Remote Sensing Milestones

“US Experience”

esp

August 04

Niranjan Vescio, ESPH
August 12, 2004

Presentation Outline

1. Brief intro to RSD Technology
2. History and Evolution
3. Applications & Regulations
4. Technology & Performance
   a. Gasoline Vehicle Measurement.
      i. Technology (HW & SW)
      ii. Matching Laboratory Analyzers
      iii. Matching Inspection Results
      iv. Matching Fleet Emissions

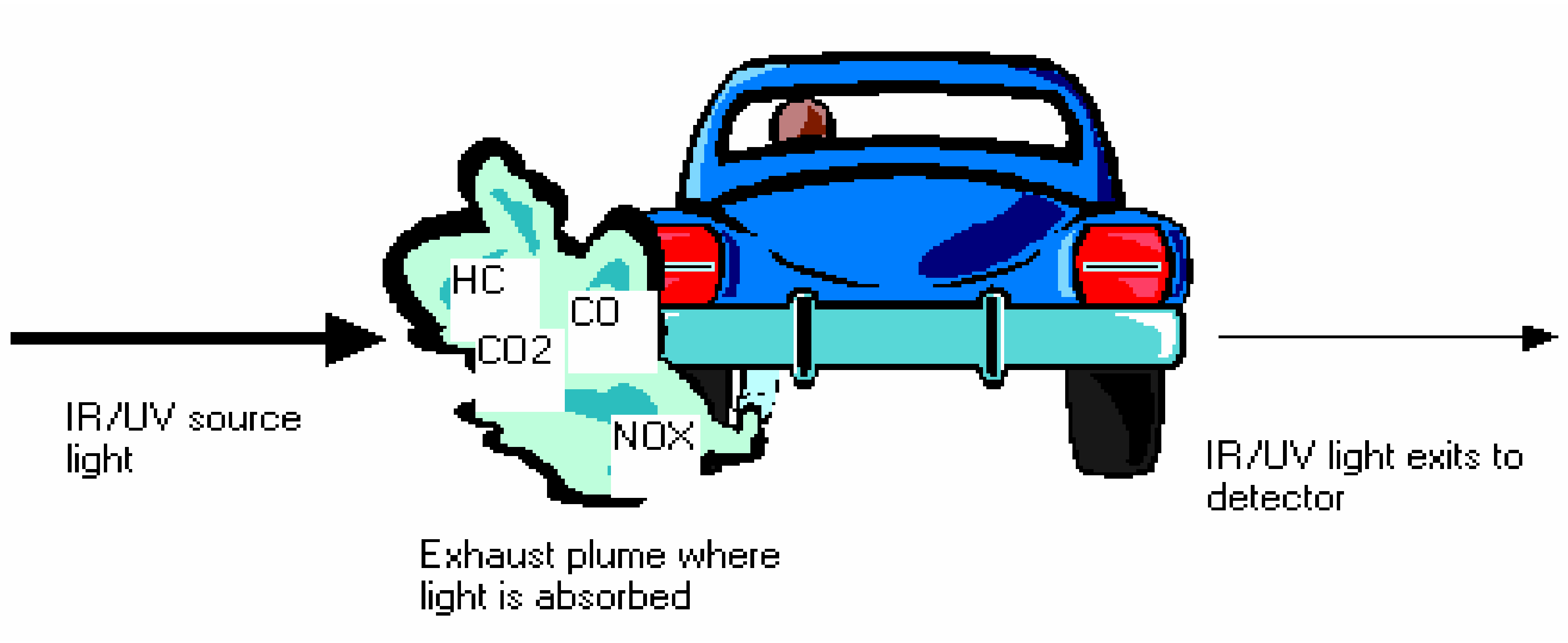
   b. Diesel Vehicles…Where are we?
      i. Technology (HW & SW)
      ii. Matching Laboratory Analyzers
      iii. Matching Inspection Results
      iv. Matching Fleet Emissions

Technology Brief

August 04

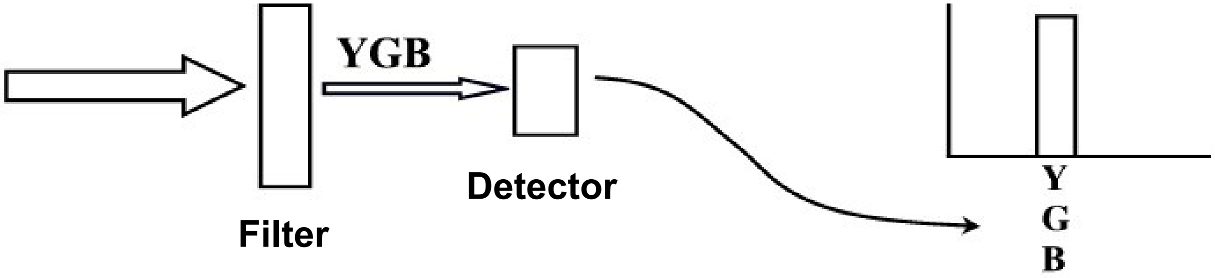
On-road Measurement Principle

Spectroscopy (Light Absorption)

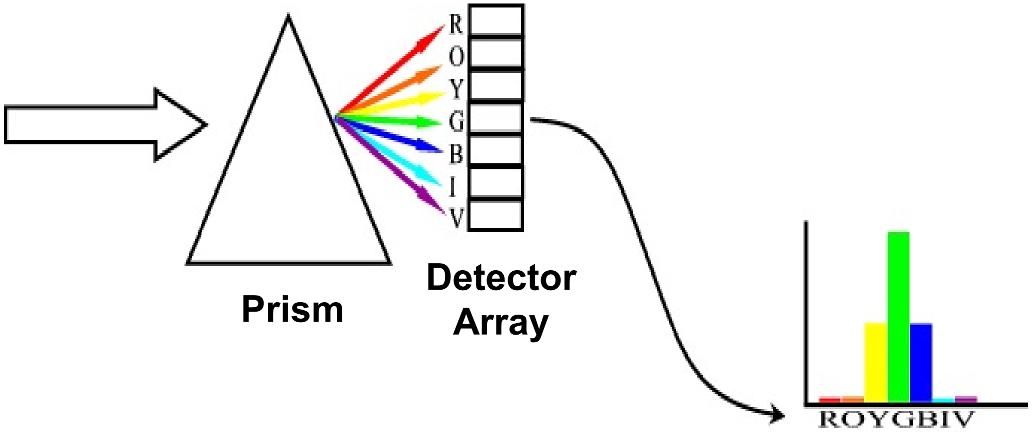


Familiar Science

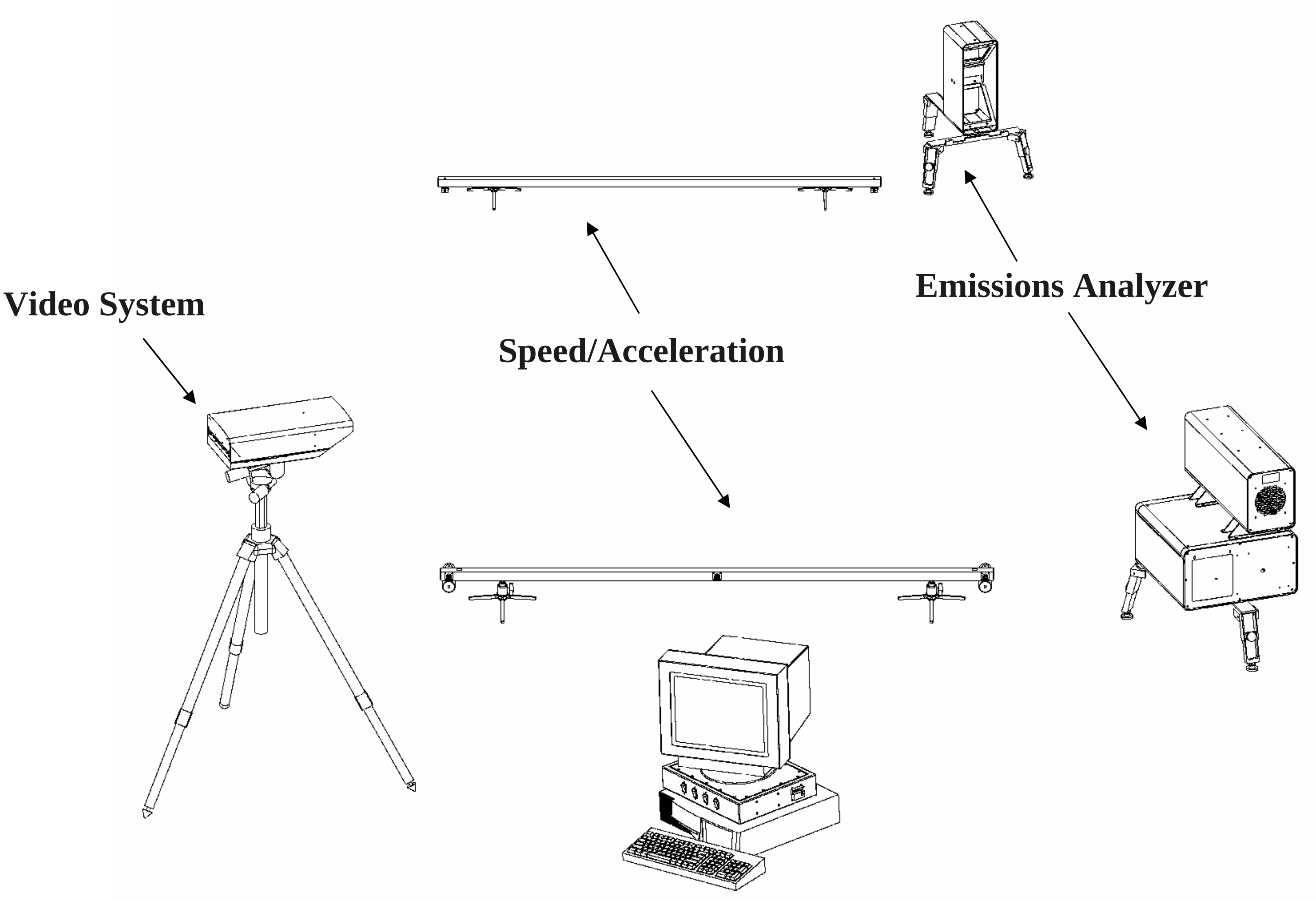
1. Infrared – CO, HC, CO_2
    a. Non-Dispersive Infrared (NDIR)



2. Ultraviolet – NO
    a. Dispersive Ultraviolet (DUV)



Remote Sensing System Components



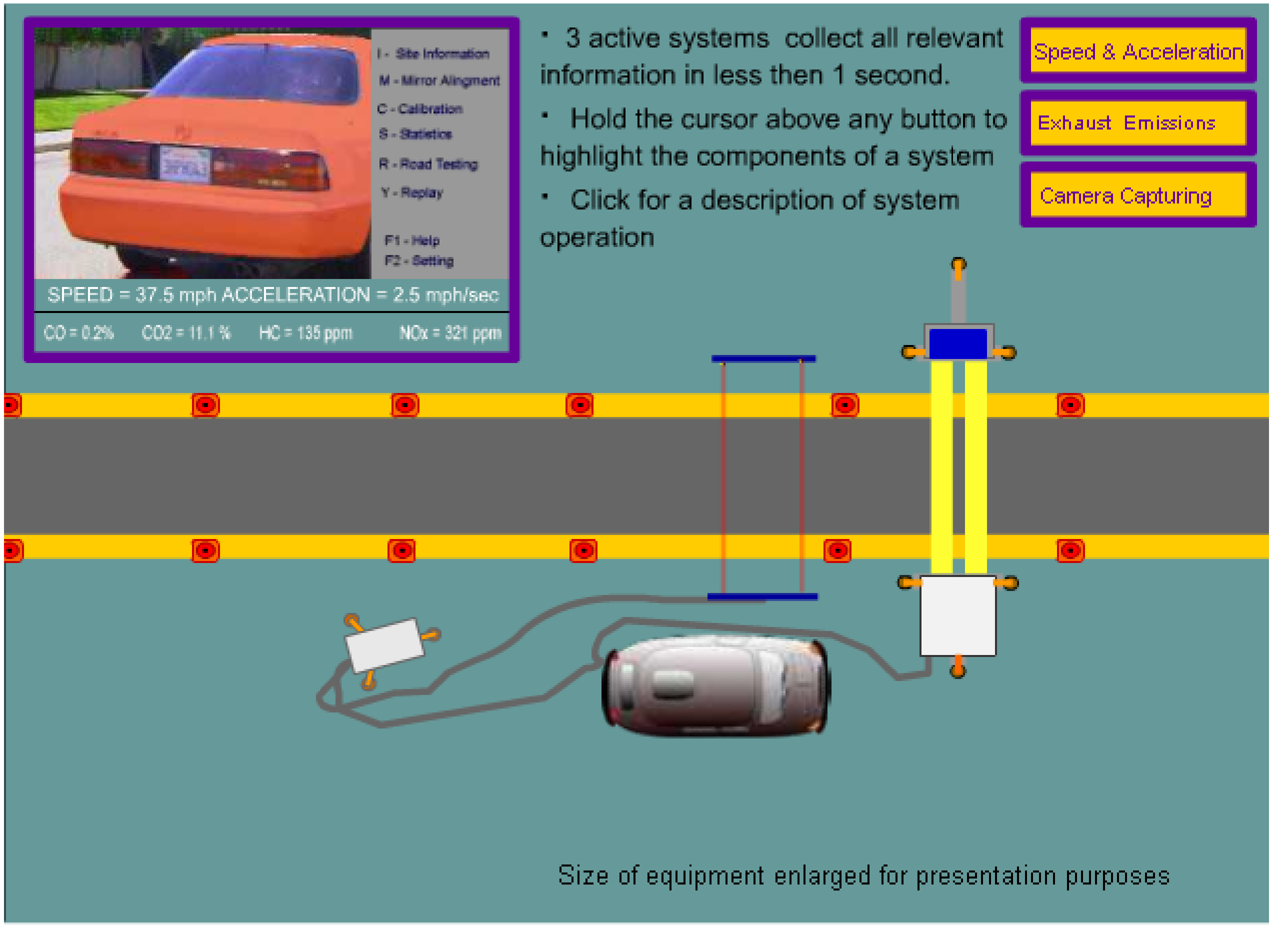
Video System

Speed/Acceleration

Emissions Analyzer

Remote Sensing Technology

Hardware: www.rsdaccuscan.com



SPEED = 37.5 mph ACCELERATION = 2.5 mph/sec

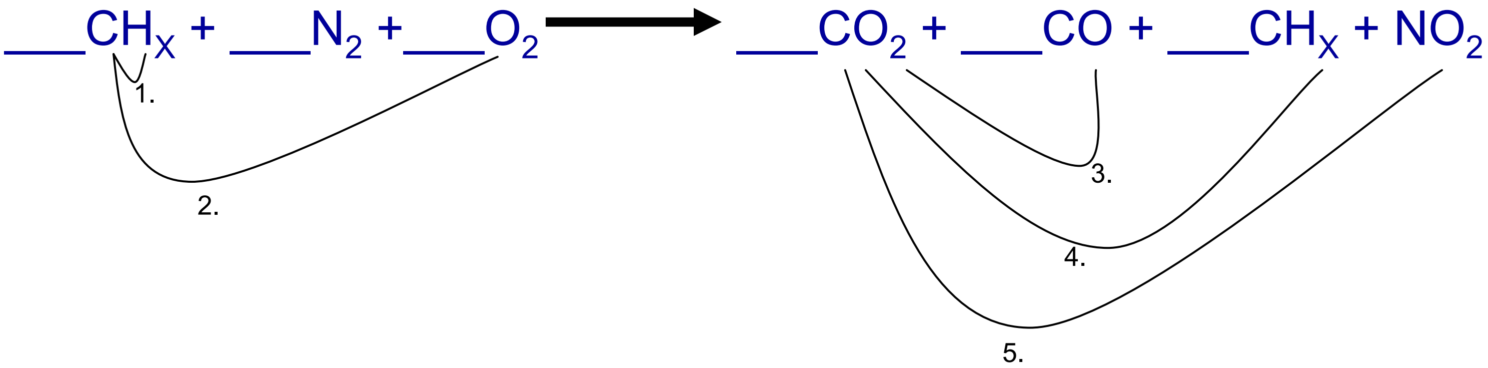
CO = 0.2%   CO2 = 11.1 %   HC = 135 ppm   NOx = 321 ppm

- 3 active systems collect all relevant information in less then 1 second.
- Hold the cursor above any button to highlight the components of a system
- Click for a description of system operation

Size of equipment enlarged for presentation purposes

RSD Mathematics

2. Software –
   a. Measure ratios in order to calculate concentrations



$$\_\_\_CH_X + \_\_\_N_2 + \_\_\_O_2 \longrightarrow \_\_\_CO_2 + \_\_\_CO + \_\_\_CH_X + NO_2$$

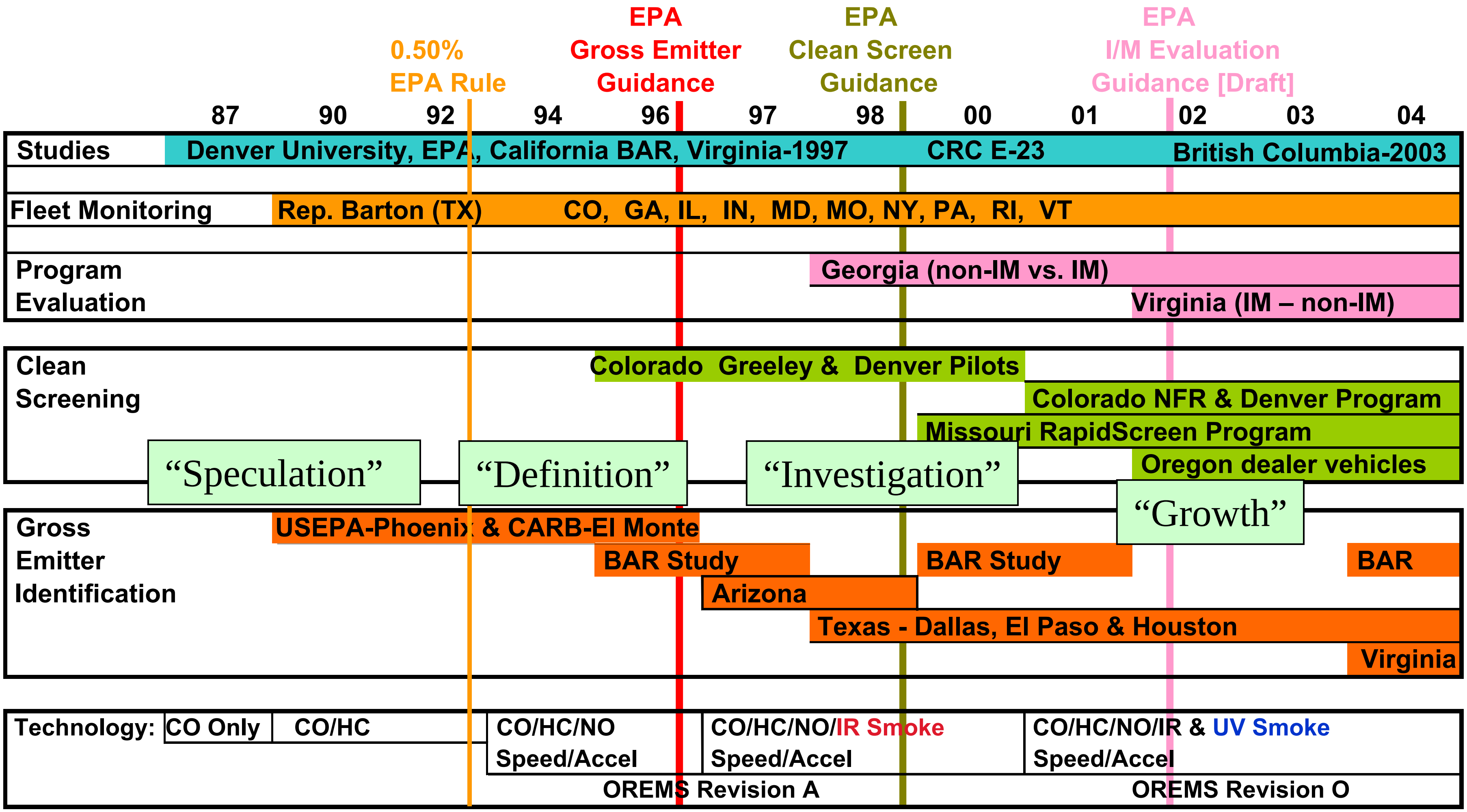
   b. “Ratios to Concentrations”
      a. Simple Explanation - http://www.rsd-remotesensing.com/user_info.asp under RSD for non-technicals.
      b. Derivation Math - http://www.feat.biochem.du.edu/whatsafeat.html under standard combustion equation.

History & Evolution

esp

August 04

History of Remote Sensing (in the USA)



Applications & Regulations

“Guidance Documents”

August 04

USEPA Guidance Documents

1. Gross Emitter Identification – EPA/AA/AMD/EIG/96-01
   a. United States: Texas (since '99), Virginia (July 2004)
   b. International: Taiwan (since 2002)

2. Clean Screening – EPA420-P-98-07
   a. United States: Missouri (since '00), Colorado (since 01)

3. Program Evaluation – EPA420-B-02-001
   1. United States: Georgia (GIT-"developed Reference Method")
      Colorado (UofD-"developed Step Method")
      Virginia (ESP-applied Reference)
      British Columbia (ESP-applied Reference)
   2. International (Fleet Characterization) : Sri Lanka (03), Singapore (since 03), India (since 03).

Technology & Performance

August 04

Performance Summary

What it took to get where we are…for LDGVs.

- Technology (HW & SW) – Done [NH_3, Cold, Unmanned]
- Matching Laboratory Analyzers - Done
- Matching Inspection Results - Done
- Matching Fleet Emissions – Done

What it will take to get where we want to go…for DVs.

1. Technology (HW & SW) – SF Done [NO_2, SO_2 Begun]
2. Matching Laboratory Analyzers - NO done [SF Begun]
3. Matching Inspection Results – NO done [SF Begun]
4. Matching Fleet Emissions - ?

