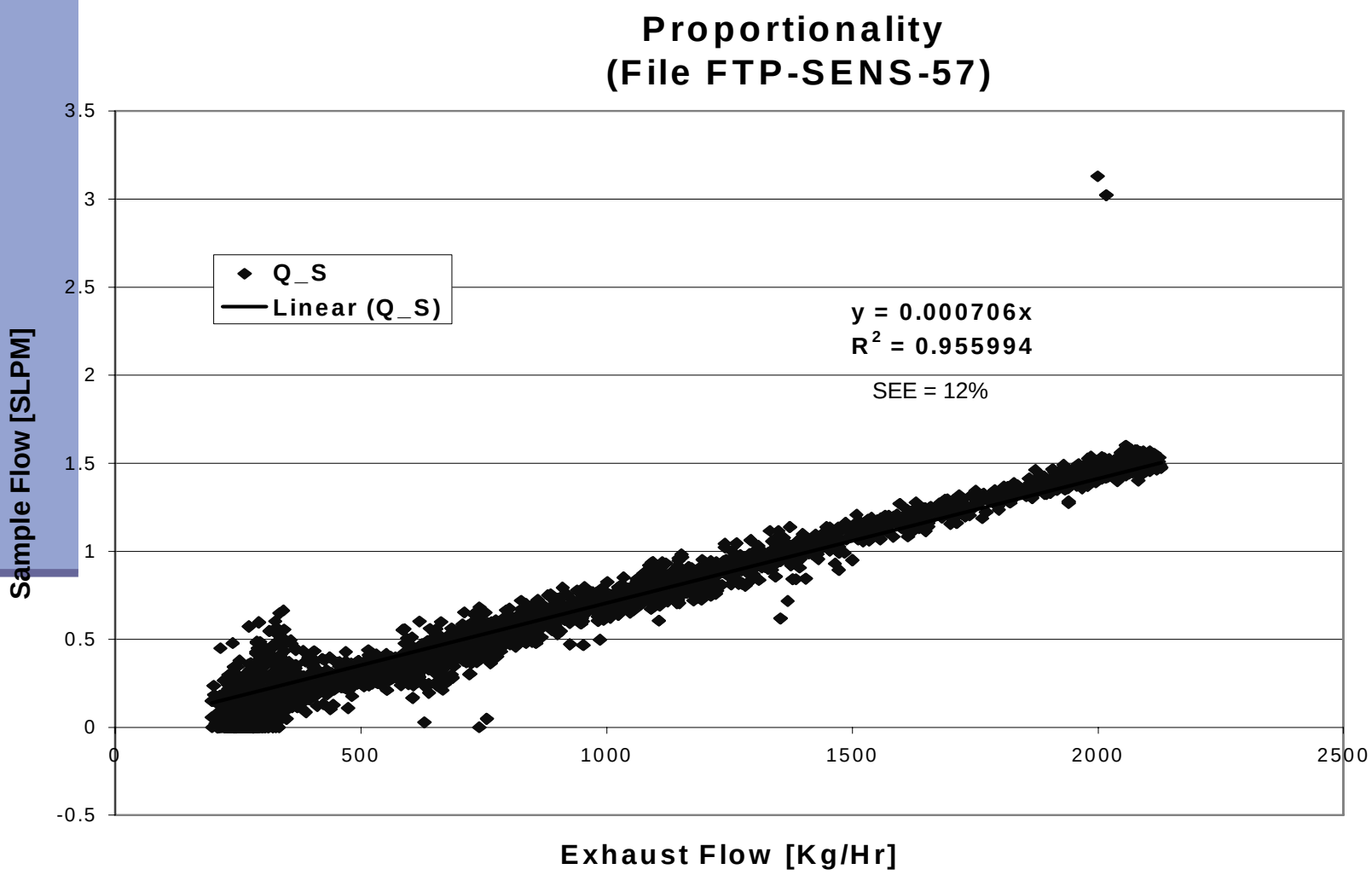
QCM and MPS Development and Testing

- KC was first large scale use of a single head QCM with an initial version of the MPS (not on board, though)
- Fall 2005 - contract with SwRI under E-66 to evaluate differing dilution systems
- Spring 2006 – EPA and Sensors, Inc. demonstration of MPS and 2 QCM's on-road and to and from San Diego, CA
- Summer 2006 – EPA and Sensors, Inc. Horiba PSU filter comparison with MPS filter system in an EPA engine dynamometer test cell