Light Duty Gasoline Measurements

“Demonstrated Performance”

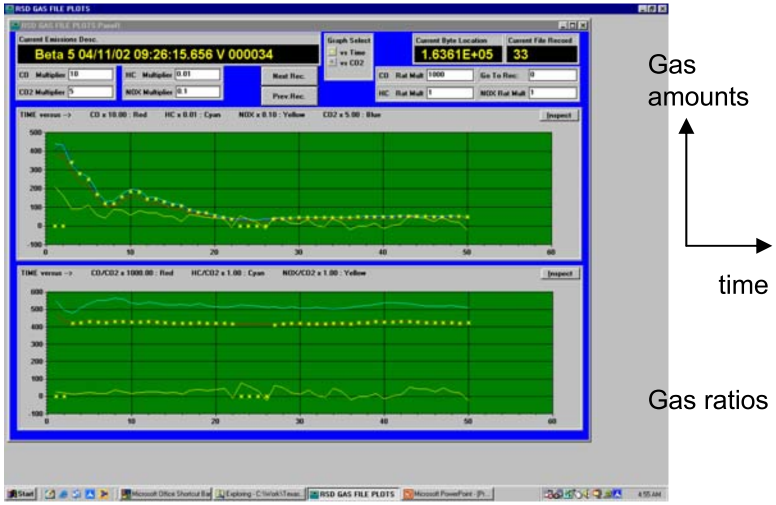
esp

August 04

LD Gasoline Measurement Technology

Today:
- CO, HC, CO_2 - NDIR
- NO - DUV
- S/A System
- Camera (No ALPR)

In Development:
- NH_3 – DUV
- Cold Start Detection
- Unattended


RSD GAS FILE PLOTS

RSD GAS FILE PLOTS Panel

Current Emissions Desc.: Beta 5 04/11/02 09:26:15.656 V 000034

Graph Select: vs Time, vs CO2

Current Byte Location: 1.6361E+05

Current File Record: 33

CO Multiplier: 10

HC Multiplier: 0.01

CO2 Multiplier: 5

NOX Multiplier: 0.1

CO Rat Mult: 1000

Go To Rec: 0

HC Rat Mult: 1

NOX Rat Mult: 1

TIME versus --> CO x 10.00 : Red HC x 0.01 : Cyan NOX x 0.10 : Yellow CO2 x 5.00 : Blue

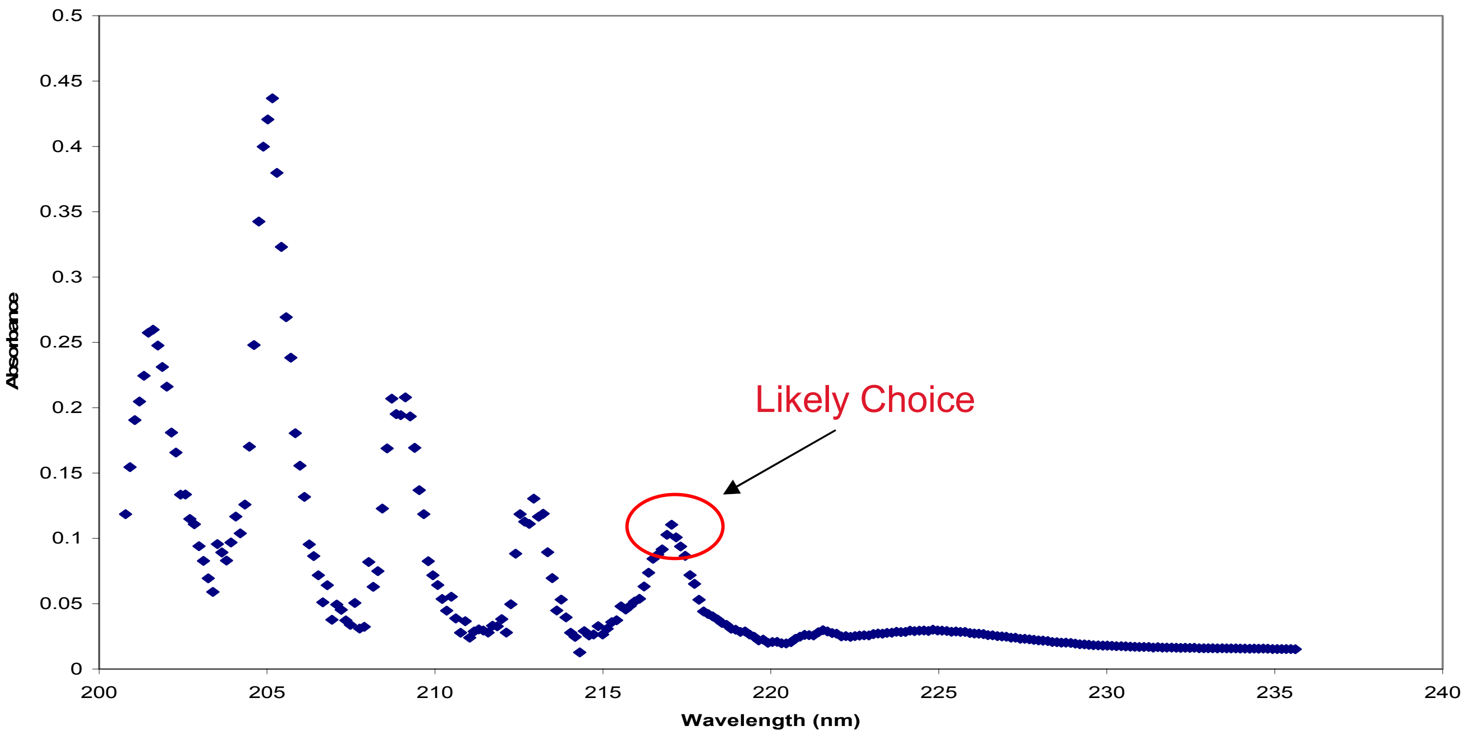
TIME versus --> CO/CO2 x 1000.00 : Red HC/CO2 x 1.00 : Cyan NOX/CO2 x 1.00 : Yellow

Gas amounts

time

Gas ratios

NH_3 Measurement



Likely Choice

- Peaks within UV Spectrometer range
- Detection limits being explored.
- Previously done by Baum using similar technology.

INFRARED THERMAL IMAGING OF AUTOMOBILES:

Identification of Cold Start Vehicles

Angela M. Monateri, Donald H. Stedman, Gary A. Bishop

University of Denver, Department of Chemistry and Biochemistry

2190 E. Iliff Ave., Denver, CO, 80208

Introduction

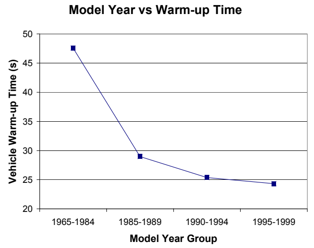
- On-road studies identify cold start vehicles as high emitters, even thought they have no repairable fault. This study investigates the use of thermal infrared imaging to identify vehicles that are high emitting because they are "cold."
- Cold vehicles can be differentiated from hot vehicles by infrared imaging, which can distinguish between:
  - Hot and cold exhaust system metal parts
  - Hot and cold reflections of the underbody of the vehicle from the road surface
  - Tires that have a uniform and bright IR emission identify hot vehicles, contrasting with cold tires, or tires that are non-uniformly hot, mostly due to solar warming.
- A FLIR A20V Infrared Camera was used to look at the infrared image from an automobile.
- The camera was set up with a FEAT 3000 unit to compare emissions vs. the reflected heat to detect if the vehicle was hot or cold.
  - Study at a Denver high school in which the vehicles are known to be cold
  - Parking lot study on vehicle warm up emissions and IR image

Cold Start Emissions

- Vehicles emit higher amounts of CO and hydrocarbons (HC) right after the vehicle has been started because the vehicle is running rich. Extra fuel is added to the combustion chamber in order to ensure ignition. Therefore a vehicle that is cold, with high emissions, has no repairable fault, while a hot vehicle with high emissions does have repairable fault.
- Fuel enrichment causes incomplete combustion and results in increased unburned HC and CO in the exhaust before catalyst light-off.
- As the vehicle's oxygen sensor and catalyst heat up, CO and HC concentrations decrease.

Analysis of CE-CERT FTP Data

- FTP vehicle data with MY 1965-1999 were obtained from Barth, *et al.* 2000.
- This FTP vehicle data were plotted as a function of time versus (CO/CO2). The resulting graph was then used to determine 90% emissions recovery, i.e. the time it took for the vehicle emissions to return from the maximum to within 90%, for each vehicle in the data set. The time was then plotted against the age of the vehicle.
- Based on this data treatment, the average catalyst-light off time was less than 30 seconds.
- Vehicles produced after 1999 would be expected to display even shorter light-off times based on newer technology.



- The above graph is of the FTP data put into five year MY bins, with the exception of 1965-1984, comparing catalyst light-off times vs. MY. These data are in agreement with Younglove, *et al.* 1999, who state that "...light-off times were found to be decreasing with newer model years."

FLIR Thermovision A20V Infrared Camera

- Field of View: 25 °
- Spectral Range: 7.5-13 μm
- Detector: Focal Point Array, Uncooled microbolometer
- Thermal Sensitivity: 90-120 mK at 25° C

References:

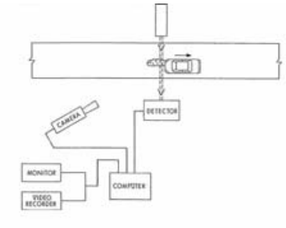
Younglove, T.; Levine, C.; Barth, M. J.;Scora, G.; Norbeck, J. M. In *Analysis of Catalyst Efficiency Differences Observed in an In-Use Light Duty Vehicle Test Fleet*, Proceedings of the CRC, San Diego, CA, April 19-21, 1999.

Barth, M.; AN, F.; Younglove, T.; Scora, G.; Levine,C.; Ross, M.; Wenzel, T. *Development of a Comprehensive Modal Emissions Model.* Final Report NCHRP Project 25-11, April, 2000.

Camera Setup

First the camera is set to a black and white color scale, with white being the hottest color; this is done because it is an intuitive color scheme and is easy for everyone to interpret. The camera is focused, set to the manual mode and is calibrated by holding down the SEL button on the top of the camera. This is done while aiming the camera at a known hot vehicle with the road surface in the FOV. For this setting we ensure that the hot exhaust system or underbody of the vehicle cannot be seen. The temperature scale is adjusted by changing the level and span scale on the camera in order to see small changes in reflected energy off the road surface. The level and scan can be likened to brightness and contrast respectively, which sets the scale of reflected energy between which the camera recognizes. While the above guidelines are specific to the FLIR A20V, other types of camera's should be set up similarly.

On-Road Setup with FEAT 3000 Unit



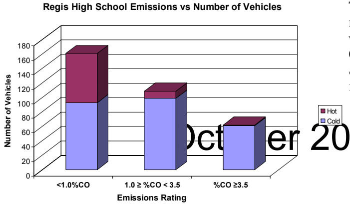
Regis H.S. Parking lot Study Dec. 2003

Regis High School

- An underclassmen parking lot, in which most of the vehicles had been sitting since the morning had been chosen.
- FEAT 3000 unit was set up across parking lot access road to measure the emissions of vehicles entering and leaving the lot. Most of the vehicle entering the lot should be hot, while those leaving the lot should be cold.
- 332 vehicles were measured on two consecutive days.

Analysis of Data

- Emissions data from the FEAT 3000 unit is extracted from computer, and the invalid vehicles removed.
- The video tape of recorded IR images are watched, and it is decided if the vehicle is hot or cold based on heat signatures that are emitted and reflected from the vehicle.
  - Bright reflections off road surface
  - Very hot tailpipes
  - Uniform heat emitted from tire treads.
- The vehicle is noted as either hot or cold in a spreadsheet.



This graph shows the number of vehicles that received a GOOD, FAIR, or POOR rating, as well as if the vehicle was a cold or hot vehicle. Only one vehicle received both a POOR rating and was a hot vehicle from both days of measuring vehicles at the high school.

	<1.0%CO	1.0 ≥ %CO < 3.5	%CO ≥3.5
Cold	93	99	61
Hot	68	10	1
Percent	48.5	32.8	18.7

Time: 09:29.16

%CO: 2.83

Time: 09:31.39

%CO: 2.07

Time: 09:34.27

%CO: 0.14

Time: 09:35.41

%CO: 0.19

- One vehicle from cold start to beyond catalyst light-off time. CO emissions are from 2.87% at cold start to 0.19% after warming up. Emissions of CO decrease with rising exhaust temperatures. In little over 5 minutes, this 1986 Chevy Celebrity (Blue) has warmed up enough to control its emissions.

Snow on Road Surfaces

- Snow is a mostly absorbing surface in the infrared, however liquid water is very reflective in the infrared.
- Breckenridge Ski Area patrol SUV had very little reflection on the snow covered parking lot surface.
- Tire treads are also cooled in the snow, and therefore are not emitting higher IR and appear to be cold, even if the vehicle had been driving around.

- Both of the vehicles in the IR images above are hot, however because snow does not reflect IR radiation, there is no reflection on the road from the underbody of the vehicles.

Conclusions

- An infrared camera can be used to differentiate between hot and cold cars on the road based on the thermal reflection that radiates from the underbody of automobiles.
- Cold cars will have the same IR reflection as the road, or only a slightly "brighter" reflection than the road. Hot vehicles will have a very intense, bright reflection off the road surface.
- When combined with a FEAT unit, vehicles can be correctly identified as gross emitters of pollution. Cold vehicles will be higher emitters, and previous to incorporating an infrared camera with a FEAT unit, these vehicles would be given a POOR rating.
- Snow is not a good surface for observing infrared images of vehicles because it is not very reflective, and also cools tires so that the heat being emitted from the tires cannot be seen in the IR.

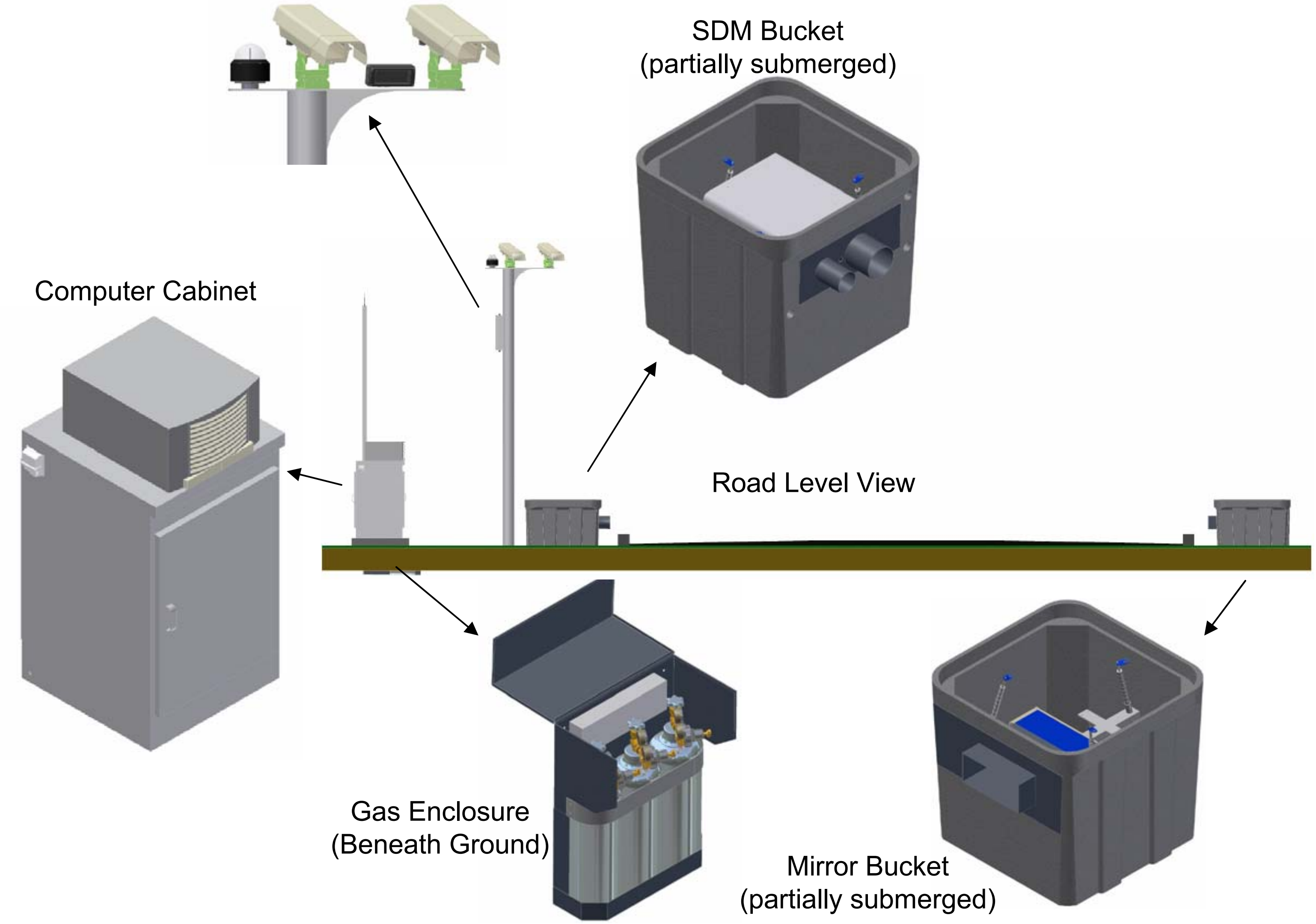
Future Work

- Using the IR camera determine hot and cold vehicle signatures on hot road surfaces. (Las Vegas, May 2004)
- Software still need to be written in order to incorporate the infrared camera with the visual camera and the FEAT.

UNIVERSITY OF DENVER

Unmanned Concept

”2002”



ALPR & RSD Cameras

SDM Bucket
(partially submerged)

Computer Cabinet

Road Level View

Gas Enclosure
(Beneath Ground)

Mirror Bucket
(partially submerged)

Unmanned Alpha Test Site - Tucson

”2004”

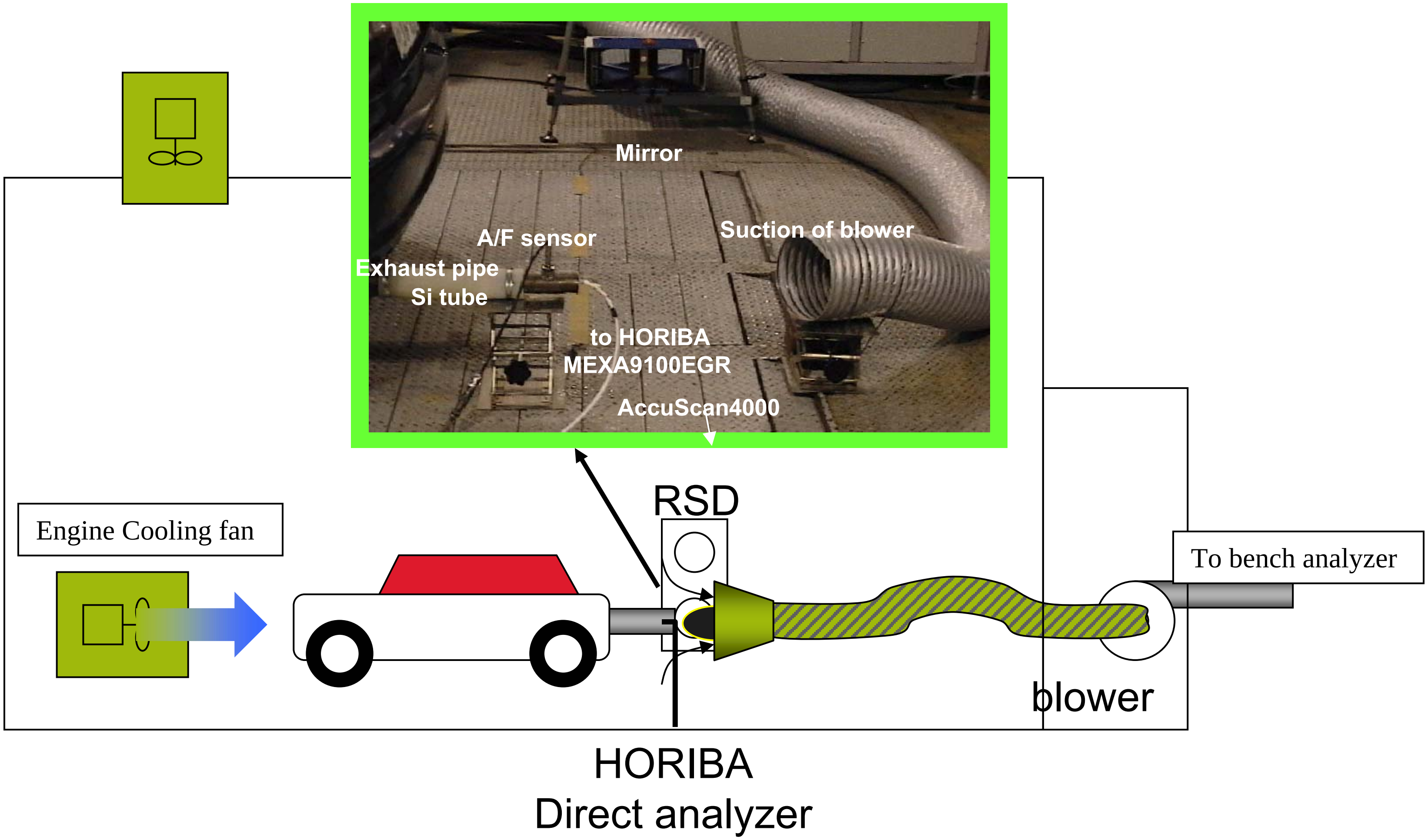
Matching Laboratory Analyzers

Gasoline Vehicles

August 04

Correlation Test Setup

Japan Petroleum Energy Center – February 2003



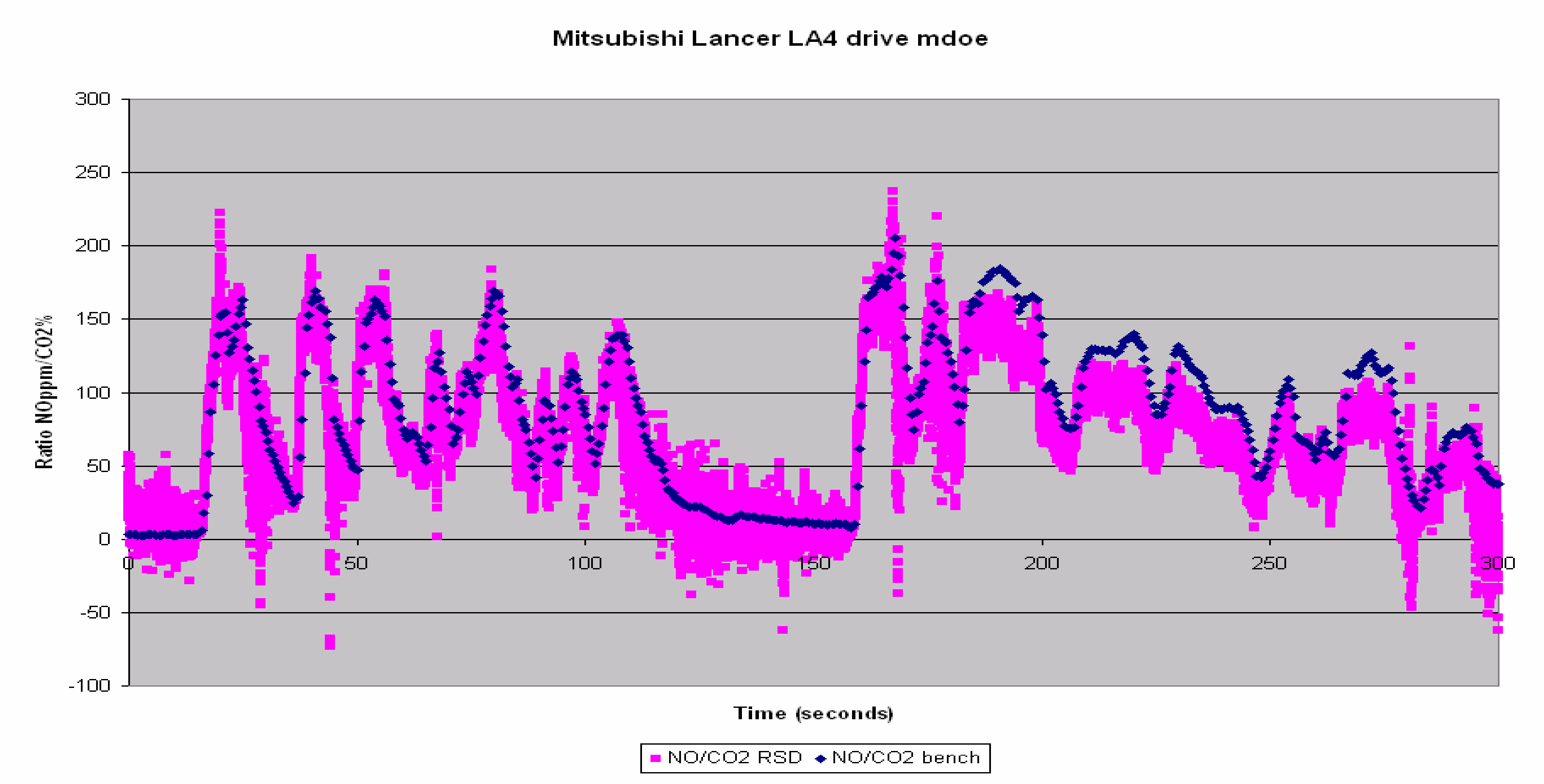
Correlation Test Method

- Several different drive modes were utilized to test the effectiveness of the RSD.
  - LA4 drive mode
  - Steady state drive modes (60,40,20kph)

- Horiba bench analyzers were compared to RSD.
  - Comparisons between the Horiba bench analyzers and the RSD unit were the gas ratios and their mean values.
    - CO/CO2, HC/CO2, NO/CO2