Fall 2005 SwRI / E-66 Dilution System Evaluations

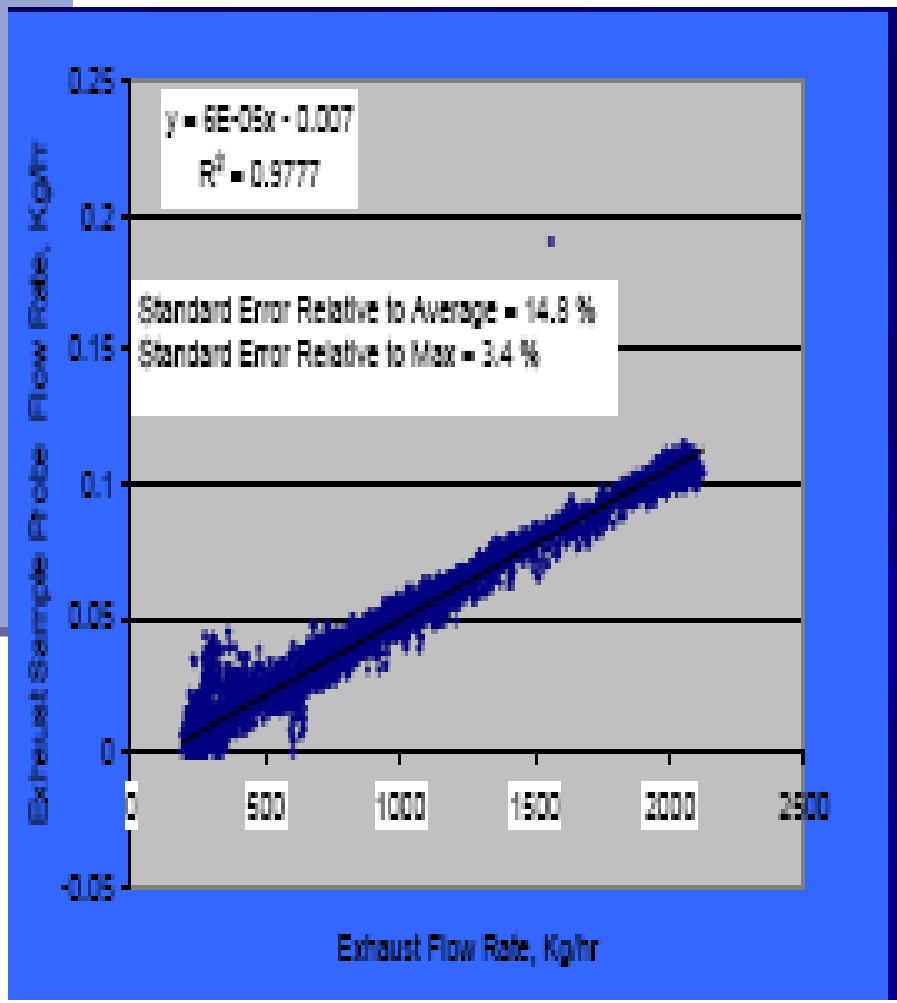
- Partially still under development and learning to operate MPS; MPS was installed with a 25mm filter
- ISO and 1065 criteria met in most runs
- Filter comparisons not completely conclusive (comparisons with 47mm filters)