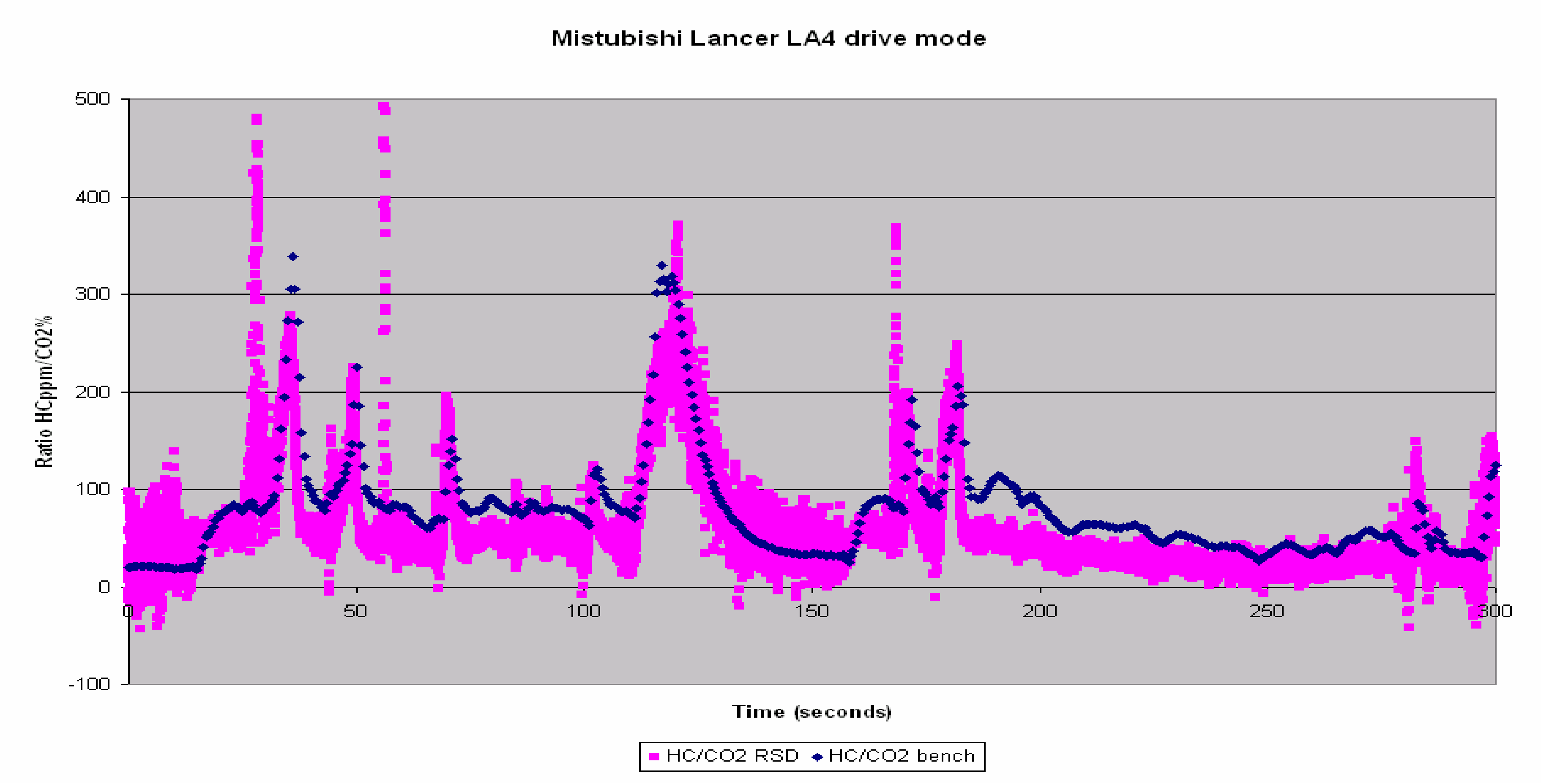
Correlation Test Results

Mitsubishi Lancer



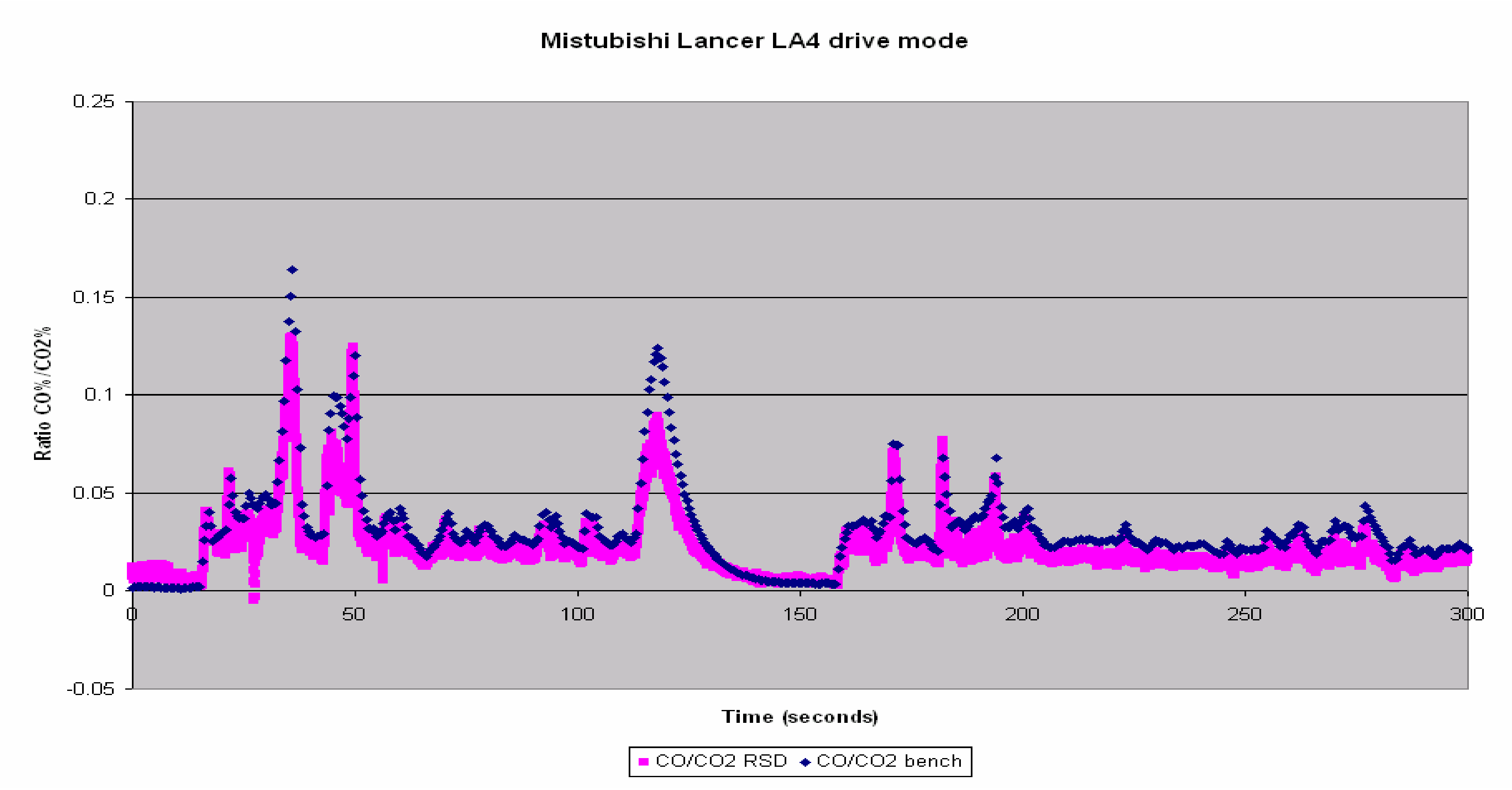
Correlation Test Results

Mitsubishi Lancer



Correlation Test Results

Mitsubishi Lancer



Correlation Result

Mean ratio comparison

Mean difference = RSD mean ratio – Bench mean ratio

- Mitsubishi Lancer
  - Mean diff CO%/CO2%
    - -0.022% CO per percent CO2
  - Mean diff HCppm/CO2%
    - -10.3 ppm HC per percent CO2
  - Mean diff NOppm/CO2%
    - -29.2 ppm NO per percent CO2

Conclusion

JCAP

- Good correlation between the Horiba bench gas analyzers and the ESP AccuScan4000 (near stoichiometric operation).
  - Accurate tracking of transient events.
  - Good mean gas ratio comparison.

Back to Performance Summary

Matching Inspection Results

Gasoline Vehicles

August 04

Clean Screening

Missouri

Gateway
Clean Air
Program

1. Started in St. Louis in April 2000
2. Designed with IM240
3. ~ 5M measurements annually
    - 5 RSD-3000s (2 shifts – total 14 hours/day)
4. 2 clean in-cycle measurements → CS
    - Cutpoints: 0.5%CO, 200ppmHC, 1500ppmNOx
5. ~ 150k exemption notices annually
6. 20 to 25% of initial inspections
7. Performance measured by 2% random audit
    - Amount of Excess Emissions False Passes represent.

Definition of Excess Tailpipe Emissions

Measured Emissions

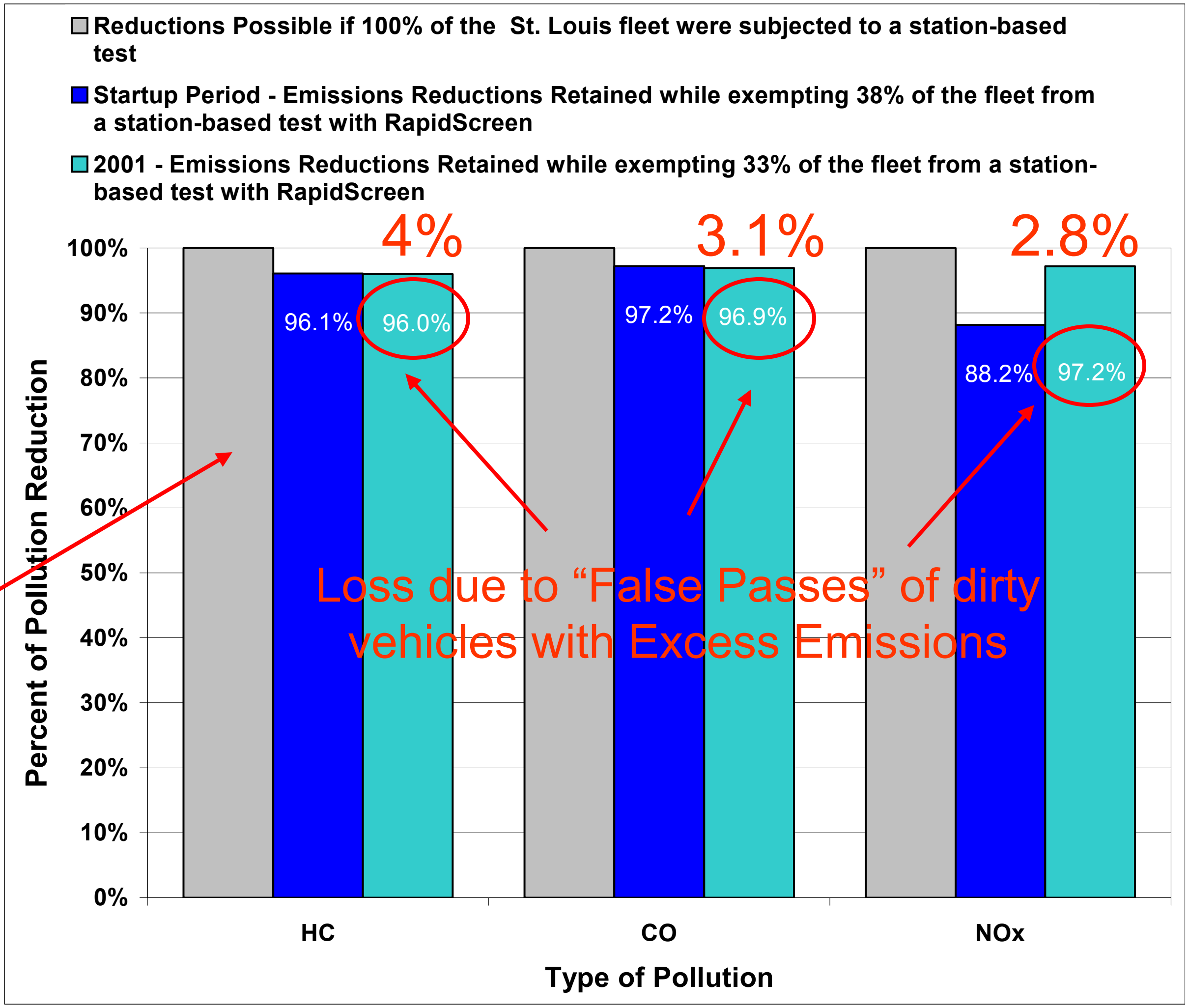
Excess Tailpipe Emissions

Emission Standard

Identifying Clean Vehicles – Results

“Loss of Excess Emissions”

Missouri Department of Natural Resources



4%

3.1%

2.8%

Loss due to “False Passes” of dirty vehicles with Excess Emissions

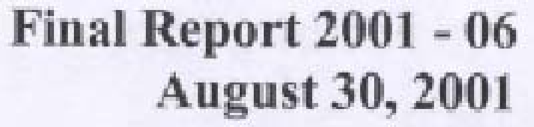
Perfect Inspection - 100% of Excess Emissions Identified

Gross Emitter Identification

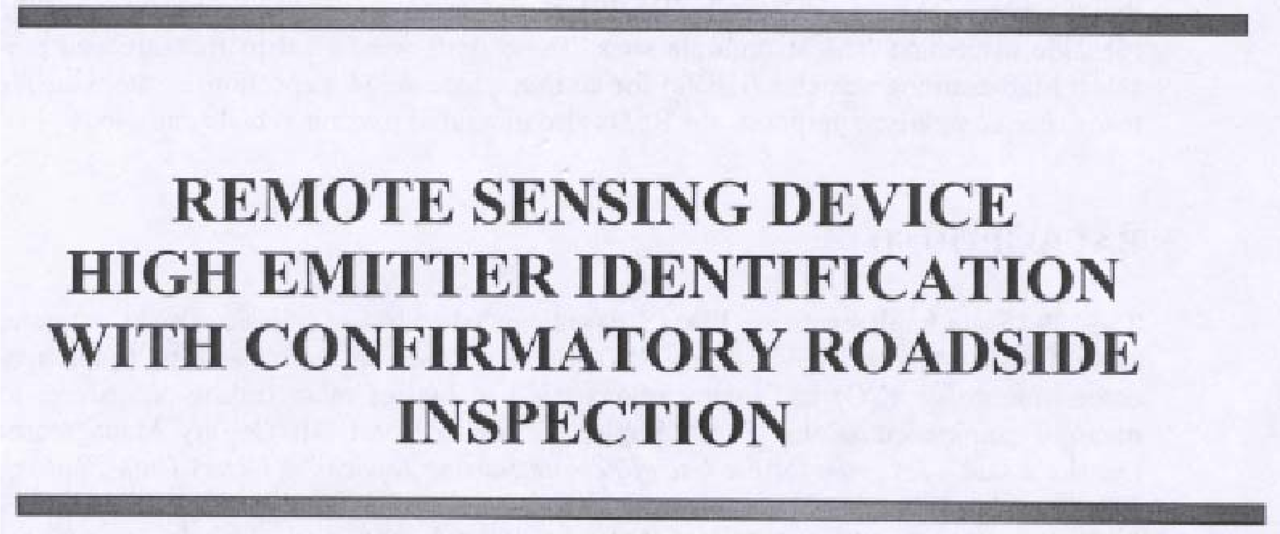
Gasoline Vehicles

BAR Pullover Study

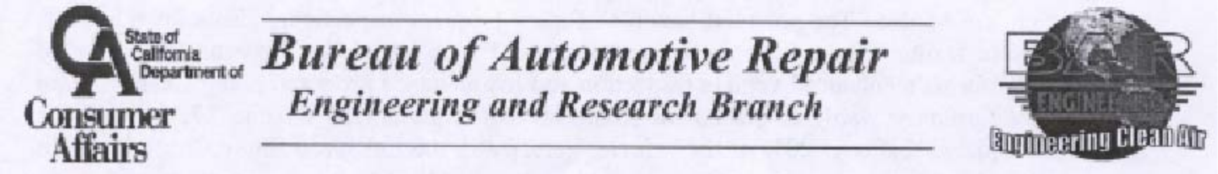
LD Gasoline Vehicles



Final Report 2001 - 06
August 30, 2001



REMOTE SENSING DEVICE
HIGH EMITTER IDENTIFICATION
WITH CONFIRMATORY ROADSIDE
INSPECTION



State of California Department of Consumer Affairs

Bureau of Automotive Repair
Engineering and Research Branch

BAR Engineering Clean Air

BAR Pullover Study

LD Gasoline Vehicles

Upstream Dual RSD Screen:

Dual Stedman FEATs 3005 & 3006

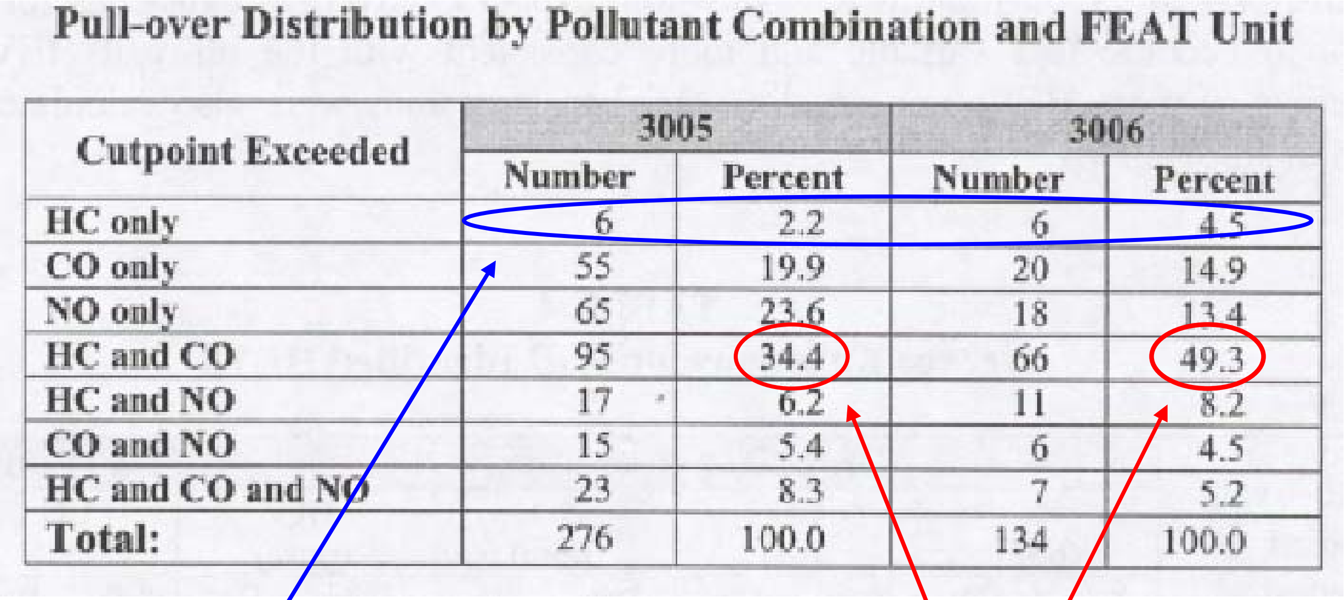
Vehicles exceeding 1% CO, 500ppm HC, 500ppm NO on either RSD

Downstream Roadside ASM:

BAR Pullover Study

Results

Sample: 326 had at least 1 RSD & and an ASM test



Pull-over Distribution by Pollutant Combination and FEAT Unit

Cutpoint Exceeded	3005		3006	
	Number	Percent	Number	Percent
HC only	6	2.2	6	4.5
CO only	55	19.9	20	14.9
NO only	65	23.6	18	13.4
HC and CO	95	34.4	66	49.3
HC and NO	17	6.2	11	8.2
CO and NO	15	5.4	6	4.5
HC and CO and NO	23	8.3	7	5.2
Total:	276	100.0	134	100.0

Implication: Perhaps HC channel can be excluded.

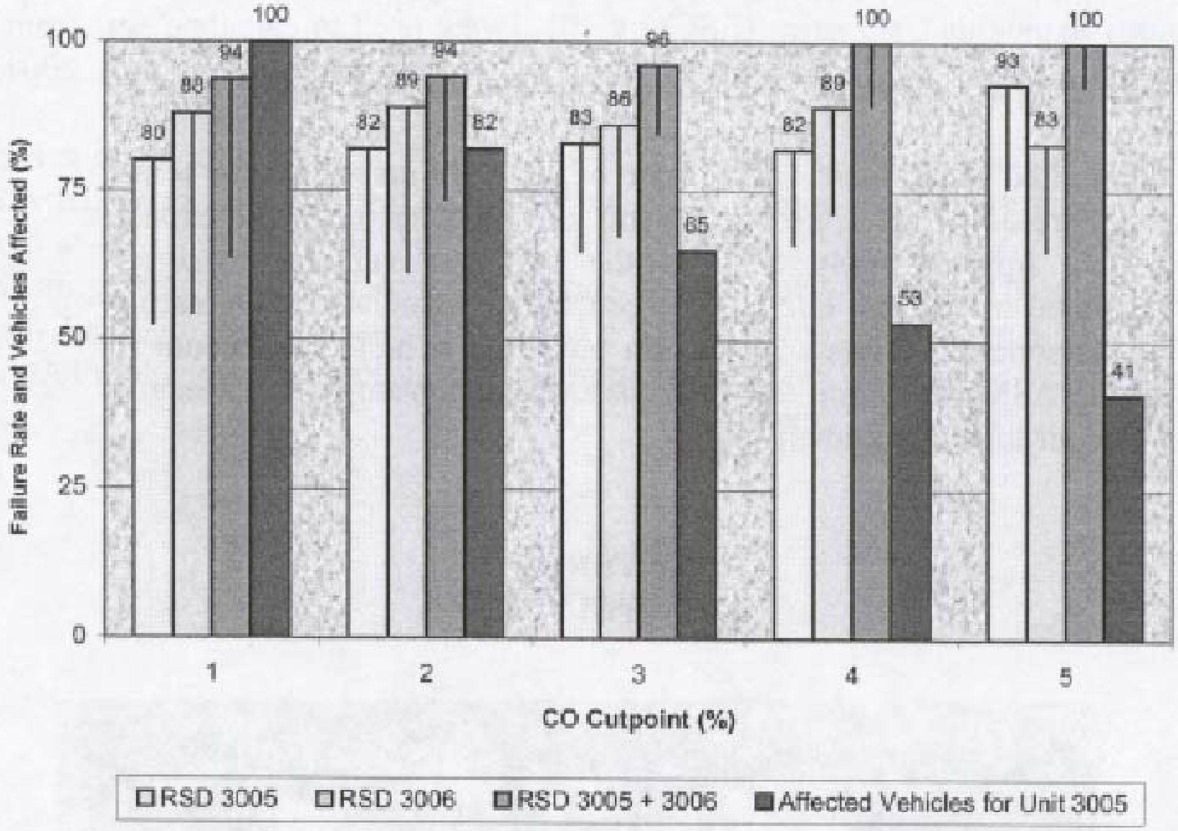
Implication: Maybe together they are better that either alone.

BAR Pullover Study

CO Results

FIGURE 4

ASM Inspection Failure Rate for RSD Identified CO HEVs



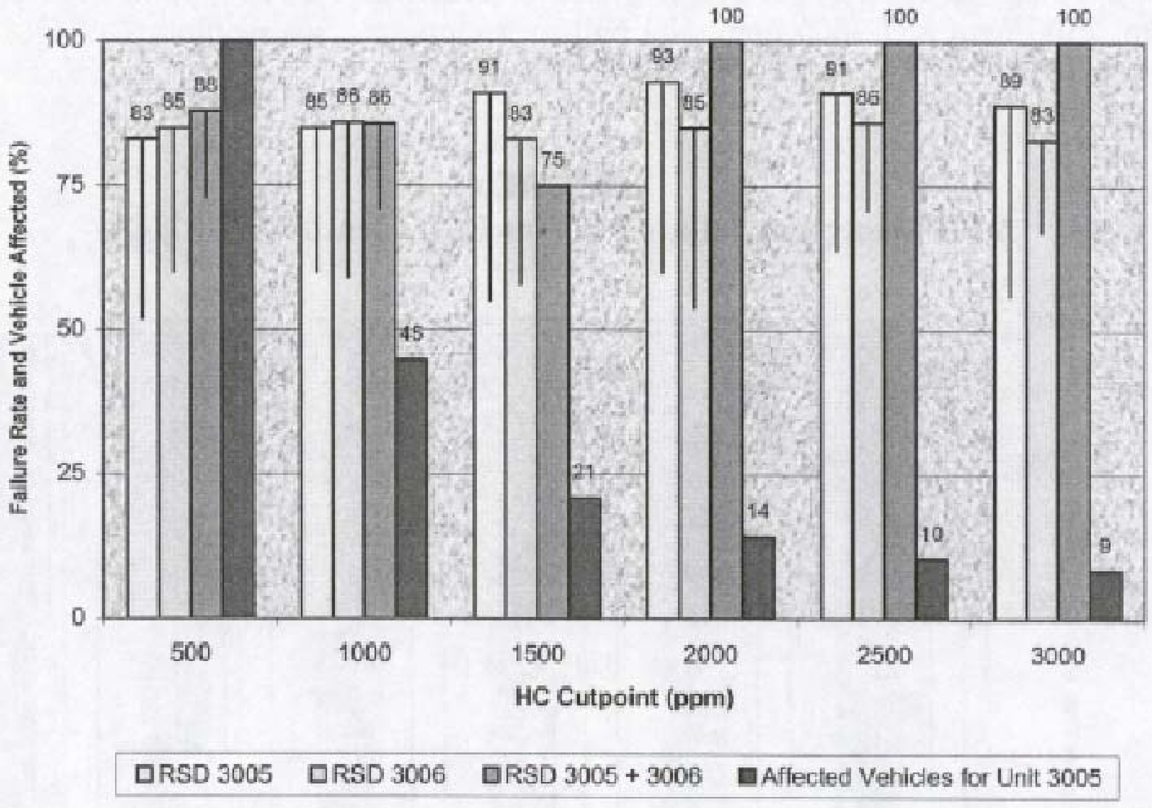
Note: Lines within bars indicate the portion of the ASM inspection failure rate due to other than CO failure.

BAR Pullover Study

HC Results

FIGURE 5

ASM Inspection Failure Rate for RSD Identified HC HEVs

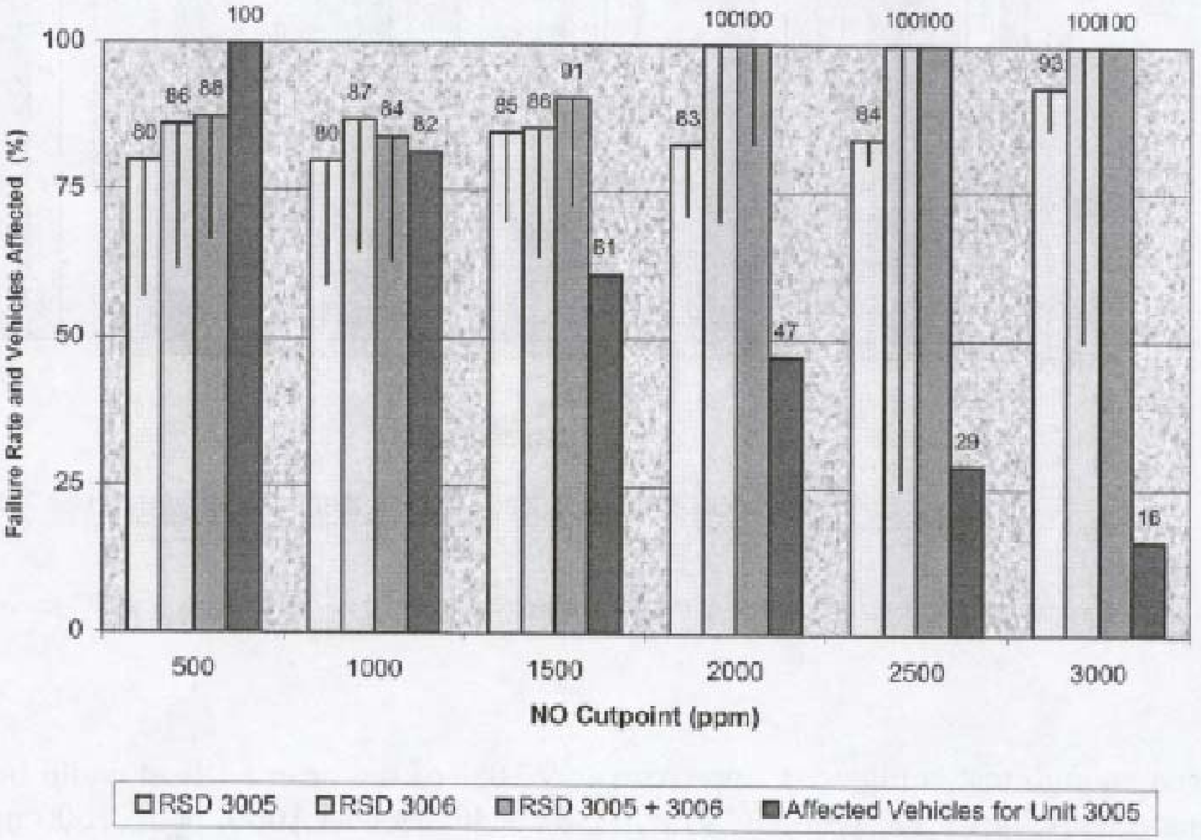


Note: Lines within bars indicate the portion of the ASM inspection failure rate due to other than HC failure.

BAR Pullover Study

NO Results

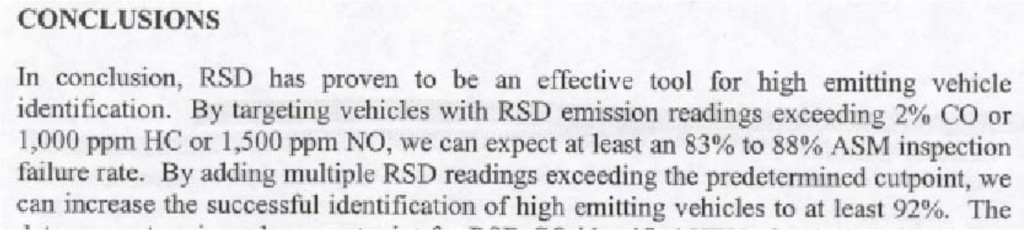
FIGURE 6
ASM Inspection Failure Rate for RSD Identified NO HEVs



Note: Lines within bars indicate the portion of the ASM inspection failure rate due to other than NO failure.

BAR Pullover Study

Conclusions



CONCLUSIONS

In conclusion, RSD has proven to be an effective tool for high emitting vehicle identification. By targeting vehicles with RSD emission readings exceeding 2% CO or 1,000 ppm HC or 1,500 ppm NO, we can expect at least an 83% to 88% ASM inspection failure rate. By adding multiple RSD readings exceeding the predetermined cutpoint, we can increase the successful identification of high emitting vehicles to at least 92%. The

- Cutpoints: 2% CO, 1000ppm HC, 1500ppm NO
- 83% - 88% ASM Failure (1 RSD Observations)
- 92% ASM Failure (2 RSD Observations)

Identifying High Emitters – Results

"False Failure Rate"

1. California RSD pull-over study results reported:
   a. 1989 Lynwood:
      i. 86% of vehicles with RSD >2% CO failed roadside inspection
   b. SCAQMD 1996:
      i. 95% of vehicles with RSD >4% CO or 1,000 ppm HC failed IM240
   c. BAR 2001:
      i. 83-88% of vehicles with RSD >2% CO or 1000ppm HC or 1,500 ppm NOx failed ASM

Back to Performance Summary

Matching Fleet Emissions

LD Gasoline Vehicles

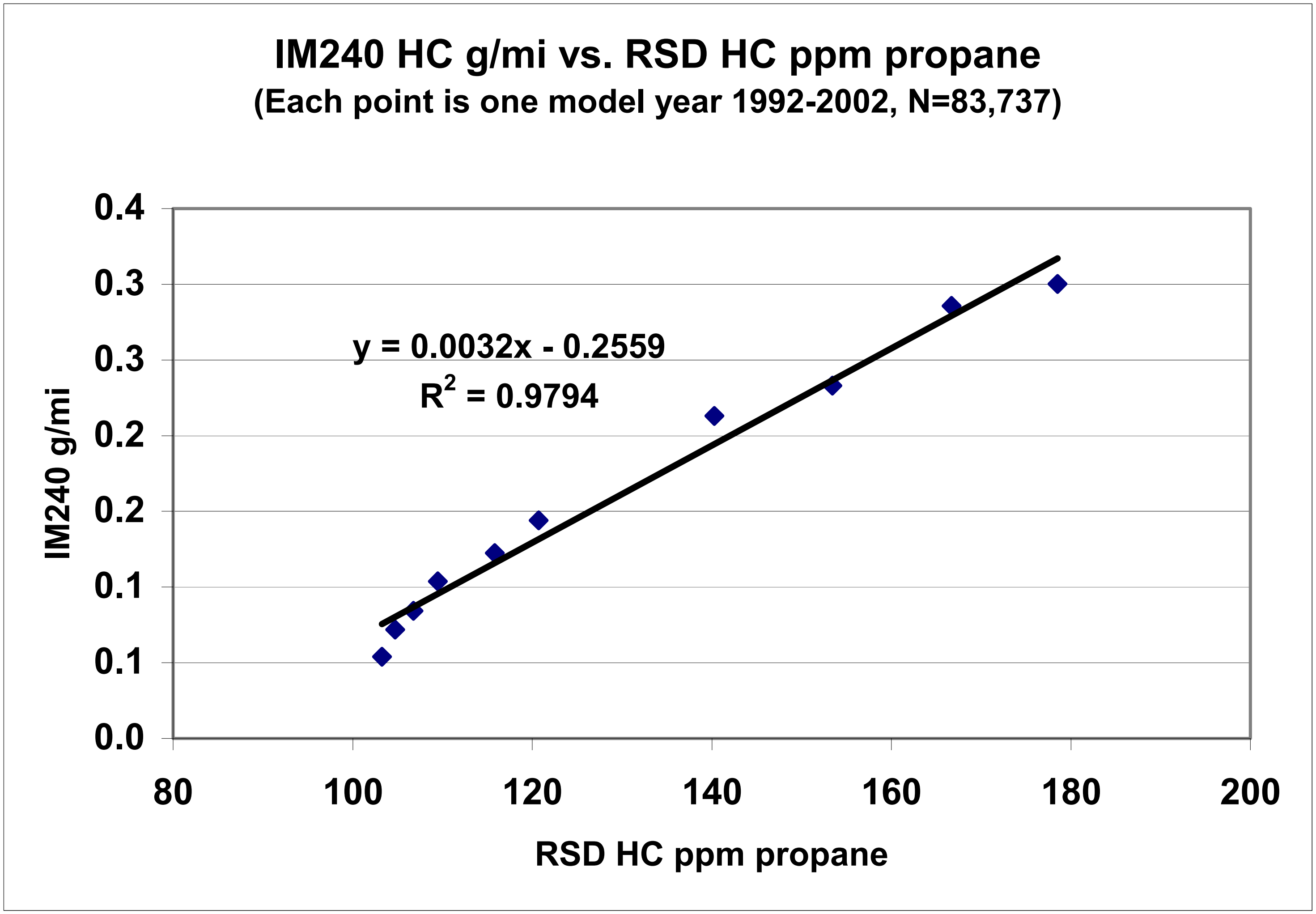
August 04

Correlation With IM240 Tests

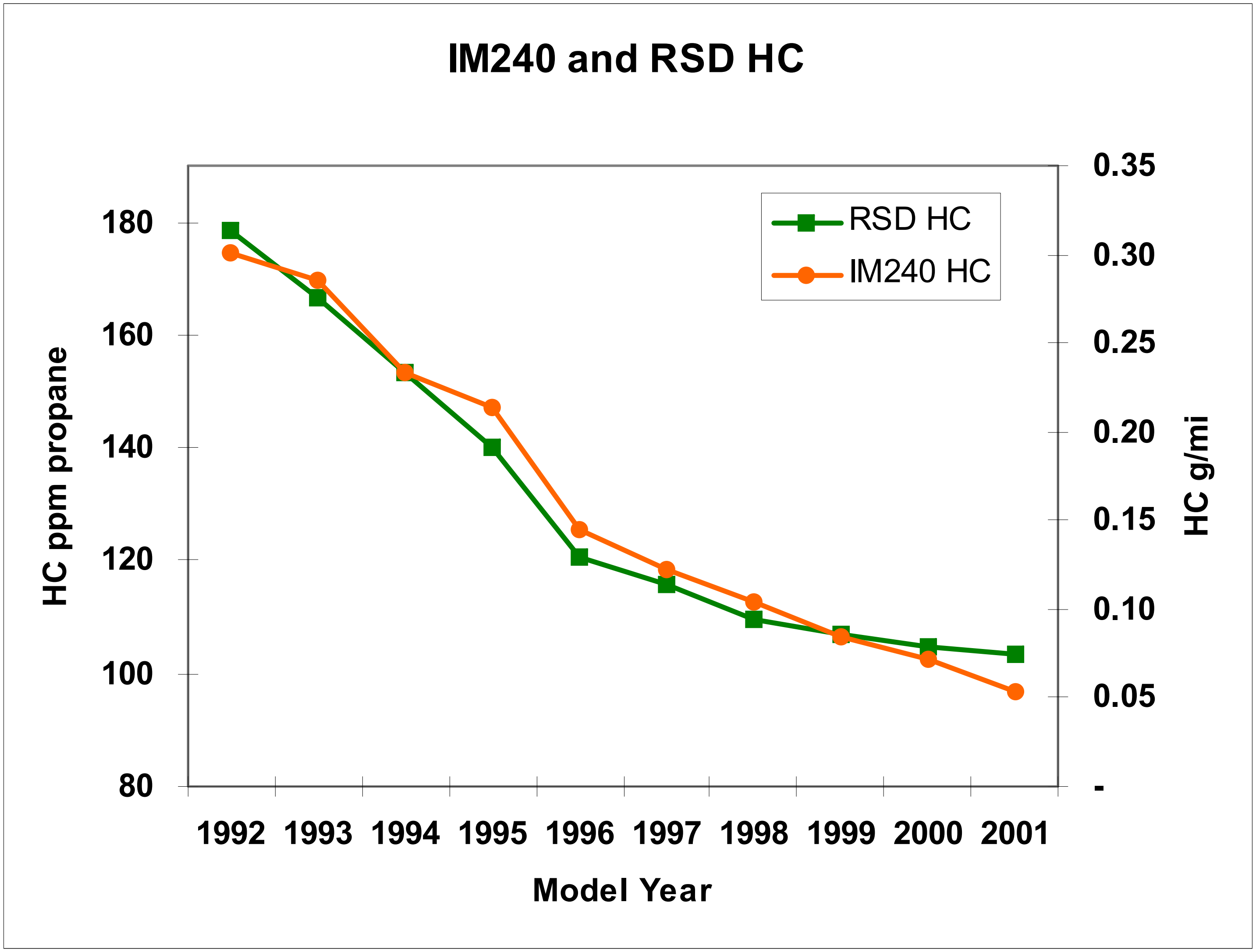
Vancouver Fleet Characterization

- 150,000 valids RSD readings
- RSD mostly after IM240 tests
- Average emissions by model year
- 1992 – 2001 models
- Model year average correlation, R^2:
  - CO 0.96
  - HC 0.98
  - NOx 0.99
- RSD HC readings biased high (software)