FTP SwRI FTP Run

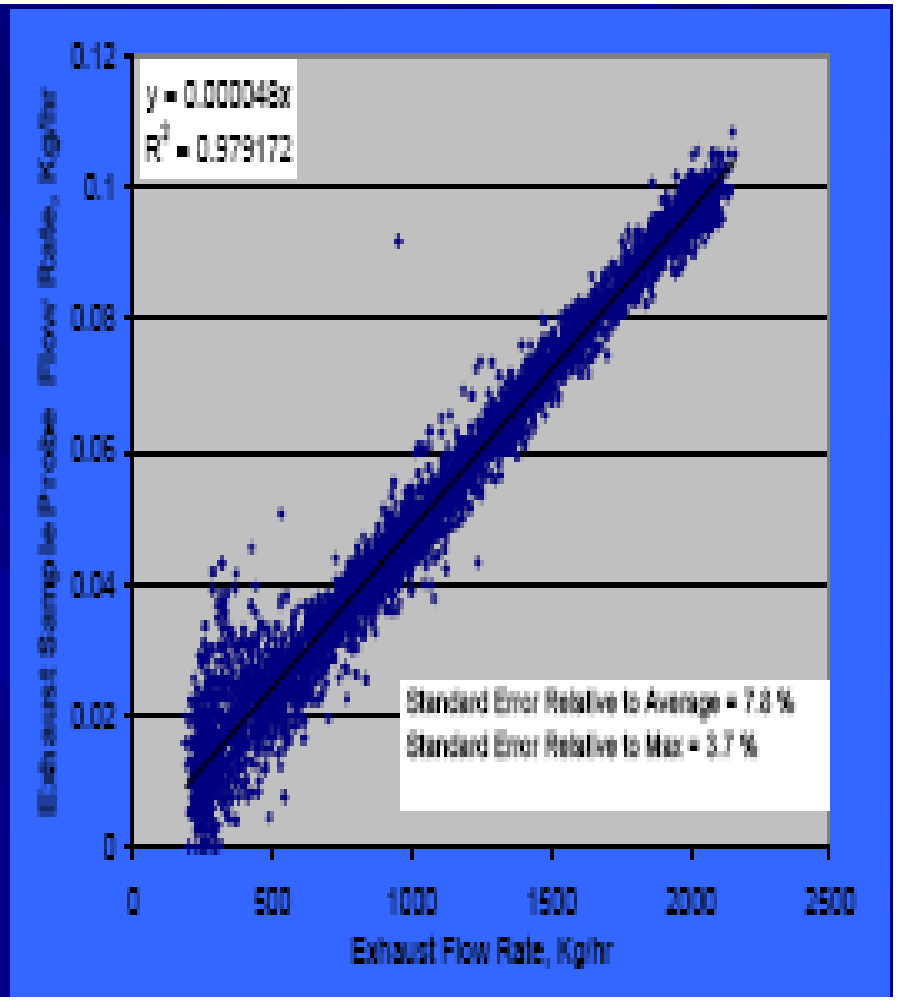


MPS Proportionality (I.Khalek)