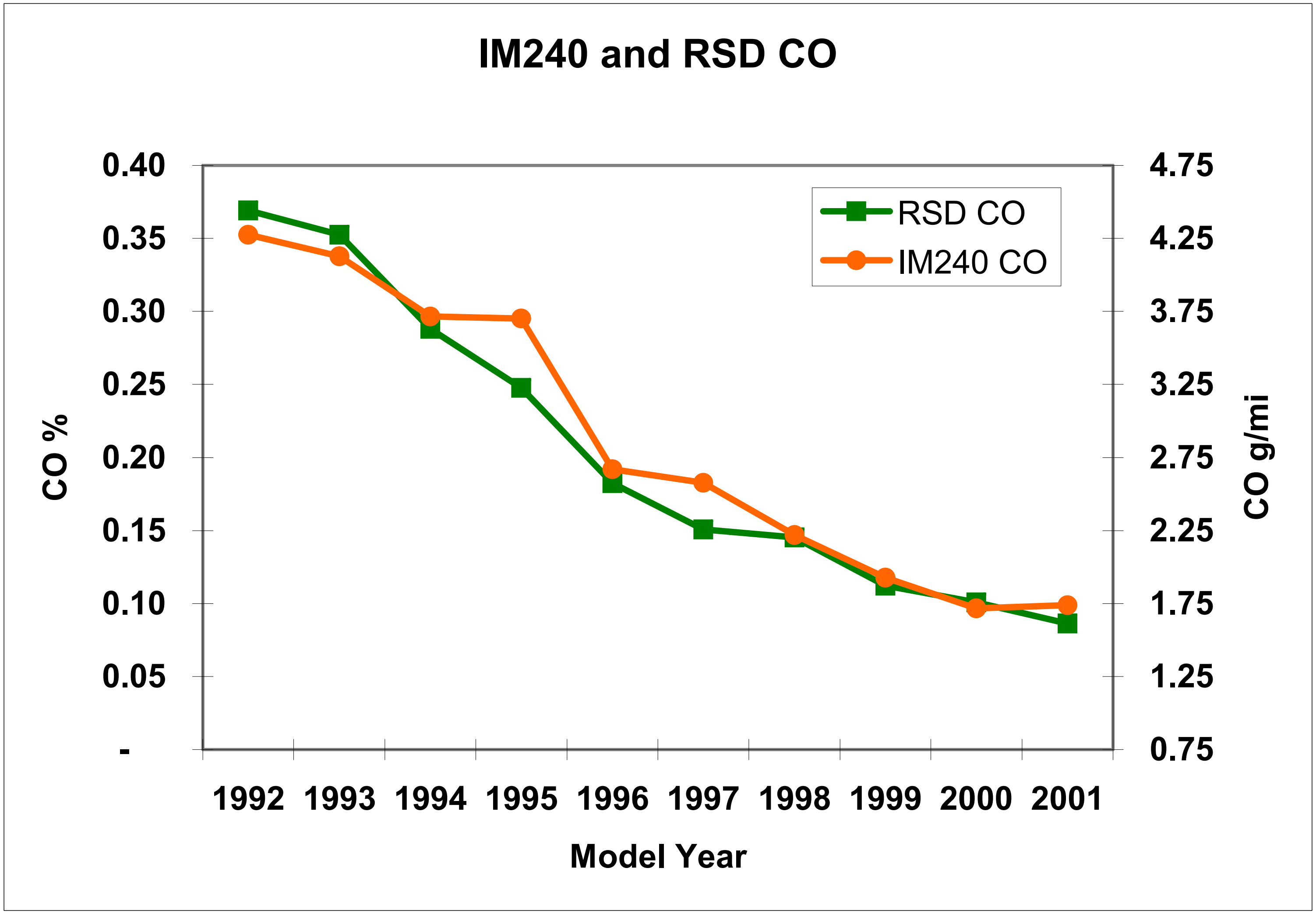
RSD vs. I/M 240 - HC



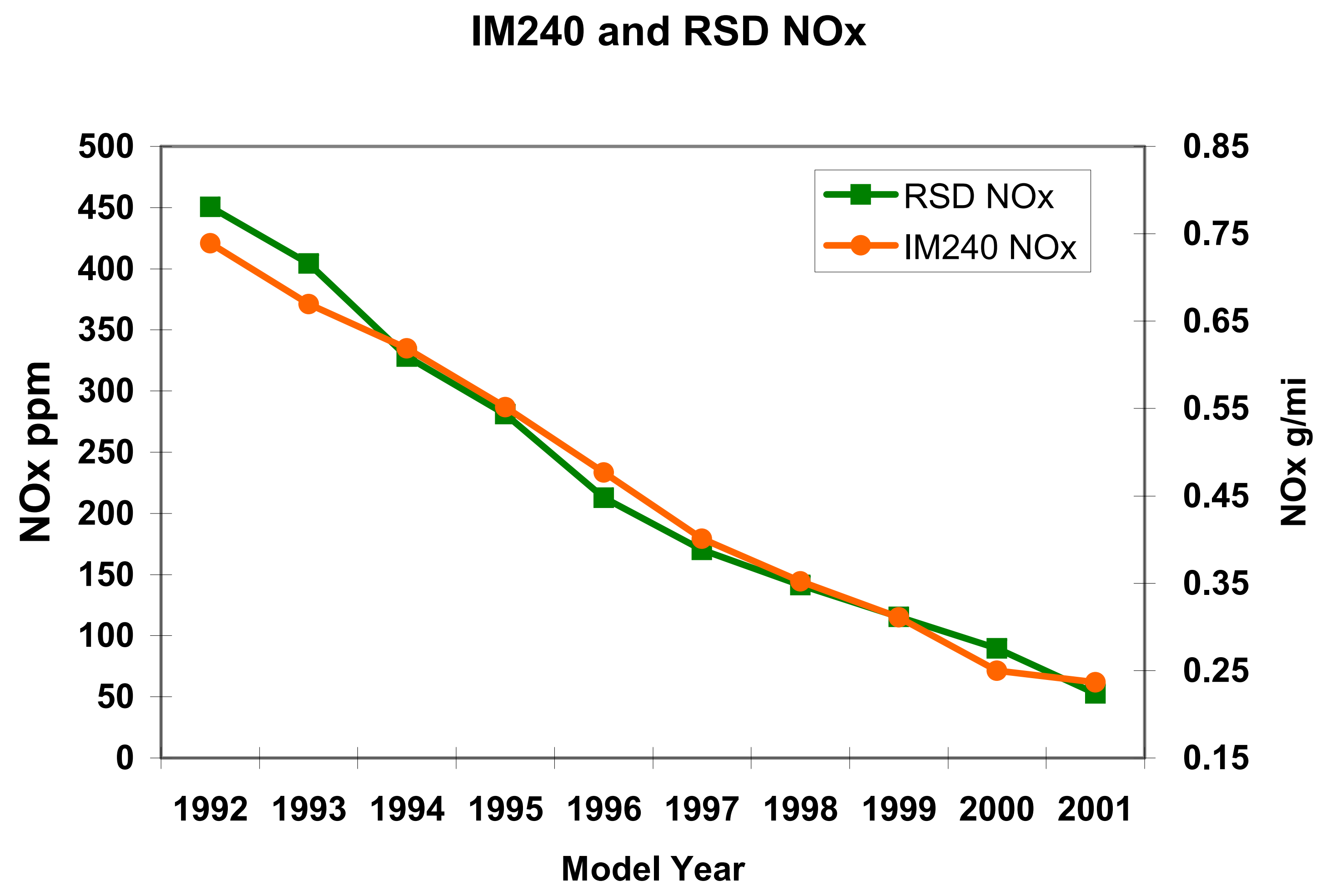
RSD and I/M 240 - HC



RSD and I/M 240 - CO



RSD and I/M 240 - NOx



Getting the Emissions Picture N=1,000

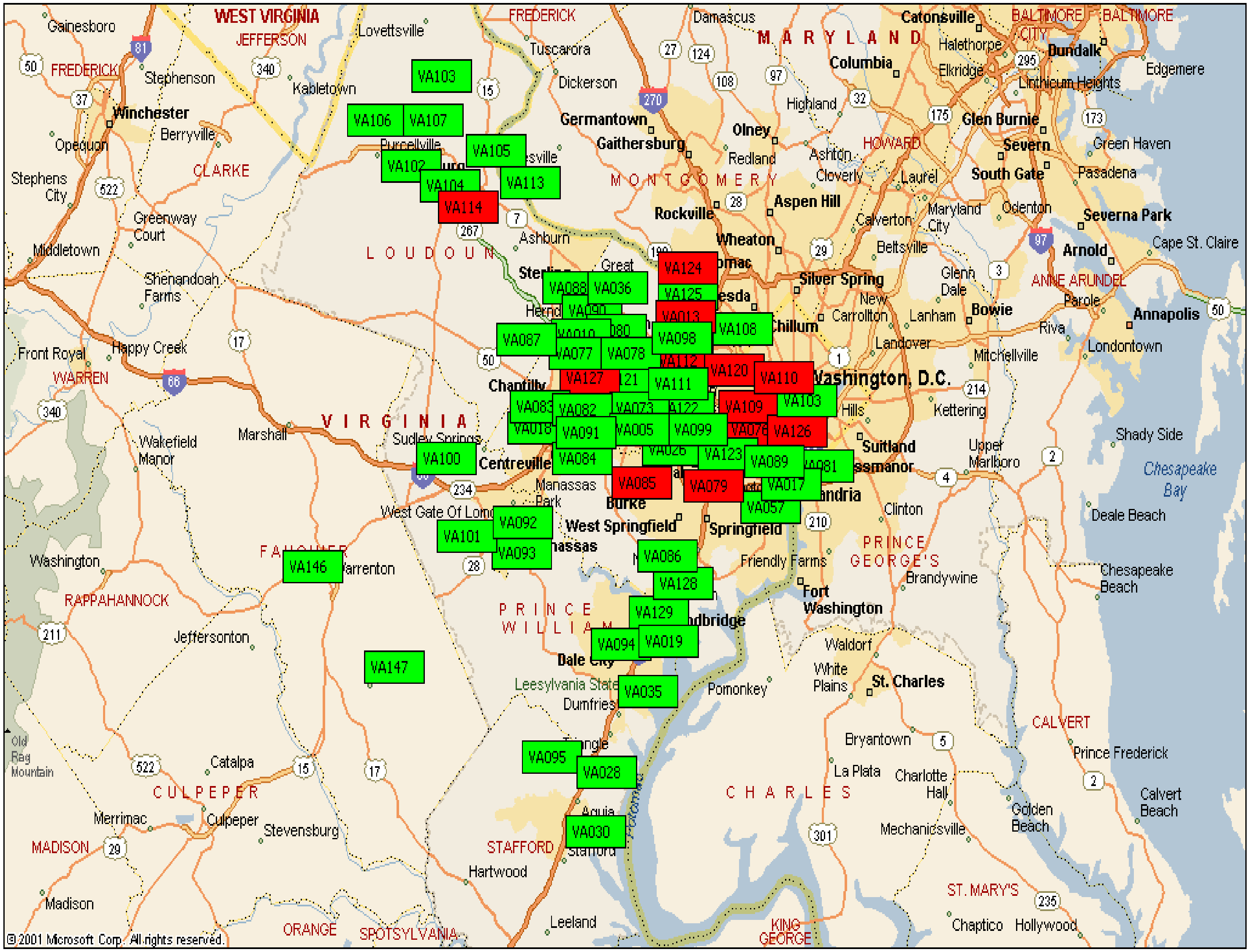
Getting the Emissions Picture N=10,000

Getting the Emissions Picture N=100,000

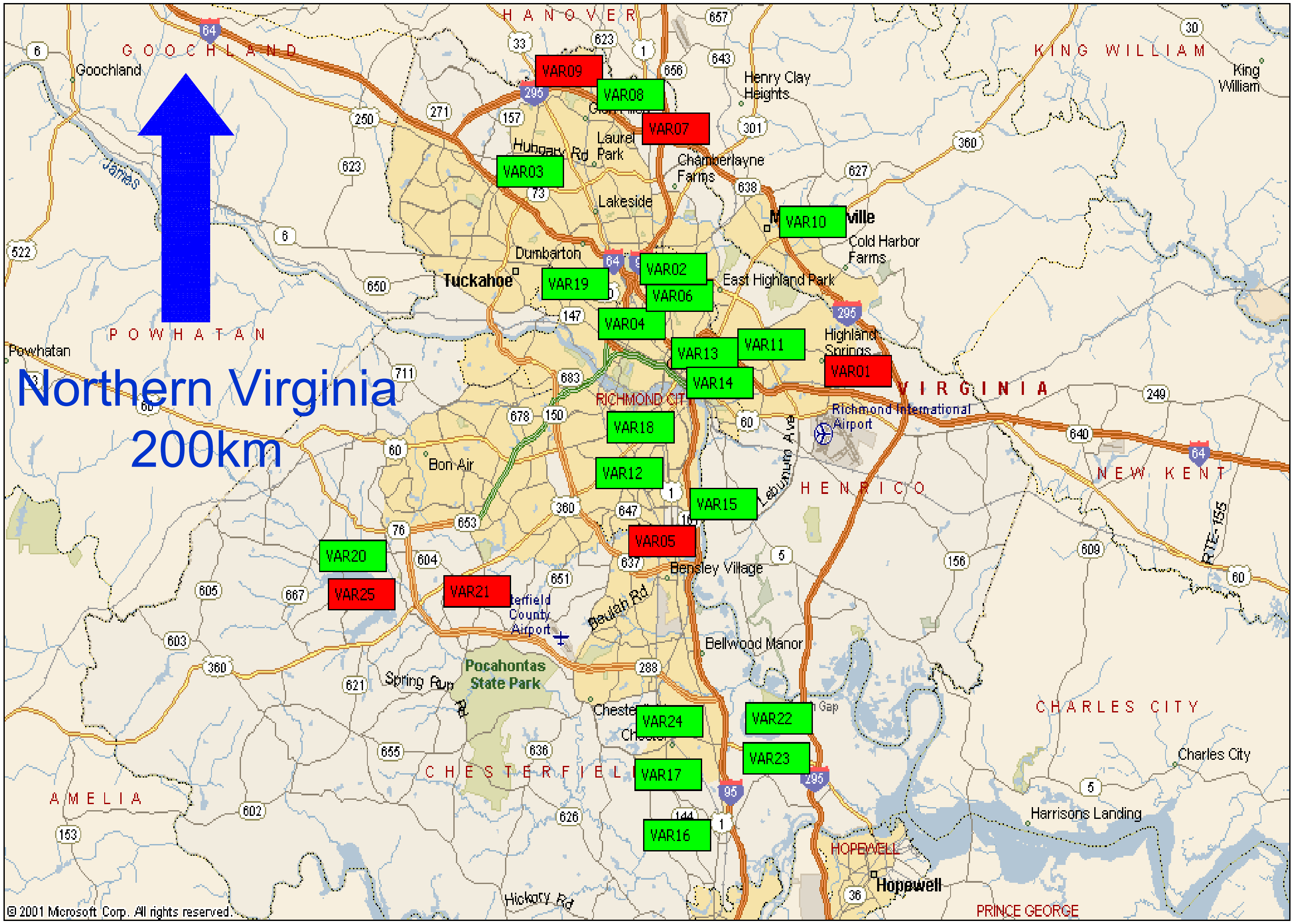
Vehicle Emissions Picture N=1,000,000

Northern Virginia I/M Area Sites

“Metro DC”



Richmond non-I/M Area Sites



Collection Summary

	Measured in I/M Program Area	Measured in Non-I/M Area*	Out of State	Total
Total Number of RSD Units Vans Utilized				2
Total Number of Sites Utilized	59	23	N/A	82
Total Number of Data Collection-Days Readings Taken	193	58	N/A	251
Total Number of Readings Taken	844,740	215,726	N/A	1,060,466
Total Number of Valid Readings Taken	466,125	140,760	73,756	680,641
Total Number of Readings With Readable License Plates	624,050	183,241	97,554	904,845
Total Number of Readings With LPs Not-in-picture, obscured or unreadable	220,690	32,485	N/A	253,175
Total Number of Unique Vehicles Identified	393,172	128,941	75,354	597,467
Total Number of Vehicles Identified Once	252,224	90,905	58,636	401,765
Total Number of Vehicles Identified Twice	87,153	27,199	12,740	127,092
Total Number of Vehicles Identified Three Times	31,420	7,299	2,705	41,424
Total Number of Vehicles Identified Four or More Times	22,375	3,538	1,273	27,186
Total VA Registered Fleet*	1,717,437	928,477	N/A	
% of registered fleet measured	23%	14%		

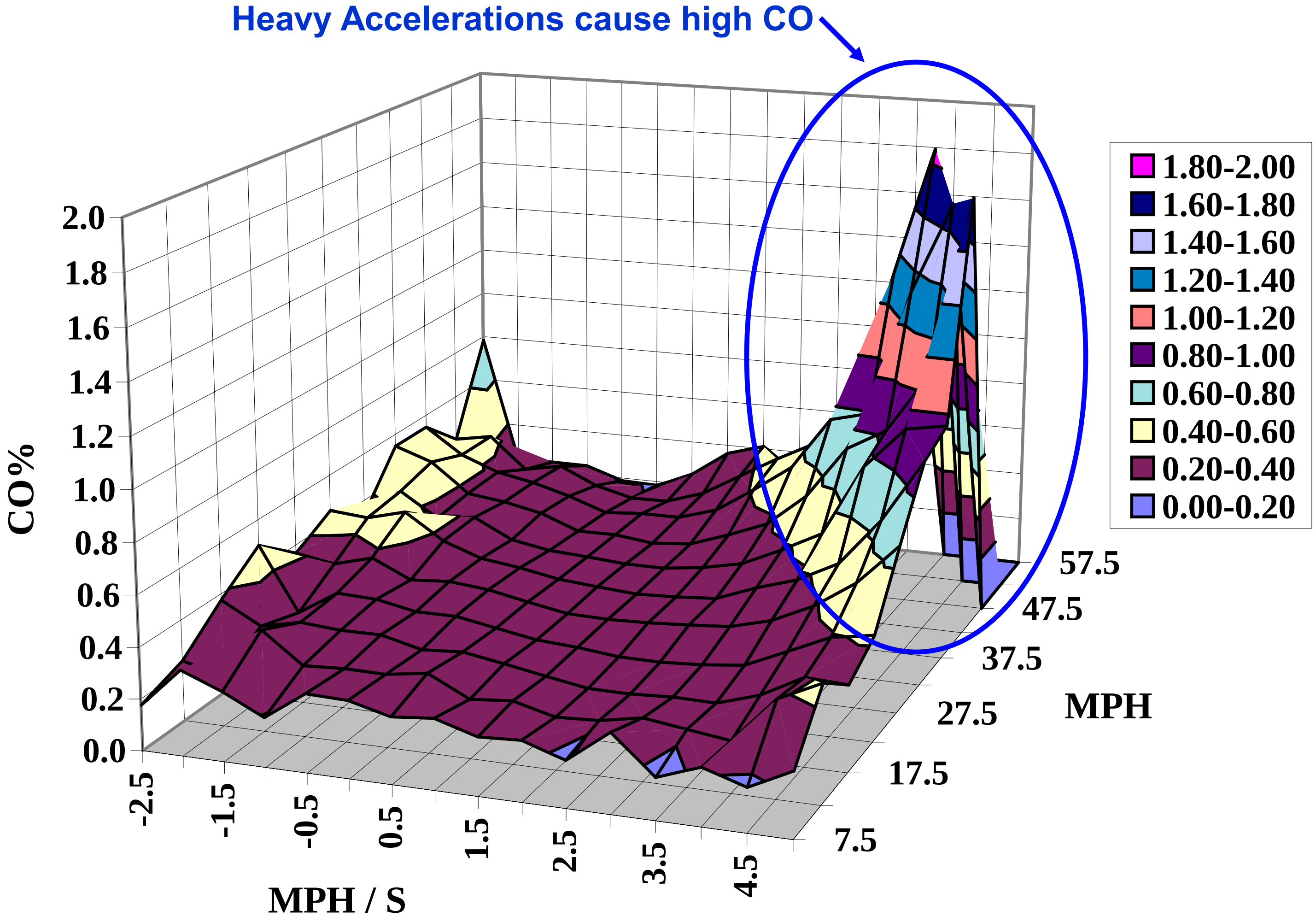
* Registrations for Non-I/M Area Counties in Study

Data Screening

Vehicle, System, Operator, Driver

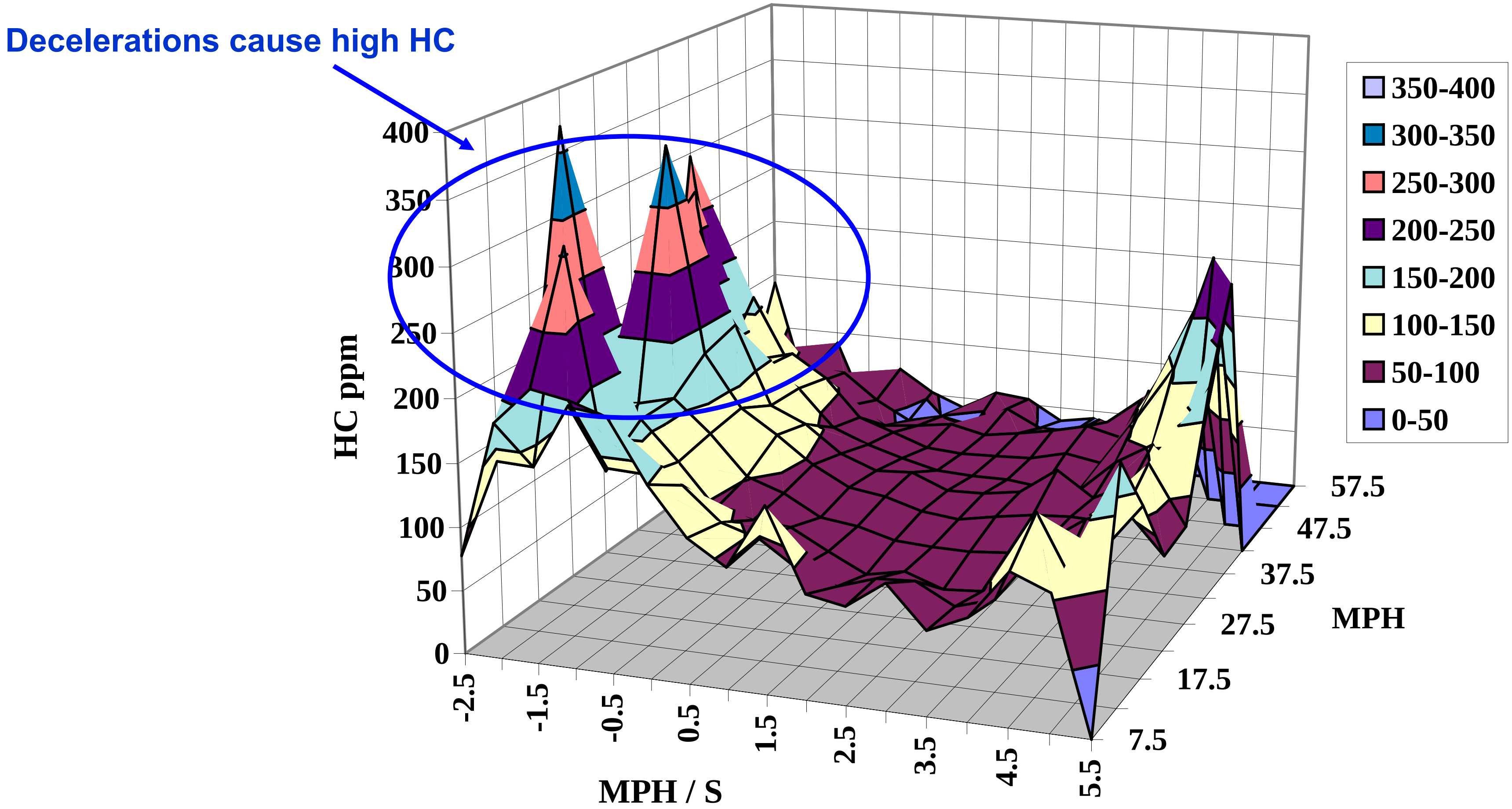
1. Screening of exhaust plumes (4000 software criteria)
    a. Software invalidates small, uncharacteristic plumes
2. Screening of hourly observations to check for cold starts
3. Screening of high values
4. Screening of day-to-day variations in emissions values
5. Screening for Vehicle Specific Power (VSP) range

CO % vs. Speed & Acceleration



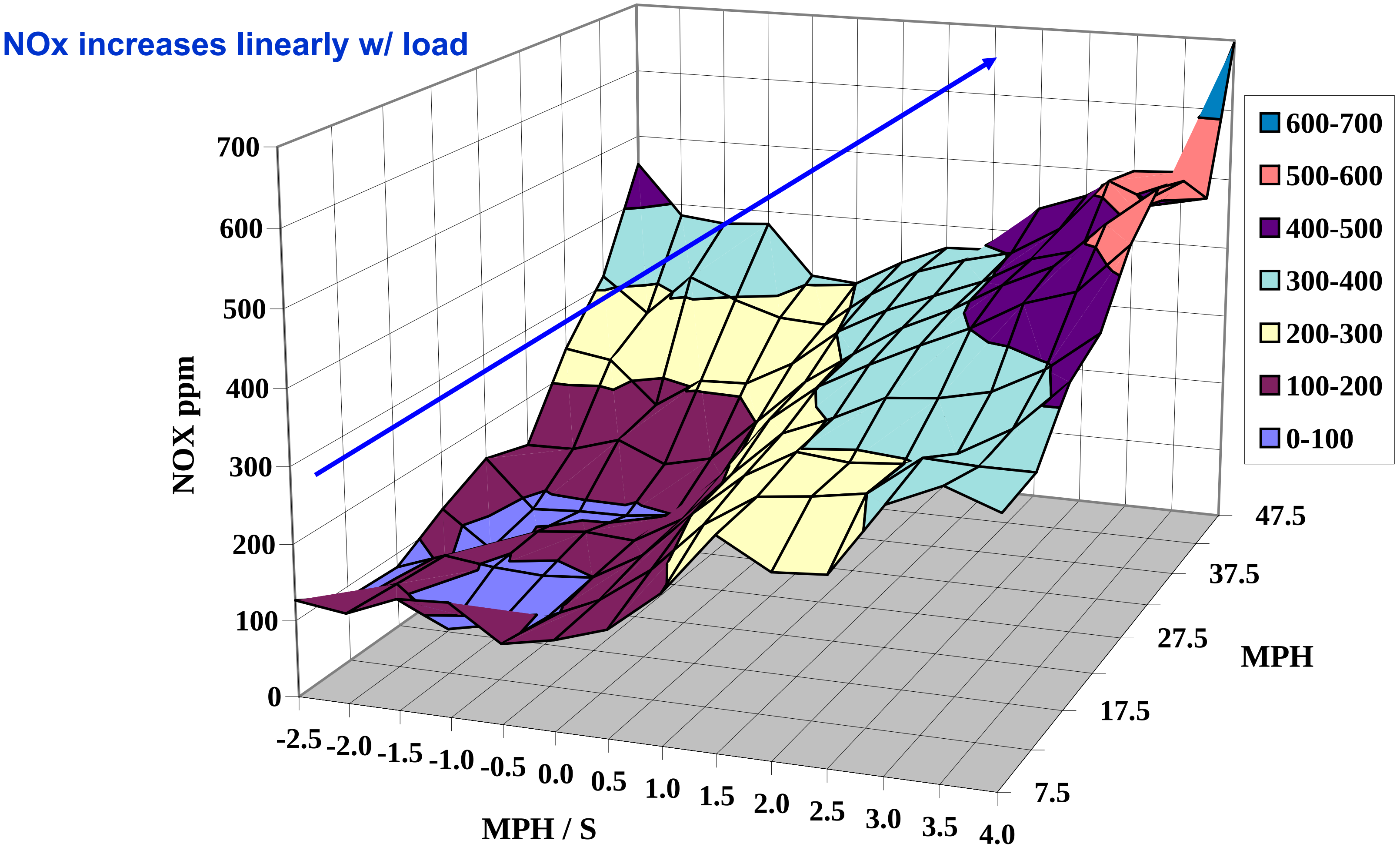
Source: Virginia Remote Sensing Device Study, February 2003

HC vs. Speed & Acceleration



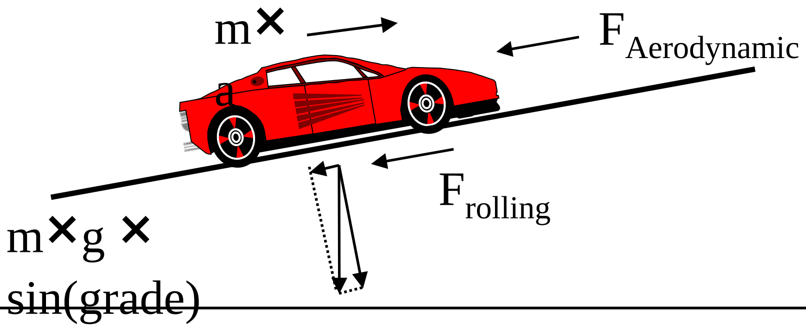
Source: Virginia Remote Sensing Device Study, February 2003

NOx vs. Speed & Acceleration



Source: Virginia Remote Sensing Device Study, February 2003

Vehicle Specific Power (VSP)



$$VSP = \frac{Power}{Mass} = \frac{\frac{d}{dt}(E_{Kinetic} + E_{Potential}) + F_{Rolling} \cdot v + F_{Aerodynamic} \cdot v + F_{internal\ friction} \cdot v}{m} =$$

$$\approx v \cdot a \cdot (1 + \varepsilon_i) + g \cdot grade \cdot v + g \cdot C_R \cdot v + \frac{1}{2} \rho_a C_D \frac{A}{m} (v + v_w)^2 \cdot v + C_{if} \cdot v =$$

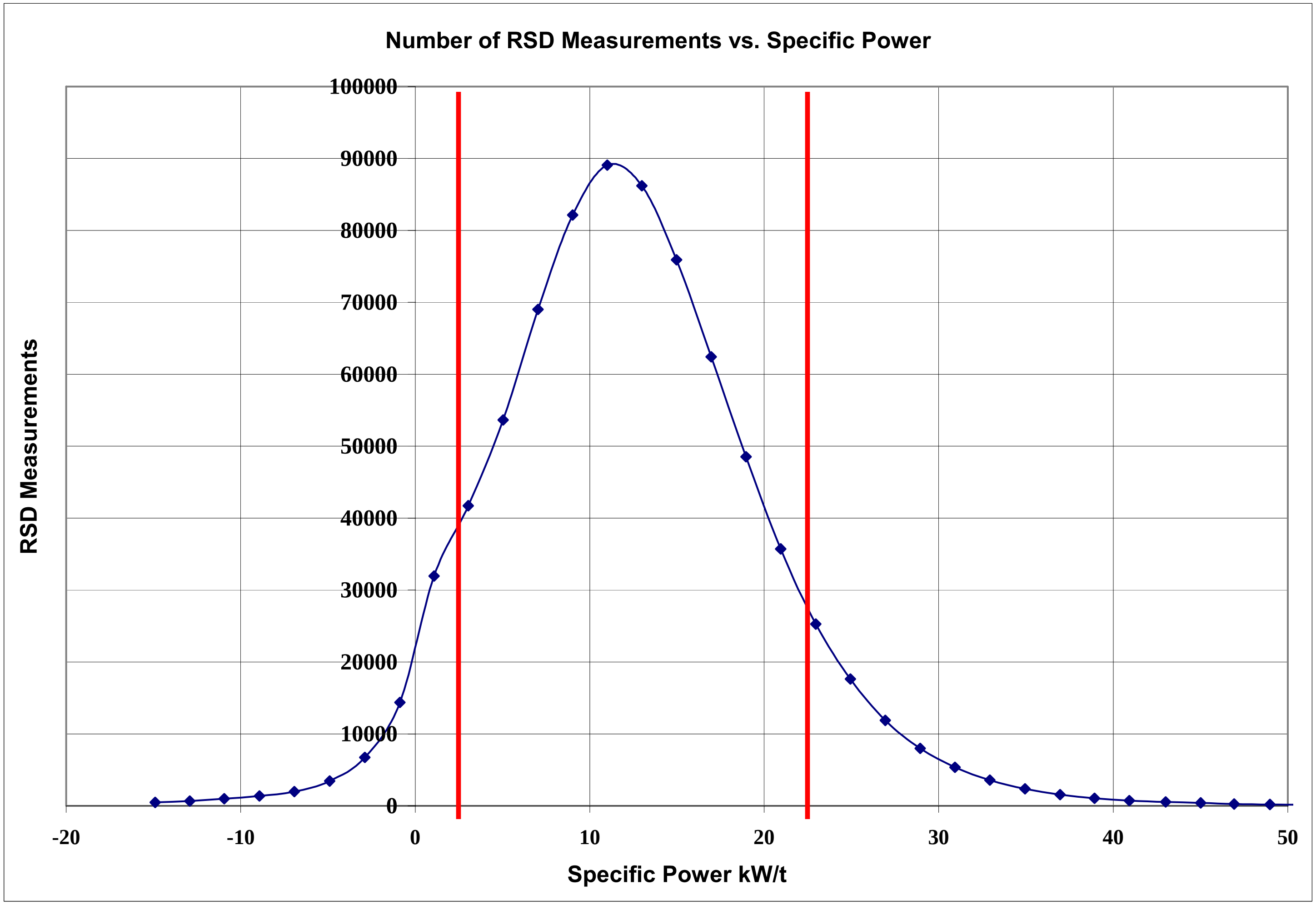
$$\approx 1.1 \cdot v \cdot a + 9.81 \cdot grade + 0.213 \cdot v + 0.000305 \cdot (v + v_w)^2 \cdot v$$

<u>Previous Work:</u>

• Specific Power	= 2×v×a	(EPA, 1993)
• Positive Kinetic Energy	= Σ pos(SP_i)/ Σ distance	(Watson et al., 1983)
• DPWRSUM	= Σ |SP_i-SP_{i-1}|	(Webster and Shih, 1996)

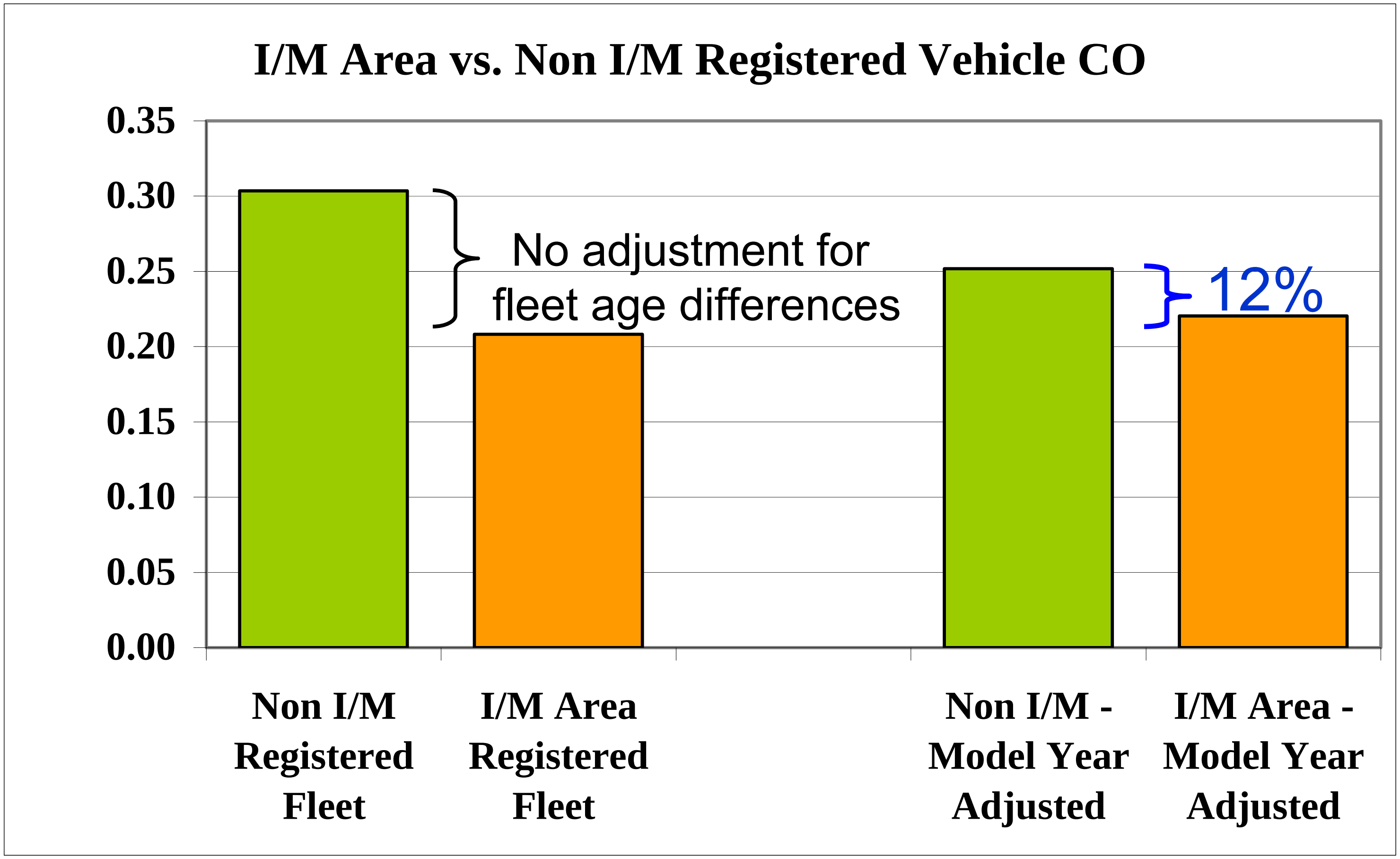
VSP Screen

3-22 KW/T



I/M vs. Non-I/M Emission Rates

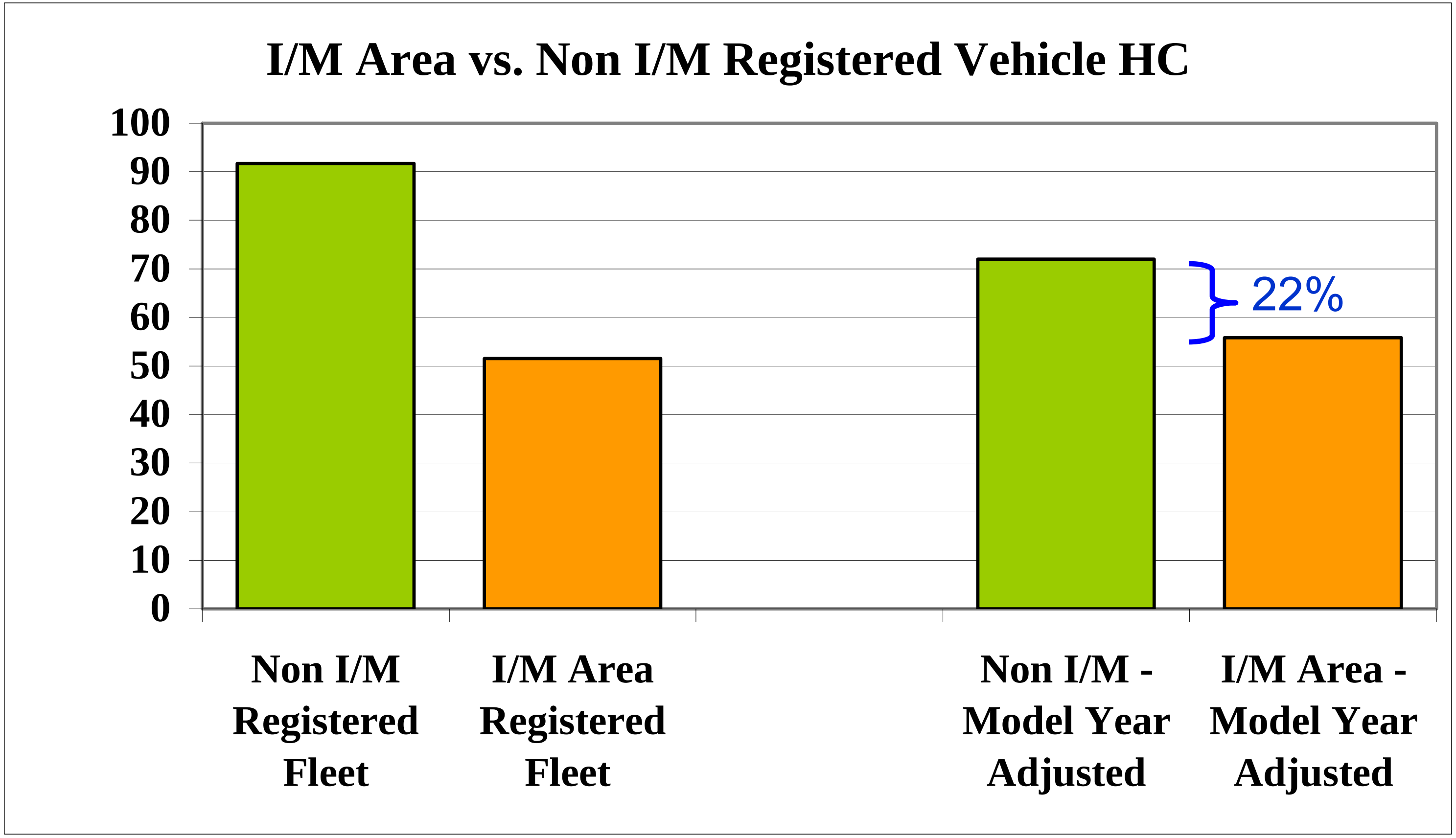
Reference Analysis



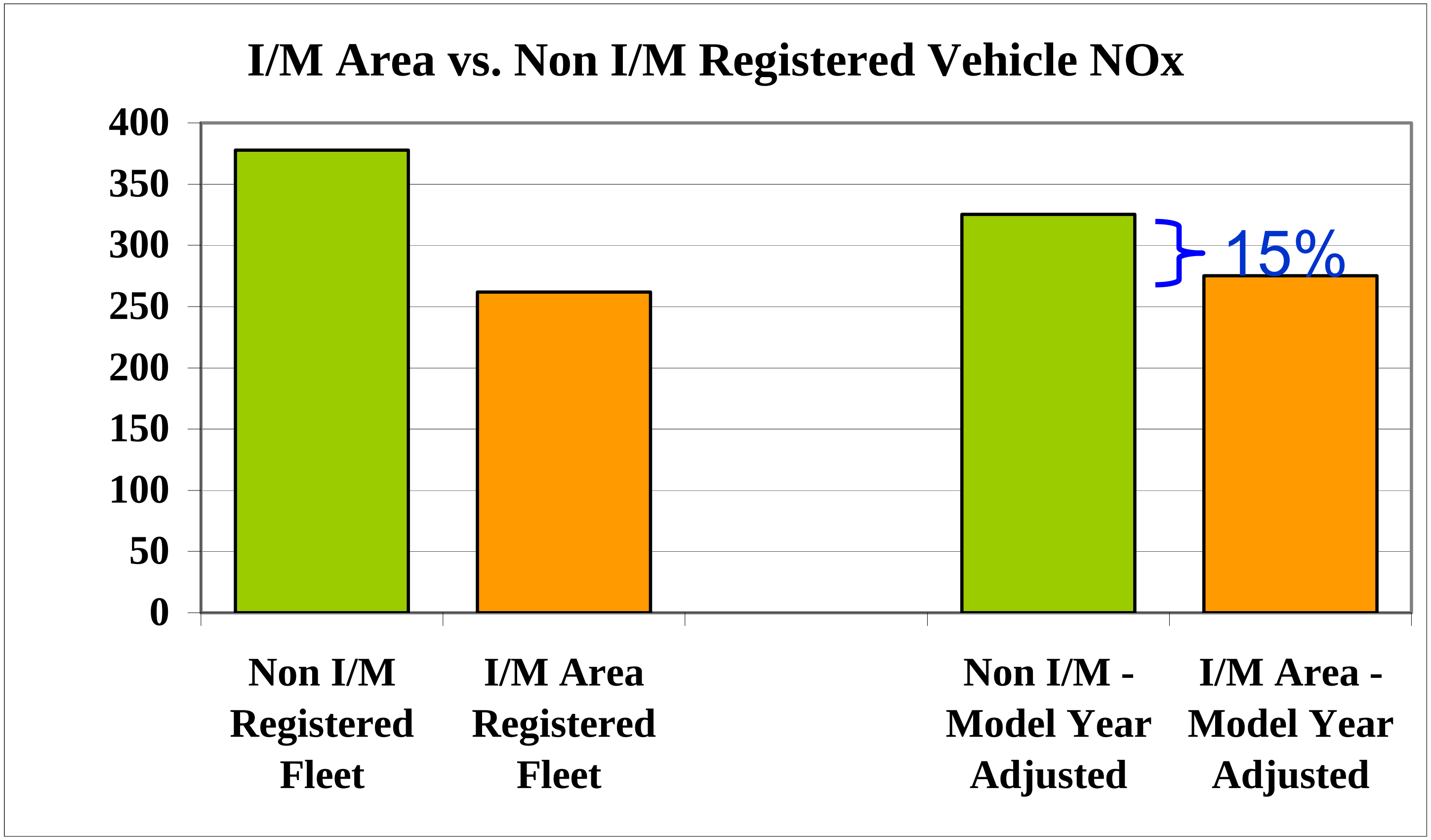
High Case

Low Case

I/M vs. Non-I/M Emission Rates



I/M vs. Non-I/M Emission Rates



Back to Performance Summary

Heavy Duty Diesel Measurements

“Demonstrated Performance”

August 04

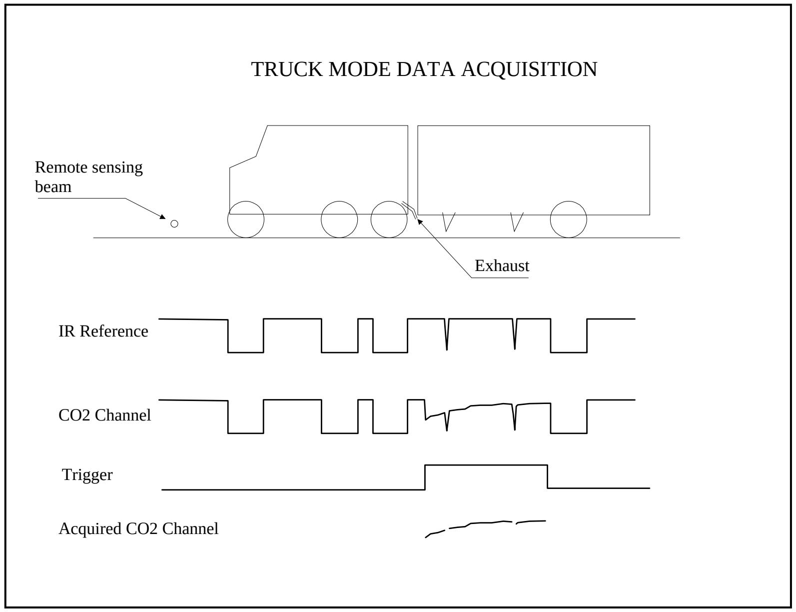
HD Diesel Measurement Technology

Today:
- CO_2 - NDIR
- NO, Smoke Factor - DUV

Future:
- NO2 – DUV
- SO2- DUV

High Pipe

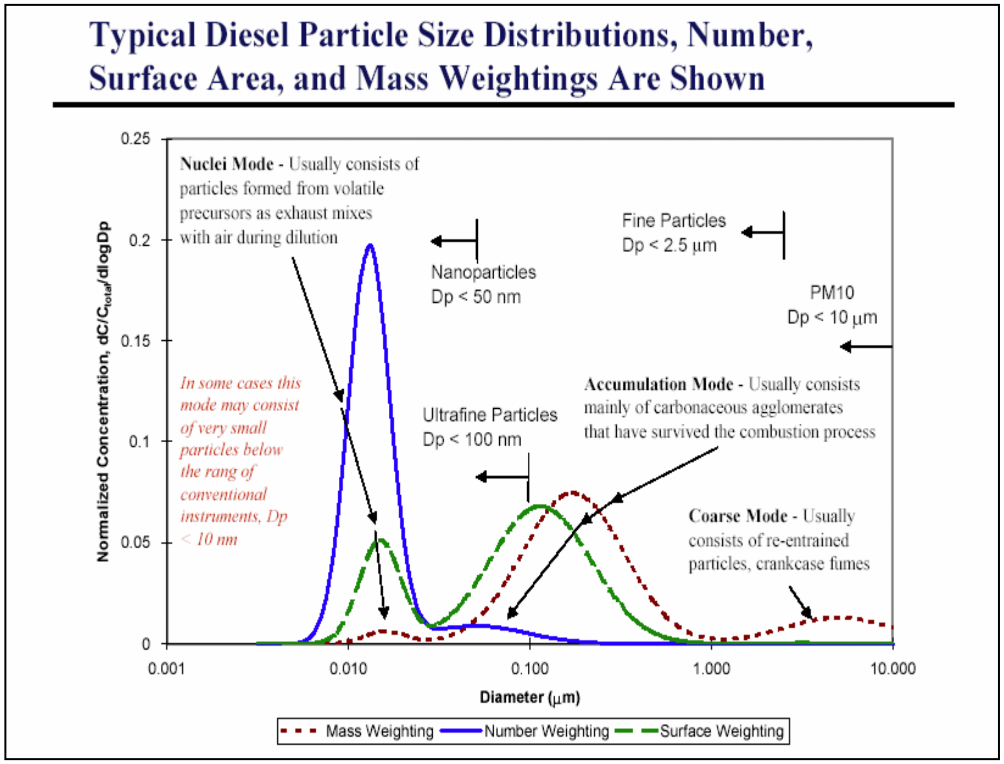
Low Pipe



TRUCK MODE DATA ACQUISITION

Modern Diesel Particle Size

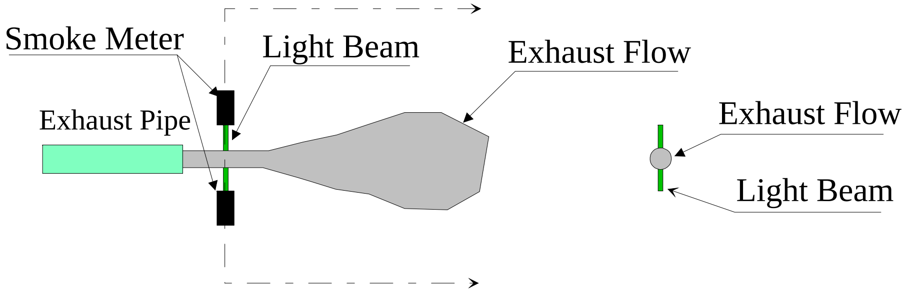
- Classical smoke meters use visible “green” light of ~550 nm. Particles much smaller than 550 nm will be practically invisible; the smoke meter will not sense them!
- Diesel technology >20+ years past: diesel particle sizes mostly larger than 550 nm (mass peak at ~1500nm).
- Diesel technology <20 years past: diesel particle sizes mostly less than 550 nm (mass peak at ~250 nm).



Source:Presentation by David Kittleson, University of Minnesota, Department of Mechanical Engineering, et al “Chemical & Physical Characteristics of Diesel Aerosol,” presented at the 12th Annual CRC Conference, April 15-17, 2002.

Standard Smoke Meter

Standard Smoke Meter
(light beam passes through entire smoke column)



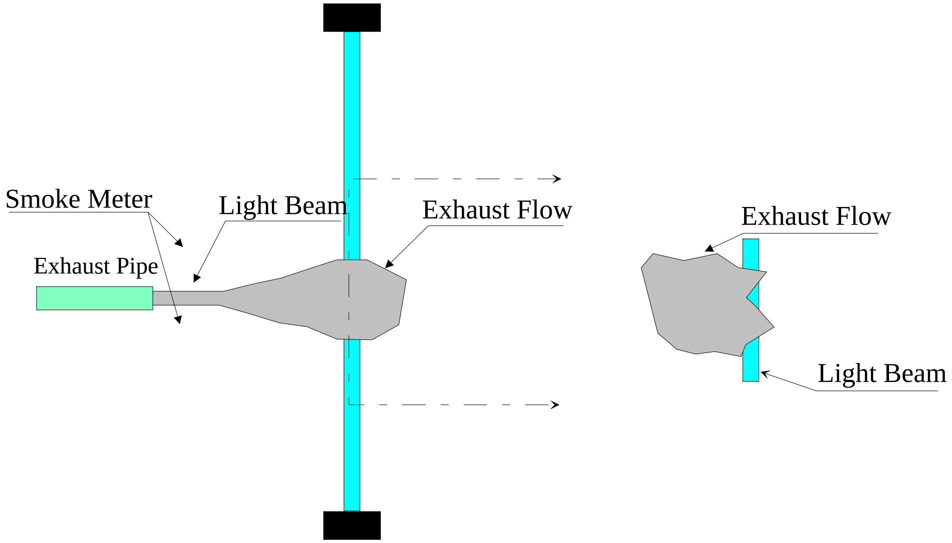
Defining Relationship

$$T_{gl} := e^{-K_{gl} \cdot N_{smk\_total}}$$

T_{gl}	Green light transmittance (1-opacity) measurement.
K_{gl}	Apparent cross-sectional size per particle at green light wavelength.
N_{smk_total}	Total number of smoke particles per unit cross-section.

RSD Smoke Factor

Remote Sensing Smoke Measurement
(light beam passes through a portion of smoke column)



Defining Relationship

$$T_{uv} := e^{-K_{uv} \cdot N_{smk\_frac}}$$

N = [-ln(T)]/K

T_{uv}	UV transmittance (1-opacity) measurement
K_{uv}	Apparent cross-sectional size per particle at UV wavelength.
N_{smk_frac}	The number of smoke particles per unit cross-sectional area; a fraction of total.

Our Smoke Number

(a value proportional to number of exhaust smoke particles per unit fuel)

$$SF := \frac{-100 \cdot \ln\left(T_{uv}\right)}{N_{CO2\_frac} + N_{CO\_frac} + N_{HC\_frac}}$$

where

N_{CO2_frac} is amount of plume CO2 in %-cm

N_{CO_frac} is amount of plume CO in %-cm

N_{HC_frac} is amount of plume HC in %-cm

Sulfur Dioxide Remote Sensing in Vehicle Exhaust

Daniel A. Burgard, Gary A. Bishop, and Donald H. Stedman
Department of Chemistry and Biochemistry
University of Denver

Sulfur in Fuel

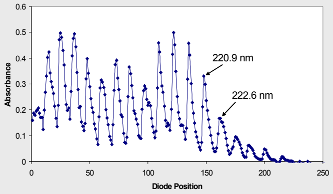
- Current caps in US Fuel
  - Gasoline 300 ppm (CA 80 ppm)
  - On-road Diesel 500 ppm
  - Off-Road Diesel 5000 ppm
- Europe has a 500 ppm cap on gasoline with a zero sulfur (10 ppm) proposal
- New Zealand on-road diesel contains 1800 ppm
- Iran on-road diesel contains 5000 ppm

- Why is Sulfur in Fuel bad?
  - Produces sulfur dioxide in exhaust
  - Poisons catalysts in emission control systems
- High sulfur fuel is still used
  - There is a cost to get rid of sulfur in fuel
  - There is an economic incentive for its use for example
    - Off-road diesel used on road
    - Untaxed high sulfur fuel brought across the border in Hong Kong

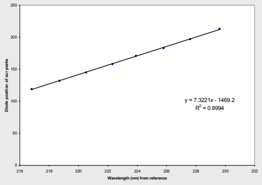
Remote Sensing

- Detecting SO_2 in the exhaust of vehicles is informative for both pollution and sulfur in fuel content.
- Our current Fuel Efficiency Automobile Test (FEAT) was adapted to measure the UV absorption of SO_2.

SO_2 Spectra Collected from a FEAT 3000 Unit



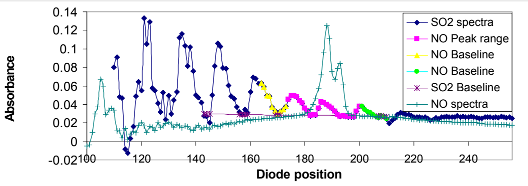
Sulfur Peak Validation



Pearse, R.W.B. and Gaydon, A.G. *The Identification of Molecular Spectra 3rd ed.*; The Whitefriars Press, Ltd.: 1963; p 268-9.

SO_2 Software

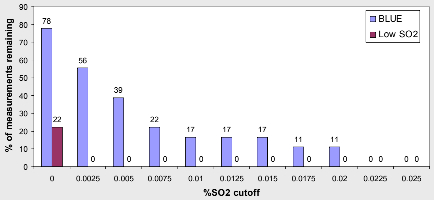
- Current FEAT software had to be adapted to include SO_2 detection.
- FEAT measures NO in the UV range at 226 nm.
- SO_2 peaks at 220.9 nm and 222.6 nm are used for detection.



Road Tests

- Our 1985 Chevrolet Celebrity Station Wagon "BLUE" had dimethyl sulfoxide added to the gas tank to reach a sulfur in fuel content of 2000 ppm.
- This car was then driven around a parking lot in front of a FEAT 3000 unit.
- A 2002 Honda Accord was driven around the parking lot in front of the same remote sensor.

LEV Honda Comparison to the Sulfur Doped Car to Establish an SO_2 Cutoff



Variable Sulfur Amounts in On Road Emissions

- The fuel line from the Chevy Celebrity's fuel tank was disconnected and an auxiliary fuel tank was attached to the roof of the car.
- This provided an easy way to quickly switch fuel samples in the car.
- One liter samples of varying sulfur doped gasoline were made and used in a parking lot study.

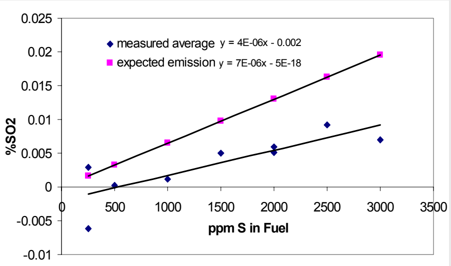
Expected SO_2 in Exhaust

- $CH_2 + S + 1.5(O_2 + 4N_2) > CO_2 + H_2O + 6N_2 + SO_2$

- 1000 ppm by weight S = 10^{-3} g S/ g Fuel
- 14 g/mole Fuel and 32 g/mole S
- = 4.4 E-4 mole S/ mole Fuel
- = 4.4 E-4 mole S/ mole CO_2
- 4.4 E-4 mole SO_2 will be made for every 1 mole CO_2 and 6 mole N_2
- 4.4 E-4 mole SO_2 / 7 moles of gas

- ~ 63 ppm by volume SO_2 in exhaust

Average Emissions of Sulfur Doped Fuel Every 500 ppm



Conclusions

- By remote sensing, the FEAT unit can catch vehicles using 2000 ppm sulfur in fuel 56% of the time with no false positives by measuring SO_2 emissions.
- By remote sensing, the FEAT unit measures increasing SO_2 emissions with increasing sulfur in fuel.
- Currently we are unable to detect SO_2 at the level expected through calculation, most likely because of interactions with the catalyst.

NO$_2$ Measurement

- The wavelengths of interest are at 380-400nm.
- Not yet determined if our light sources have adequate intensity at these wavelengths to be useful.