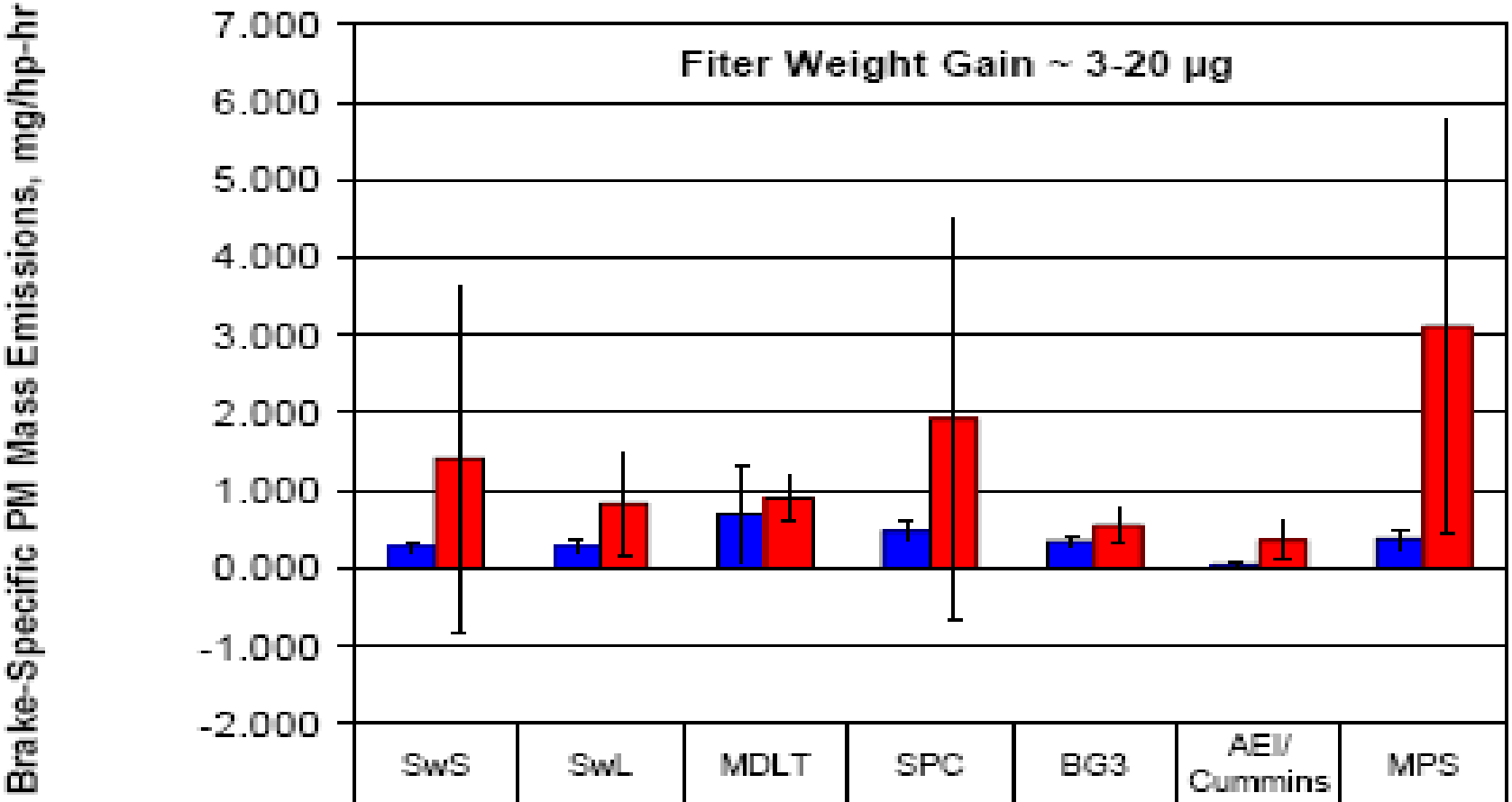
FTP



Non-Road Transient

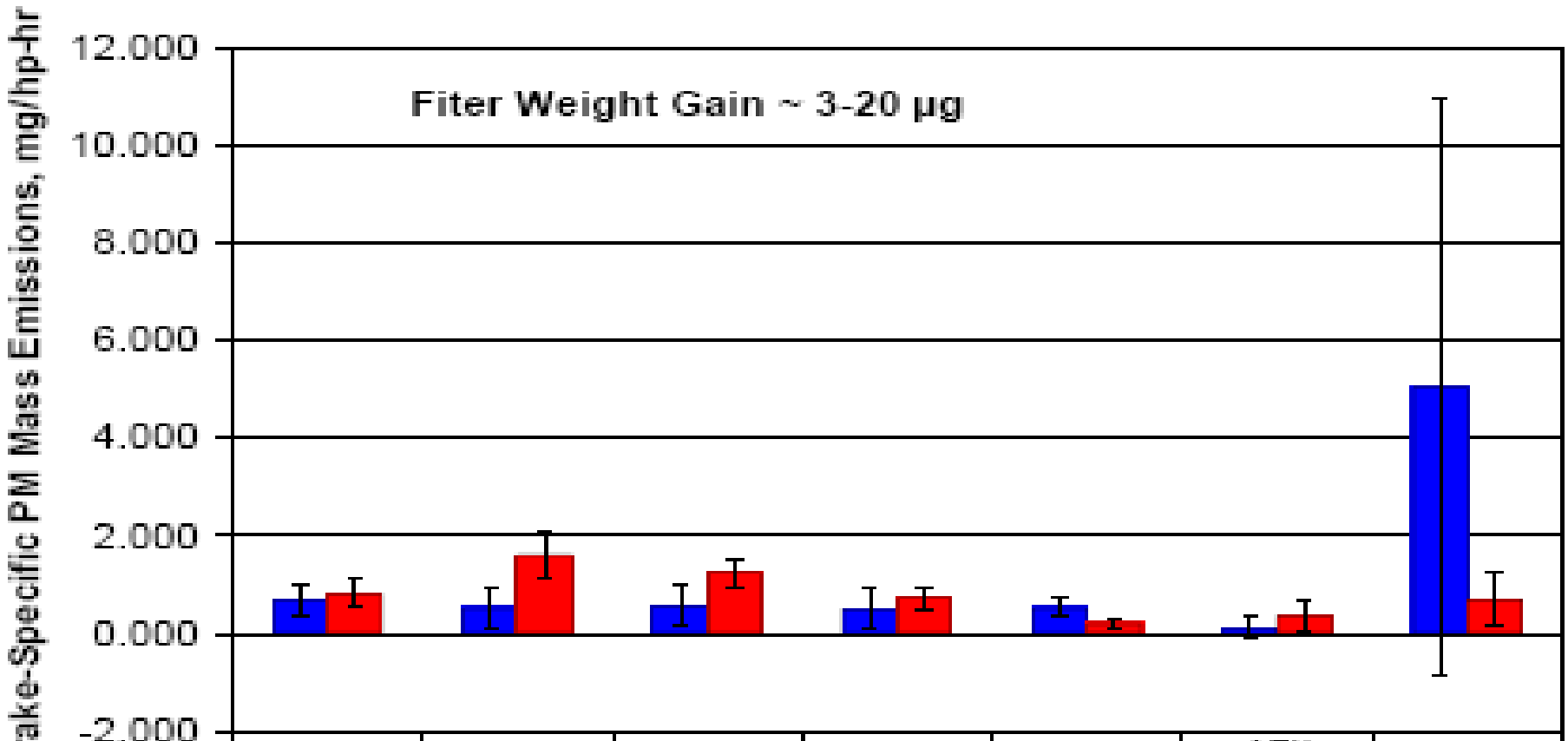


Performance of Different Sampling Systems