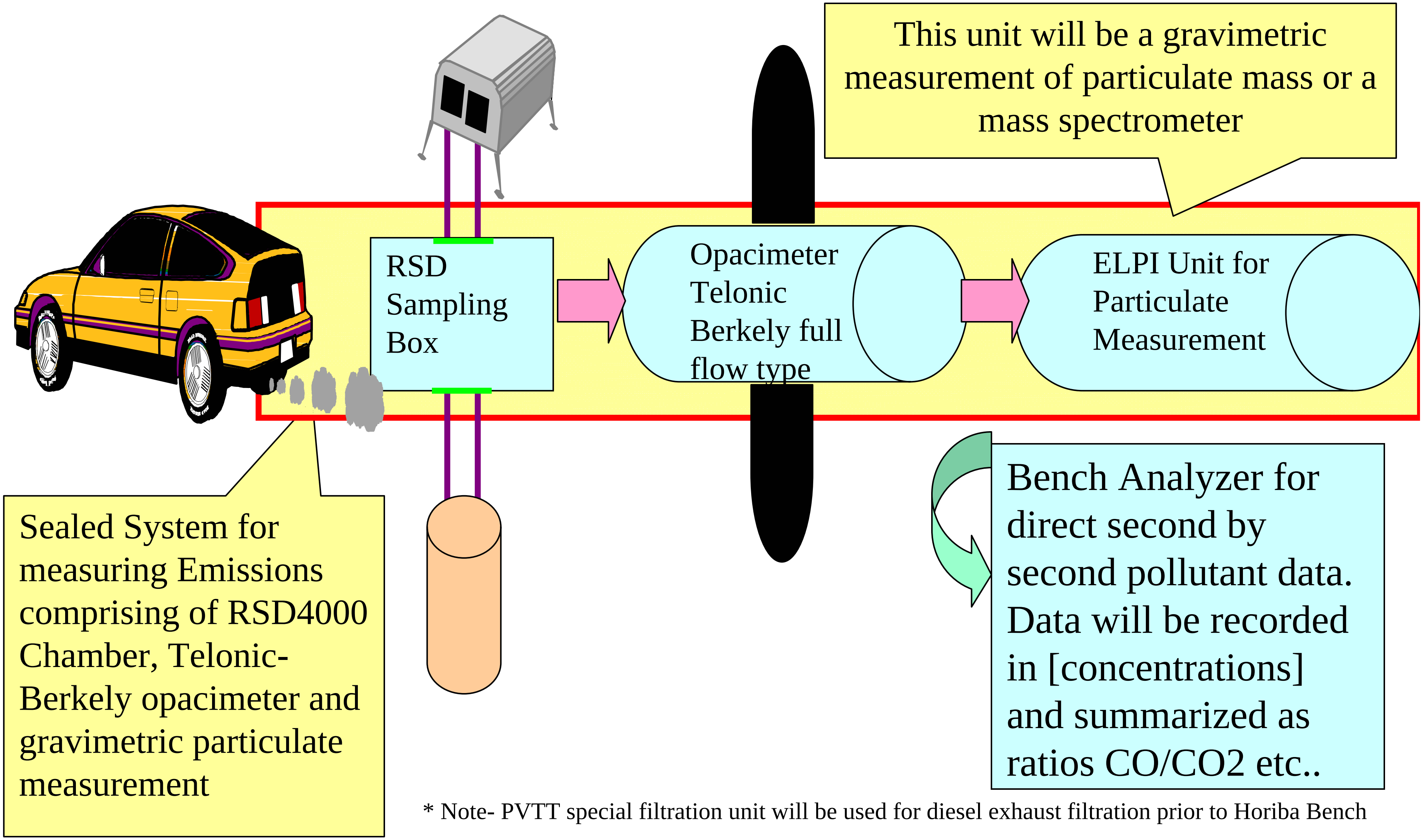
Back to Performance Summary

Matching Laboratory Analyzers

Diesel Vehicles

August 04

Correlation Test Configuration



This unit will be a gravimetric measurement of particulate mass or a mass spectrometer

RSD Sampling Box

Opacimeter Telonic Berkely full flow type

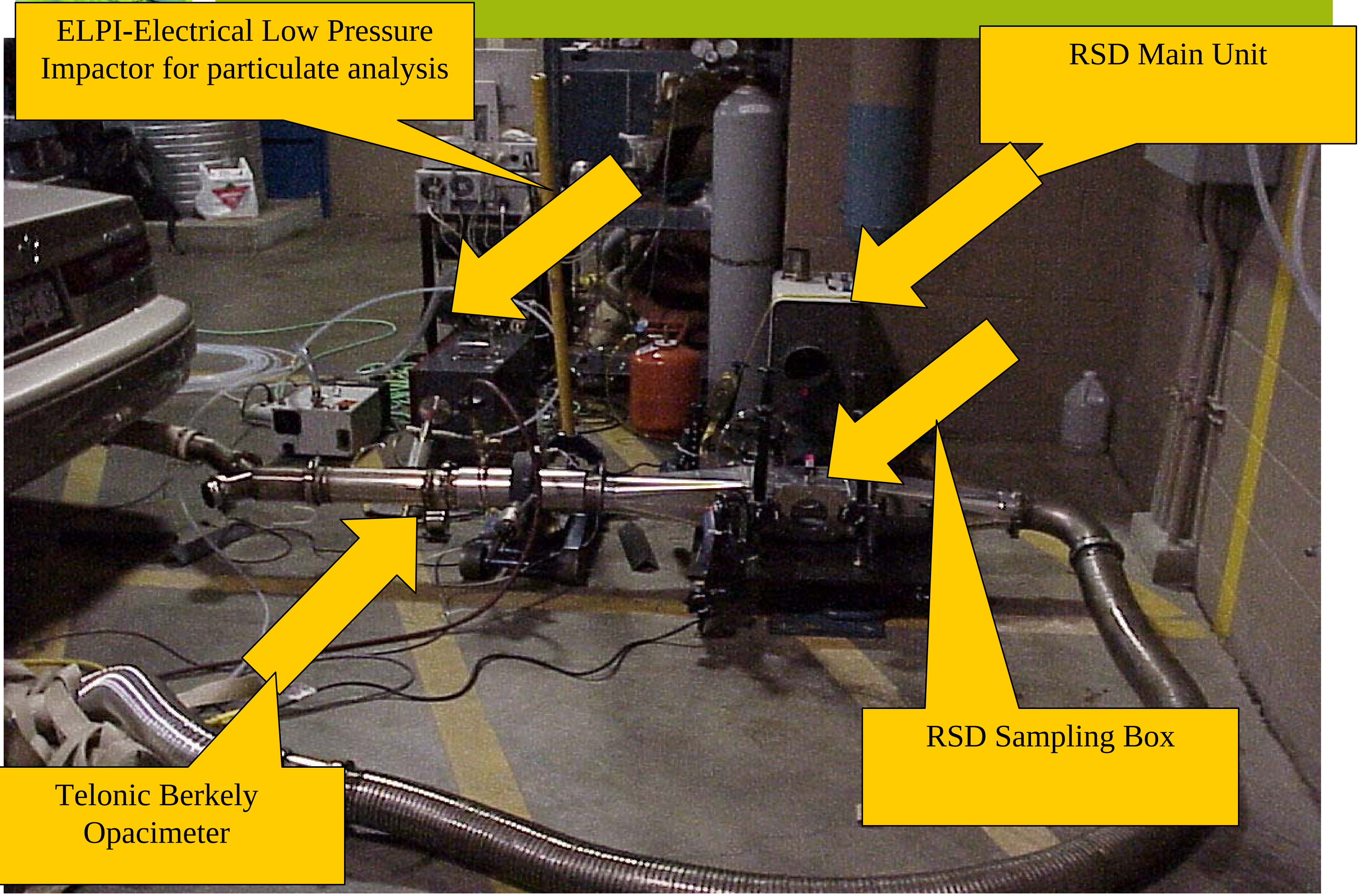
ELPI Unit for Particulate Measurement

Sealed System for measuring Emissions comprising of RSD4000 Chamber, Telonic-Berkely opacimeter and gravimetric particulate measurement

Bench Analyzer for direct second by second pollutant data. Data will be recorded in [concentrations] and summarized as ratios CO/CO2 etc..

* Note- PVTT special filtration unit will be used for diesel exhaust filtration prior to Horiba Bench

Test Layout



ELPI-Electrical Low Pressure Impactor for particulate analysis

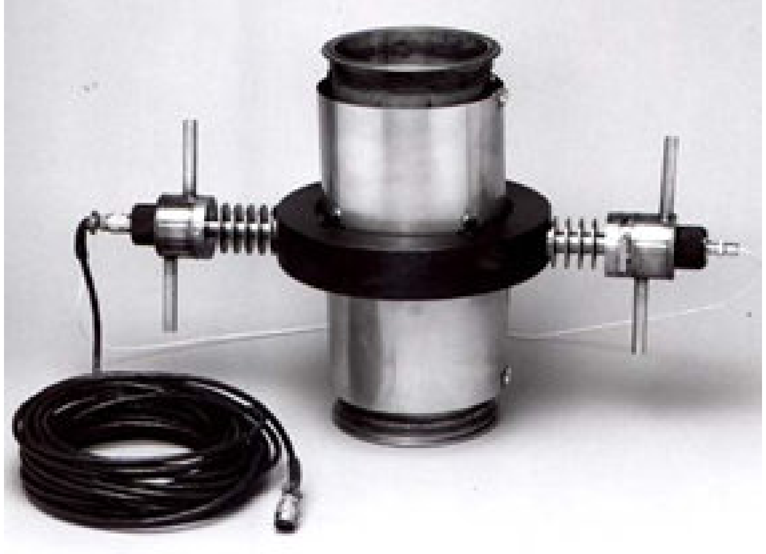
RSD Main Unit

RSD Sampling Box

Telonic Berkely Opacimeter

Equipment and Specifications

- Telonic-Berkeley Opacimeter
  - In-line, Full flow
  - + or - 0.5% Accuracy
  - ISO/DIS 11614
  - Euro III
  - EPA 40 CFR 86.884-9
- Meets requirements for diesel engine Federal test cycle
- Measures opacity in the 0-100% range



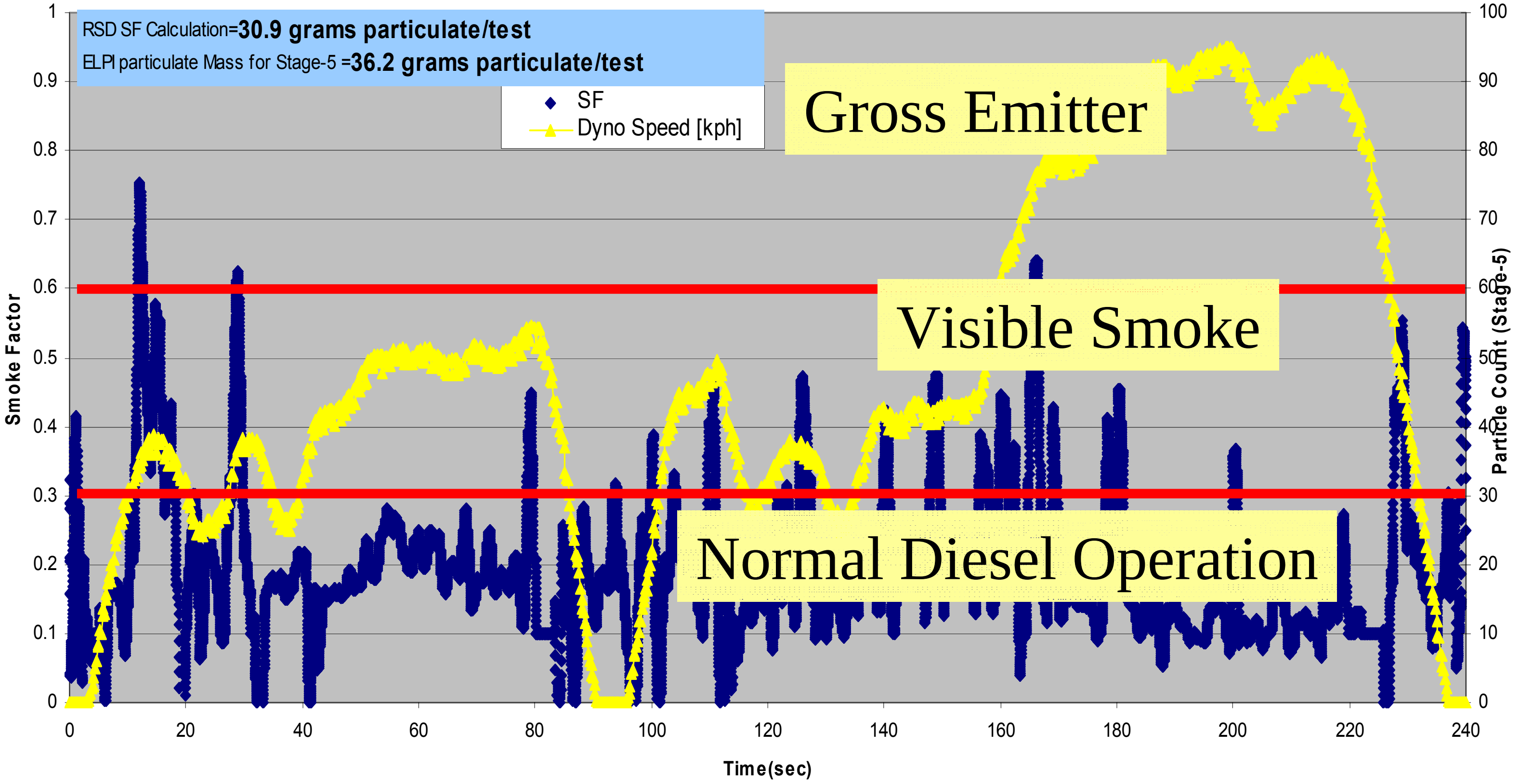
ELPI-Electrical Low Pressure Impactor (Dekati)

The impactor has 13 successive impactor stages: 10 µm, 6.8 µm, 4.4 µm, 2.5 µm, 1.6 µm, 1.0 µm, 0.65 µm, 0.4 µm, 0.26 µm, 0.17 µm, 0.108 µm, 0.060 µm and 0.030 µm. Particle size distribution is defined by measuring the number of particles impacted on the stages of the cascade impactor.

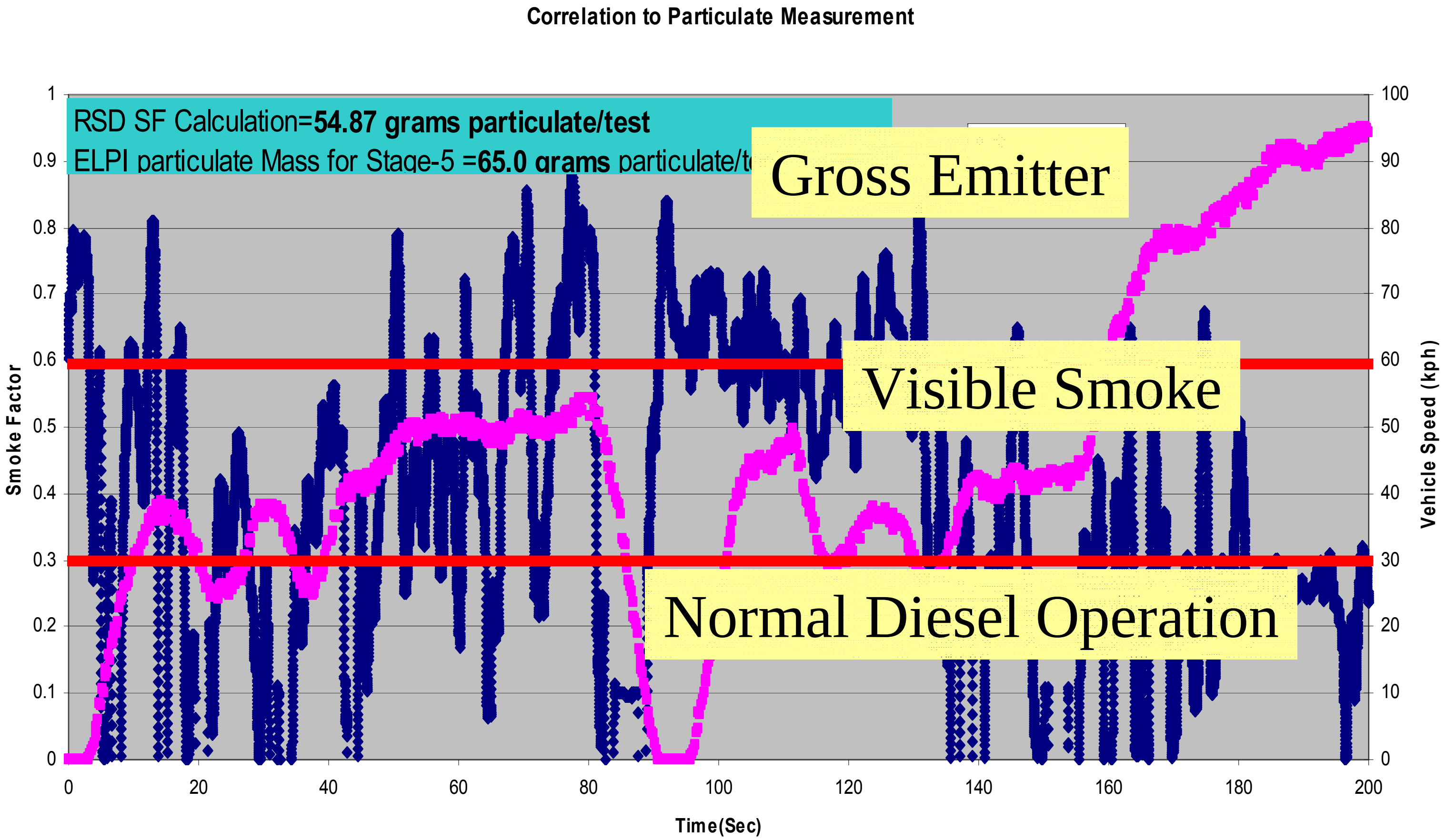
Particle size range	0.030-10 µm, with filter stage 0.007-10µm
Number of Stages	12 with electrical detection, total 13
Volumetric flow rate	10 or 30 l/min
Impactor dimensions	ø 65 mm x 300 mm
Collection plate diameter	25 mm
Lowest stage pressure	100 mbar
Pump requirements	7 m³/h at 100 mbar (10 lpm), 21 m³/h at 100 mbar (30 lpm)
Operation temperature	5-40°C
Operation humidity	0-60 % R.H.
Response time	below 5 seconds
ELPI unit dimensions	H 540 x W 400 x D 230 mm
Unit weight	35 kg
Charger voltage	5 kV
Charger current	1 µA
Computer requirements	Pentium processor, 16 MB RAM, MS-WINDOWS 95™, 98™, NT 4.0™ or 2000™