Using CRT-DPF Without Partial Exhaust Flow Bypass (Steady-State Engine Operation) (from I.Kahlek)



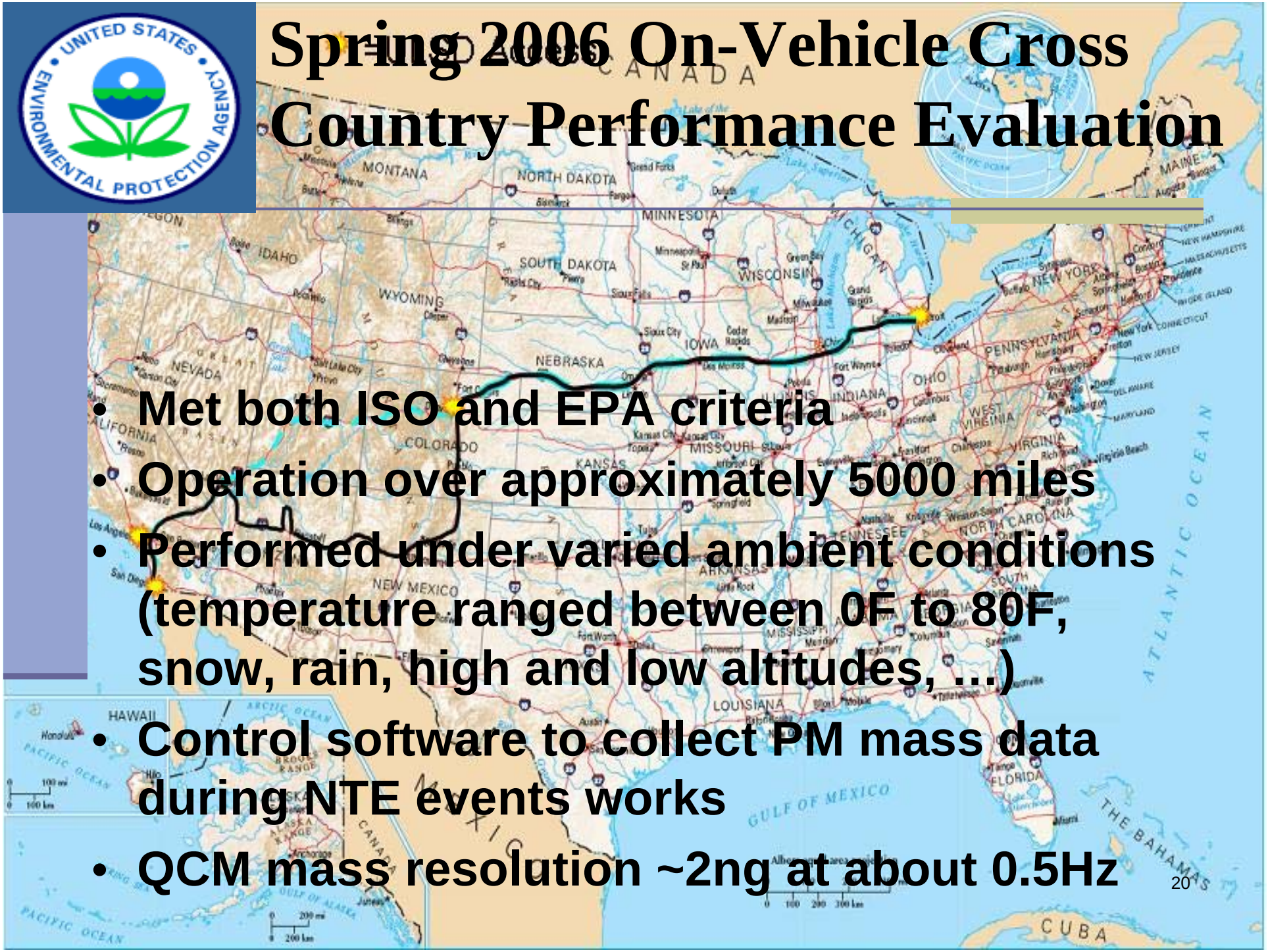
	SwS	SwL	MDLT	SPC	BG3	AEI/ Cummins	MPS
Rated Speed, 100 % Load	0.276	0.292	0.701	0.488	0.348	0.045	0.380
Rated Speed, 10 % Load	1.413	0.832	0.910	1.925	0.554	0.362	3.112

Performance of Different Sampling Systems Using CRT-DPF Without Partial Exhaust Flow Bypass (Transient Engine Operation) (I.Khalek)



	SwS	SwL	MDLT	SPC	BG3	AEI/ Cummins	MPS
FTP	0.680	0.513	0.562	0.505	0.518	0.120	5.034
NRTC	0.812	1.596	1.244	0.715	0.196	0.363	0.682

Spring 2006 On-Vehicle Cross Country Performance Evaluation

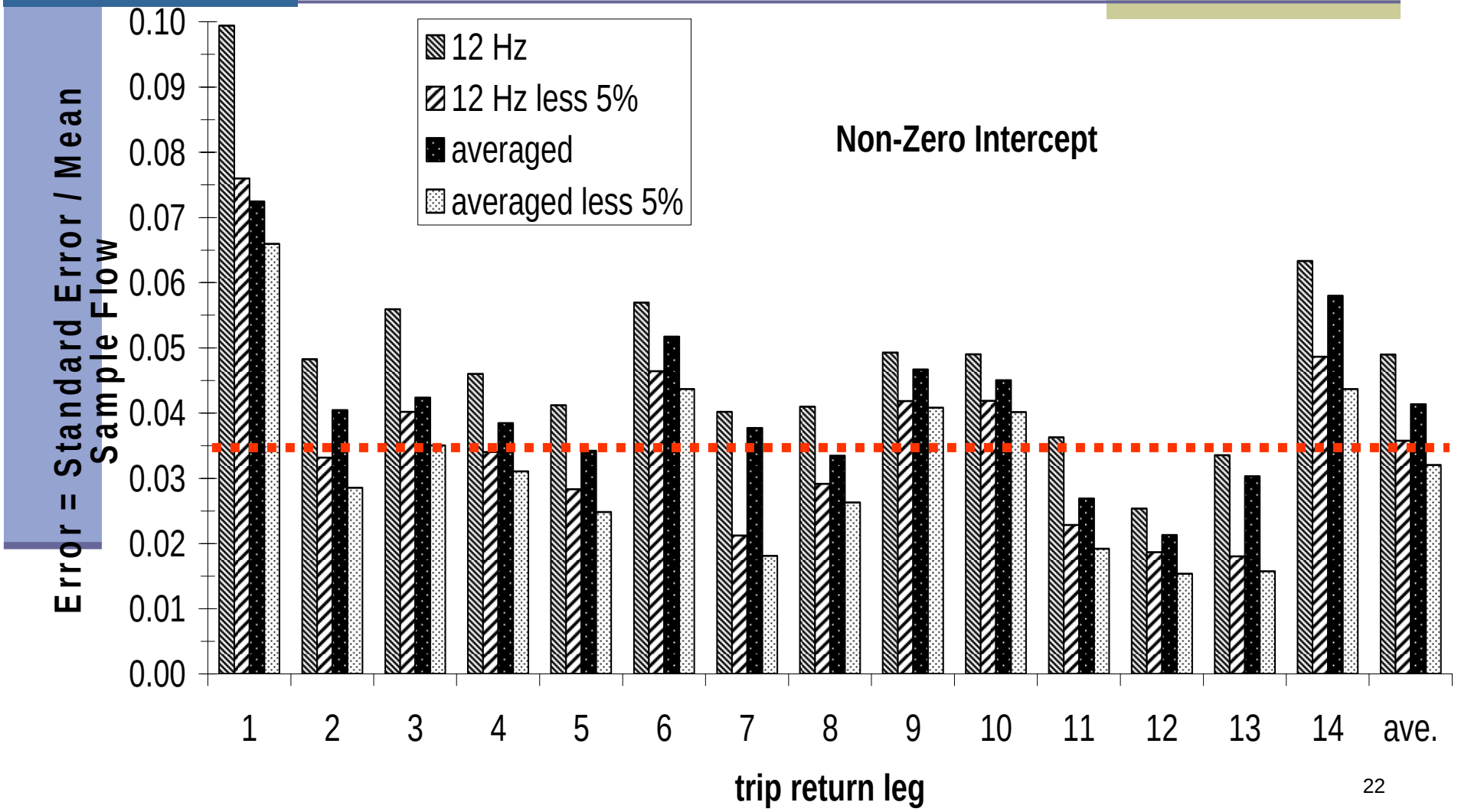


- Met both ISO and EPA criteria
- Operation over approximately 5000 miles
- Performed under varied ambient conditions (temperature ranged between 0F to 80F, snow, rain, high and low altitudes, …)
- Control software to collect PM mass data during NTE events works
- QCM mass resolution ~2ng at about 0.5Hz

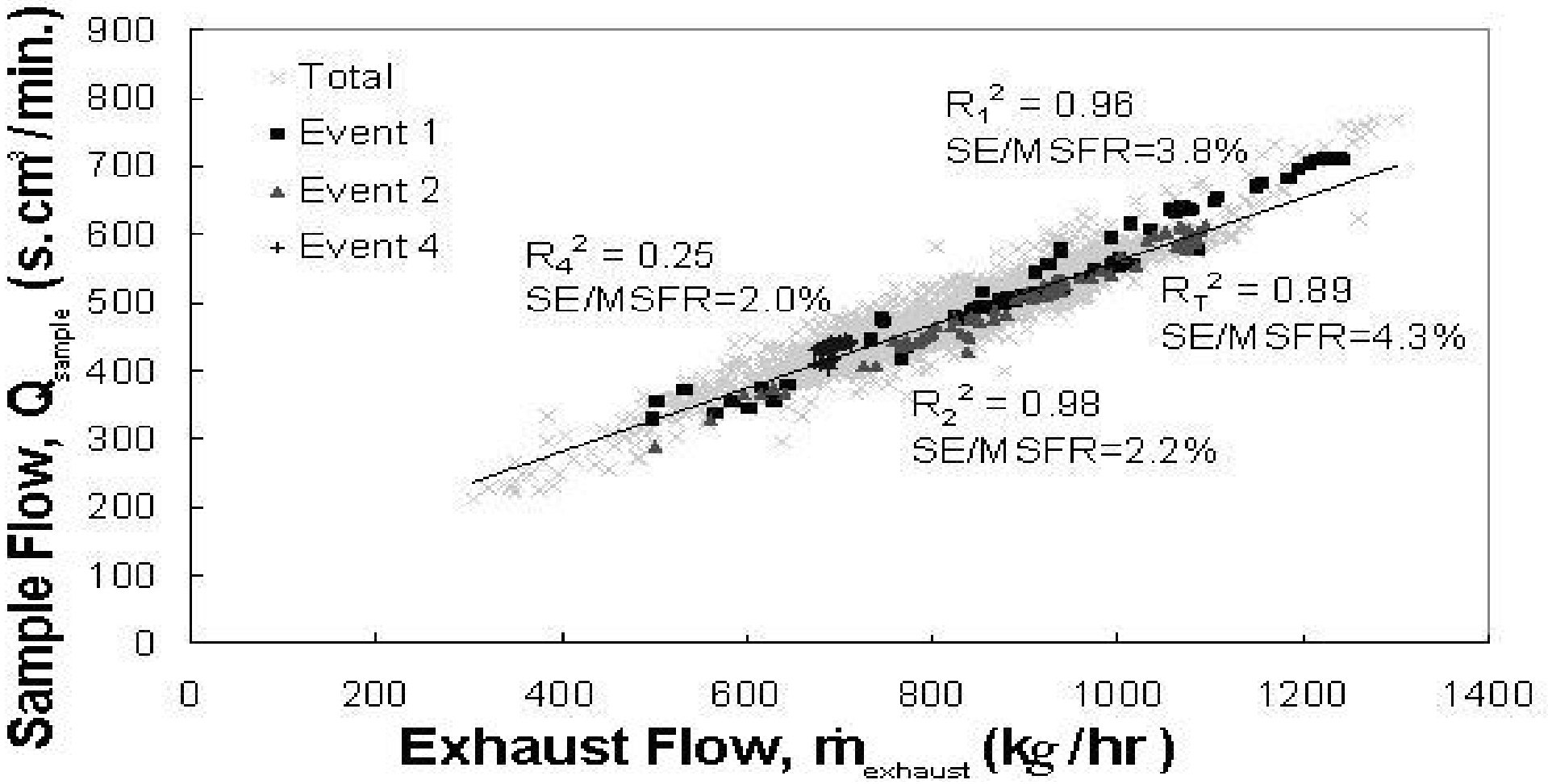
MPS CRC Road Test Overall Performance

filename	mean sample flow (SLPM)	standard error (SLPM)	ERROR	Slope (SLPM)/(kg/hr)	R^2	actual number of points	total drive time (minutes)
return 1	0.2702	0.0178	0.0660	0.000558	0.9843	656	6.4
return 2	0.336	0.0096	0.0286	0.000529	0.9943	6452	77.3
return 3	0.284	0.0099	0.0350	0.000559	0.9938	15044	156.8
return 4	0.343	0.0107	0.0311	0.000511	0.9933	16457	173.8
return 5	0.306	0.0076	0.0248	0.000536	0.9969	19204	343.2
return 6	0.360	0.0157	0.0437	0.000500	0.9805	16923	226.7
return 7	0.489	0.0088	0.0181	0.000467	0.9835	1980	18.5
return 8	0.386	0.0102	0.0263	0.000538	0.9881	15512	170.4
return 9	0.403	0.0164	0.0408	0.000488	0.9538	9293	148.8
return 10	0.386	0.0155	0.0401	0.000523	0.9703	13491	188.8
return 11	0.405	0.0078	0.0192	0.000523	0.9921	25304	266.3
return 12	0.404	0.0062	0.0154	0.000553	0.9963	12575	195.9
return 13	0.415	0.0065	0.0158	0.000521	0.9879	2721	97.4
return 14	0.335	0.0146	0.0437	0.000506	0.9670	759	167.1

CFR1065 Errors



MPS performance in three typical events and in the total NTE area of trip leg #6



Summer 2006 : Horiba PSU filter - MPS Filter Inter-comparison

- FTP tests and 6 constant load at a constant speed runs
- FTP and constant load runs without MPS to compare MPS and Horiba filter systems
- ISO and 1065 criteria limited due to CVS (exhaust system acoustics and flow disturbances), user operational issues (EFM and MPS cleaning), and loose circuit board (obvious temperature reading fluctuations)
- Preliminary analysis shows a MPS filter system collected about 10% less mass than the Horiba filter system

Preliminary Summer 2006 Engine Test Cell Results

test	R^2	SEE (%)	MPS filter / ave. of 2 psu filters (normalized to baseline runs)
ftp	0.98	12	0.89 (0.92)
Mode 1	-	1.8	0.84 (0.90)
Mode 2	-	1.9	0.78 (0.86)
Mode 3	-	2.8	0.8 (0.85)
Mode 4	-	1.4	0.85 (0.93)
Mode 5	-	4.2	0.85 (0.93)
Mode 6	-	5.3	0.9 (1.0)

1-3% standard deviations in the B & C masses; 10% test-to-test mass standard deviations; mass scale has about a 2% uncertainty for this mass range

Next Steps

- Continue analysis of EPA engine test cell data
- Evaluation of recently delivered MPS's considering the analysis of first MPS (chassis and engine test cells)
- Follow-up engine test cell evaluation of MPS and eight head QCM
- SwRI study of MPS and eight head QCM (E66)
- Consider all PM loss mechanisms
- QCM evaluation with procured PM source

Conclusions

- MPS operates on-road within ISO and EPA 1065 standards under varied ambient conditions
- NTE event mass collection with MPS-QCM system has been demonstrated
- MPS and QCM PM mass losses need further quantification
- Eight head QCM has been procured and now needs complete evaluation