Particulate Correlation to SF - Black Smoke

Correlation to Particulate Measurement



Particulate Correlation to SF - White Smoke



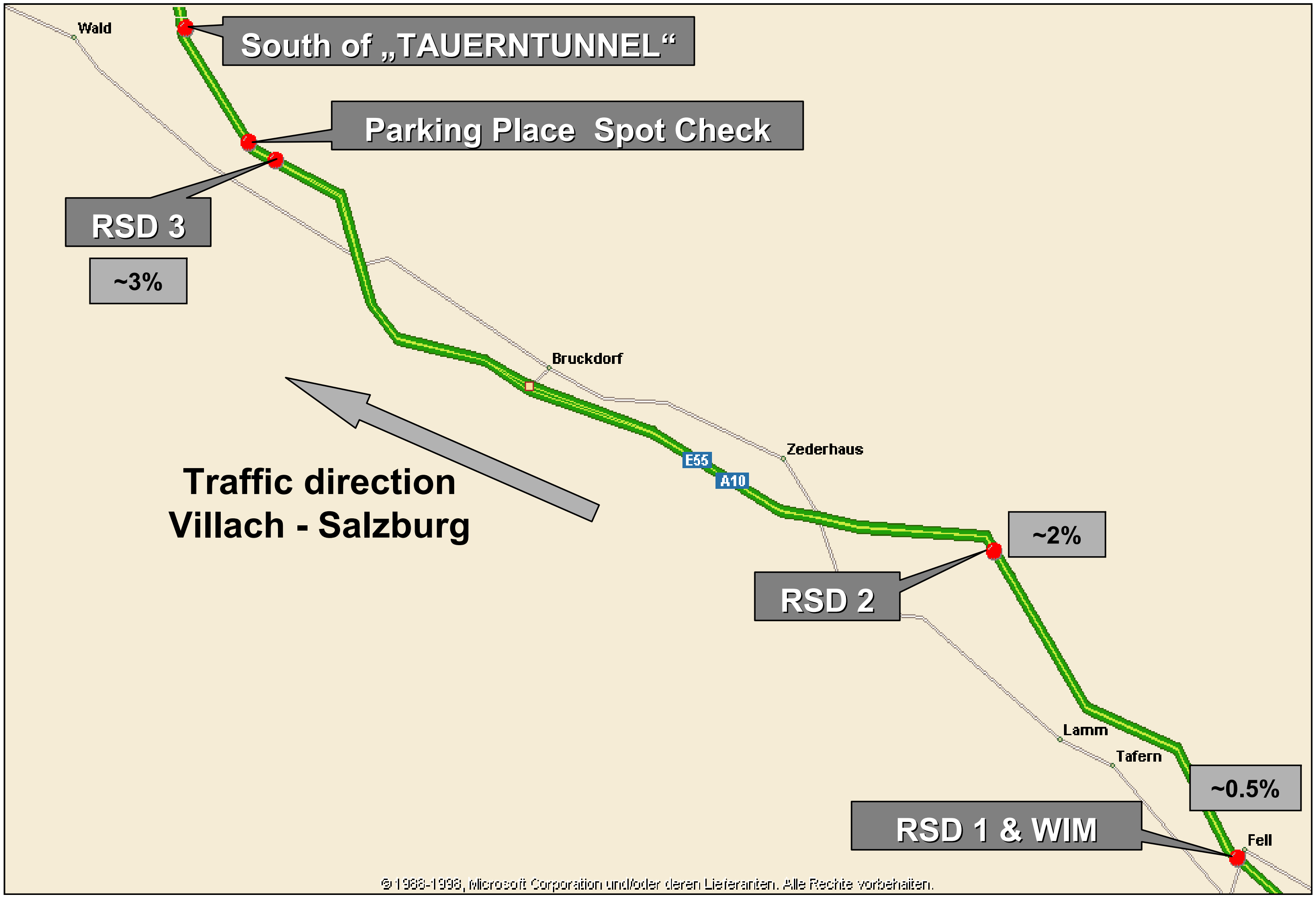
Back to Performance Summary

Matching Inspection Results

August 04

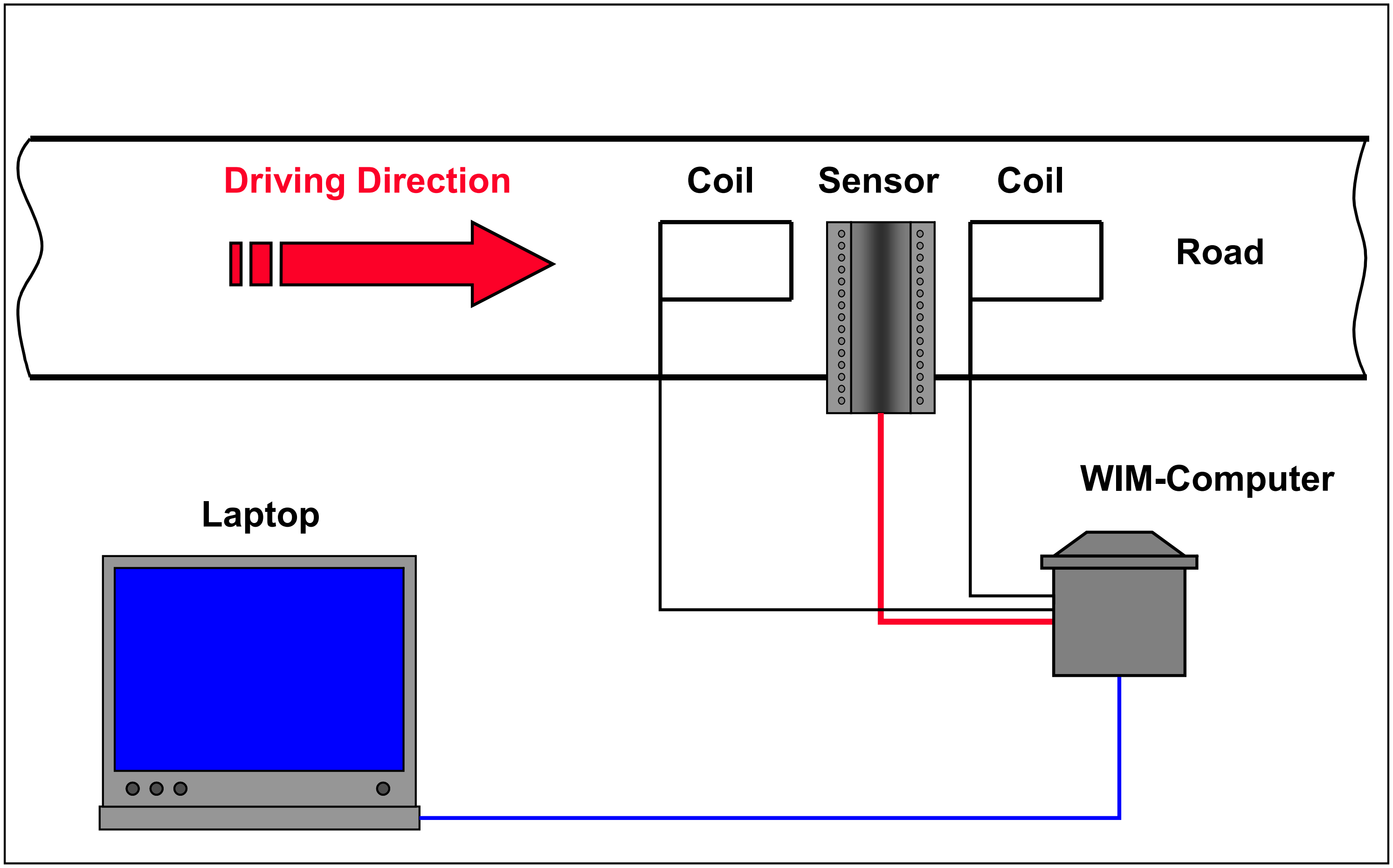
NO Correlation Study

BPA & Univ. of Vienna



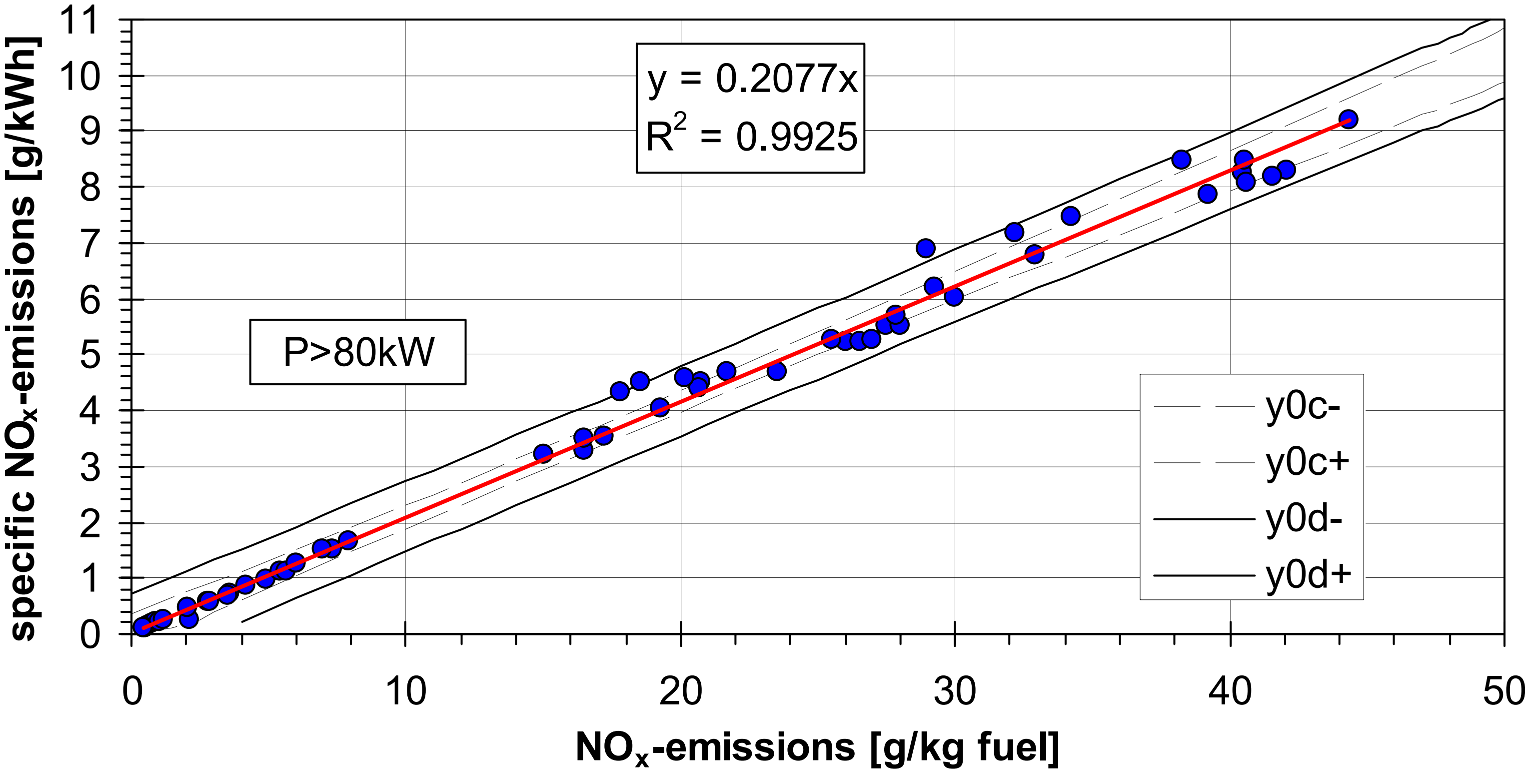
NO Correlation Study

BPA & Univ. of Vienna



NO Correlation Study

BPA & Univ. of Vienna



Vancouver Diesel Smoke Study

RSD vs. Lane Opacity - June 2002

Test Methods Comparison

RSD Test

- Snap shot (<0.5-sec)of vehicle operating condition.
- Measurement: Fuel specific UV opacity → opacity/unit fuel

- Pass/fail: maximum reading of several drive-by’s (typically 3).
- Lane operator drove vehicle trying to pass RSD station under varying acceleration, but steady throttle.
- Opacity measurement in UV region.

- Measurements include: Smoke Factor, CO, CO2, HC, and NO.

IM147 Test

- Chassis dynamometer test cycle of 147-seconds.
- Opacity (corrected to J1667 exhaust pipe sizes).
- Peak opacity during test cycle.

- Lane operator drives vehicle trying to maintain IM147 speed profile. Loads can vary on manual transmissions.
- Opacity measurement in “green” visible light region.
- Measurements include: opacity

RSD Installation

Langley Parking Lot

RSD Installation

Abbotsford Entry Lane

Overview of Testing Methods

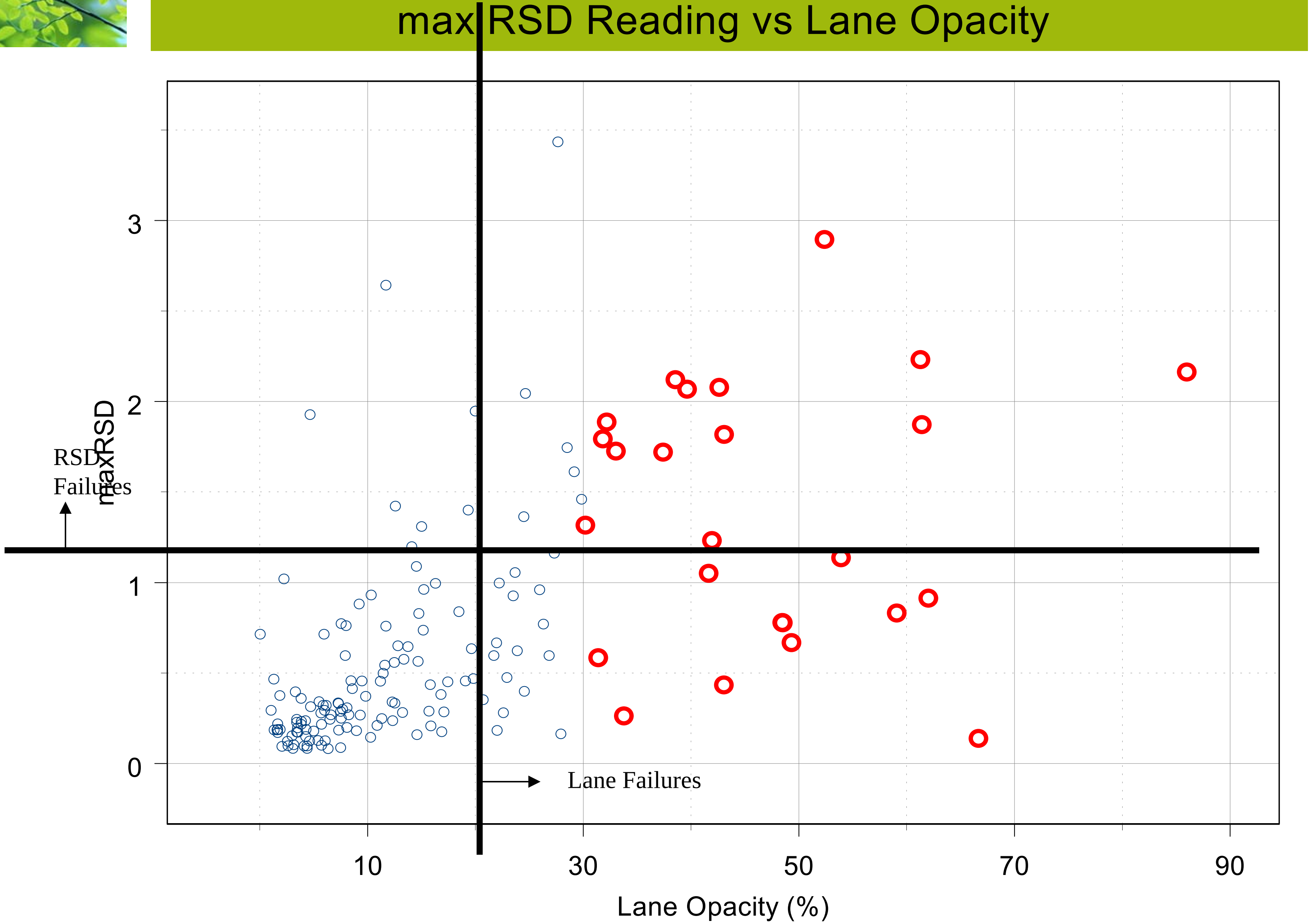
- Station Lane Test:
  - IM147 (last 147-seconds of IM240 driving cycle) test cycle.
  - Wager full-flow opacity meter, Beer-Lambert corrected opacity.
  - Running average filtering
  - Test value is peak opacity value during test cycle.
  - Fail limit set to 30%.

- RSD Test:
  - Conducted immediately after lane test.
  - Test reading is maximum of multiple passes (typically 3 passes).
  - Lane inspector drives vehicle
  - Langley (parking lot): accelerate from dead stop; typical speeds (18-25 mph); typical accelerations (0-3.5 mph/second).
  - Abbotsford (entry lane): slight down slope; similar speeds and accelerations to Langley.
  - Fail Limit of 1.0 on smoke factor.

Test Results Overview

- 156 Test Comparisons
- Scatter Diagram Format
  - Results with lane readings >30% are highlighted on scatter diagram.

max RSD Reading vs Lane Opacity



Summary Statistics

- 156 Comparison Tests
- Assuming Lane Opacity Failures (OP>30)
- Assuming RSD Failure as (SF>1.0)
  - Total of 25 Lane Failures
  - Total of 32 RSD Failures
  - Total of 16 common failures
  - 9 Lane failures not common to RSD
  - 16 RSD failures not common to Lane

Questions/Follow-up Analysis

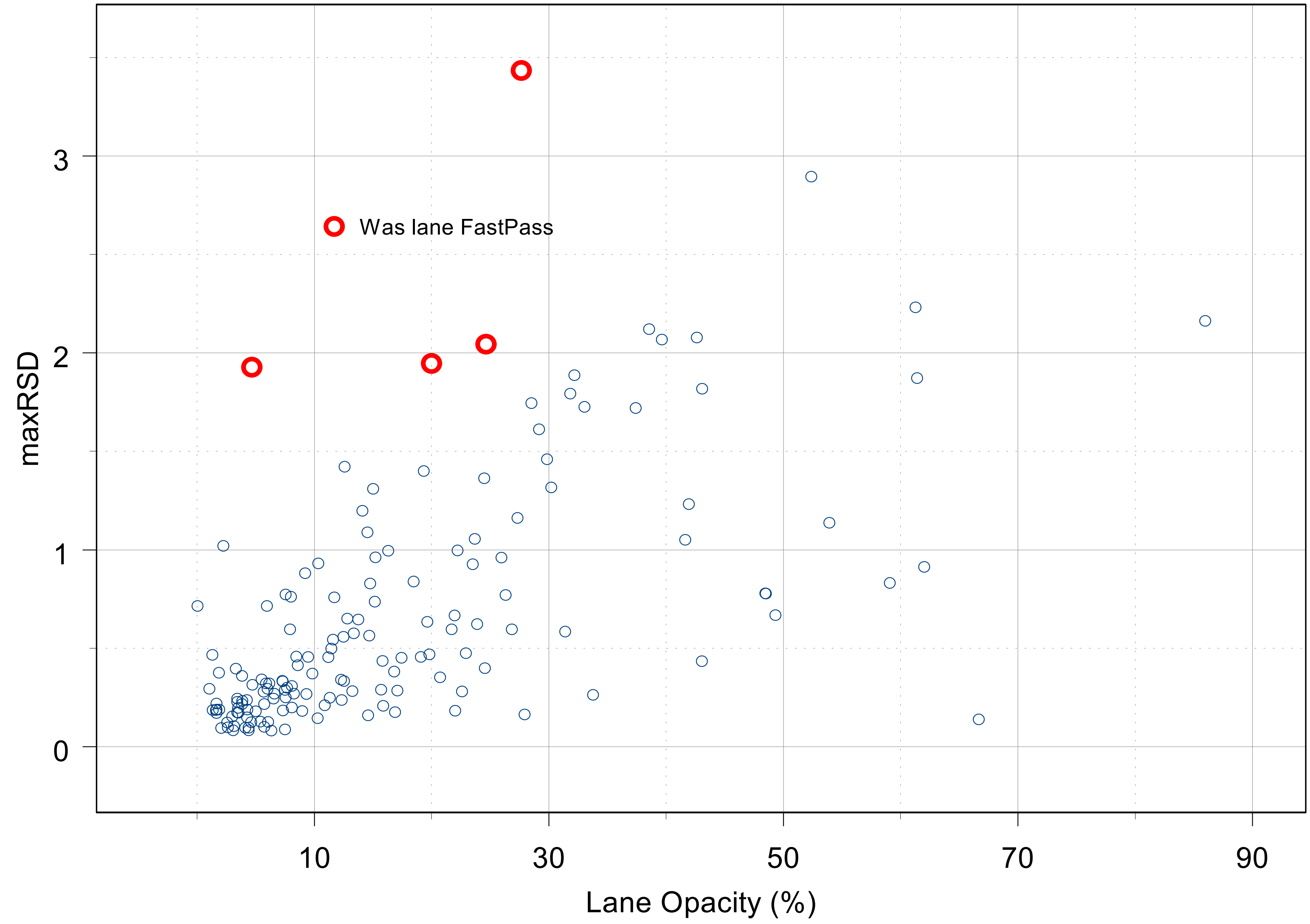
- 16 RSD “failures” did not show up as Lane “failures”. Why?
  - Were these vehicles smoking? Were there instrumentation problems?
  - Other explanations?
- 9 Lane “failures” did not show up as RSD “failures”. Why?

16 RSD “Failures” NOT Common to Lane High Readings

- Several of highest RSD test failures that are lane passes are highlighted.

- Were they really smoking vehicles? **Yes**, they were generally “visible to eye” smoking vehicles. See following pictures.

max RSD Reading vs Lane Opacity



RSD Failure/Lane Failure

CO CO2 HC NO

RSD Failure/Lane Failure

Was lane Fast Pass

RSD Failure/Lane Failure

RSD Failure/Lane Failure

High RSD Low Lane Results

- Since the RSD readings are high because vehicles are truly “smoking” (evidence is the pictures), the questions then become –
  - Why doesn’t the lane test reveal the high smoke content?
  - Do the RSD tests exceed the engine/vehicle power levels of the lane test?
  - Are there other factors such as oil-based “blue smoke”?
  - Was the lane test designed to reveal all smoking vehicles?

Hypotheses
High Lane Low RSD Results

- Basic Assumption is that an engine condition is realized in the lane that does not occur during drive-bys.
- Some evidence exists that lane test failures that occur in the initial acceleration period (start of test cycle) can be caused by late shifting (accelerating in 1st gear thereby over-speeding the engine).
- At least one test failed at the lane, passed very clean through several RSD passes, was retested in the lane starting in 2nd gear, and passed cleanly.
- Lane failures occurring on the 2nd acceleration phase of the test cycle are at speeds higher than could be produced at the RSD site.

Conclusions

- Both RSD and IM147 Opacity Test identify high smoke emitters.

- RSD tests identified more high smoke emitters than did the lane test.
  - Lane: 25
  - RSD: 32
  - Common: 16

- Additional RSD high smoke emitters are generally confirmed by visual evidence.

- Additional investigation is required to determine testing differences.

Back to Performance Summary

Matching Fleet Emissions

1. MBTA Bus Monitoring and Control Program

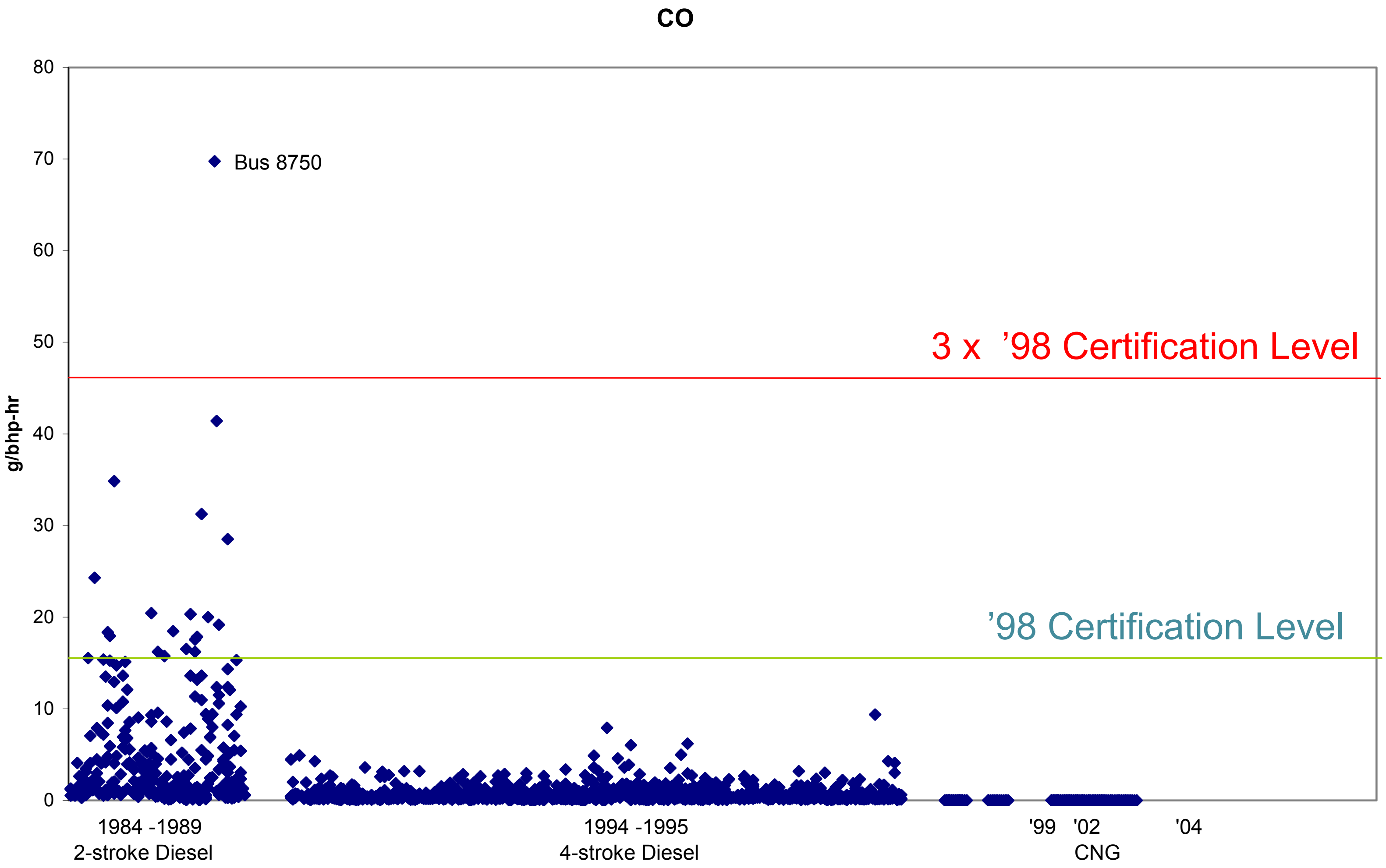
August 04

MBTA Transit Fleet Screening

- Approximately 400 buses screened over a two-week period, with multiple data points per bus (approx 1,500 total)

‘84-’89 two-stroke diesel	80 buses
‘94-’95 diesel (98 spec rebuilds)	280 buses
‘99 CNG (40’ transit)	11 buses
‘02 CNG (60’ artic)	10 buses
‘04 CNG (40’ transit)	40 buses

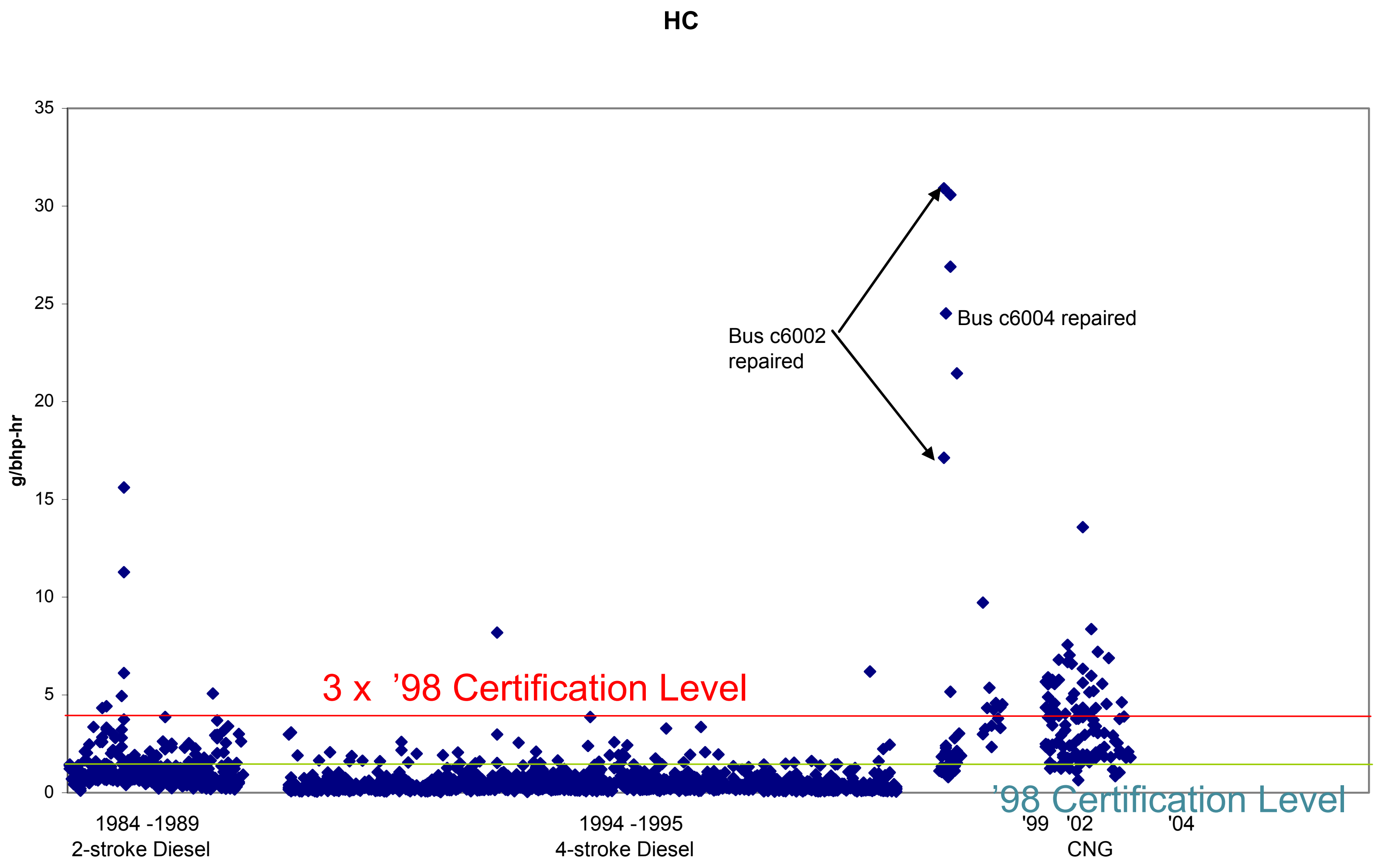
CO Data


CO
80
70
60
50
40
30
20
10
0
g/bhp-hr
◆ Bus 8750
3 x ’98 Certification Level
’98 Certification Level
1984 -1989
2-stroke Diesel
1994 -1995
4-stroke Diesel
'99
'02
'04
CNG

CO Lessons Learned

- CO tracks as expected for all buses
  - Older two-stroke buses
    - One possible outlier in need of repair
    - Same bus flagged later from Smoke data
  - All remaining buses in fleet well within engine certification standard

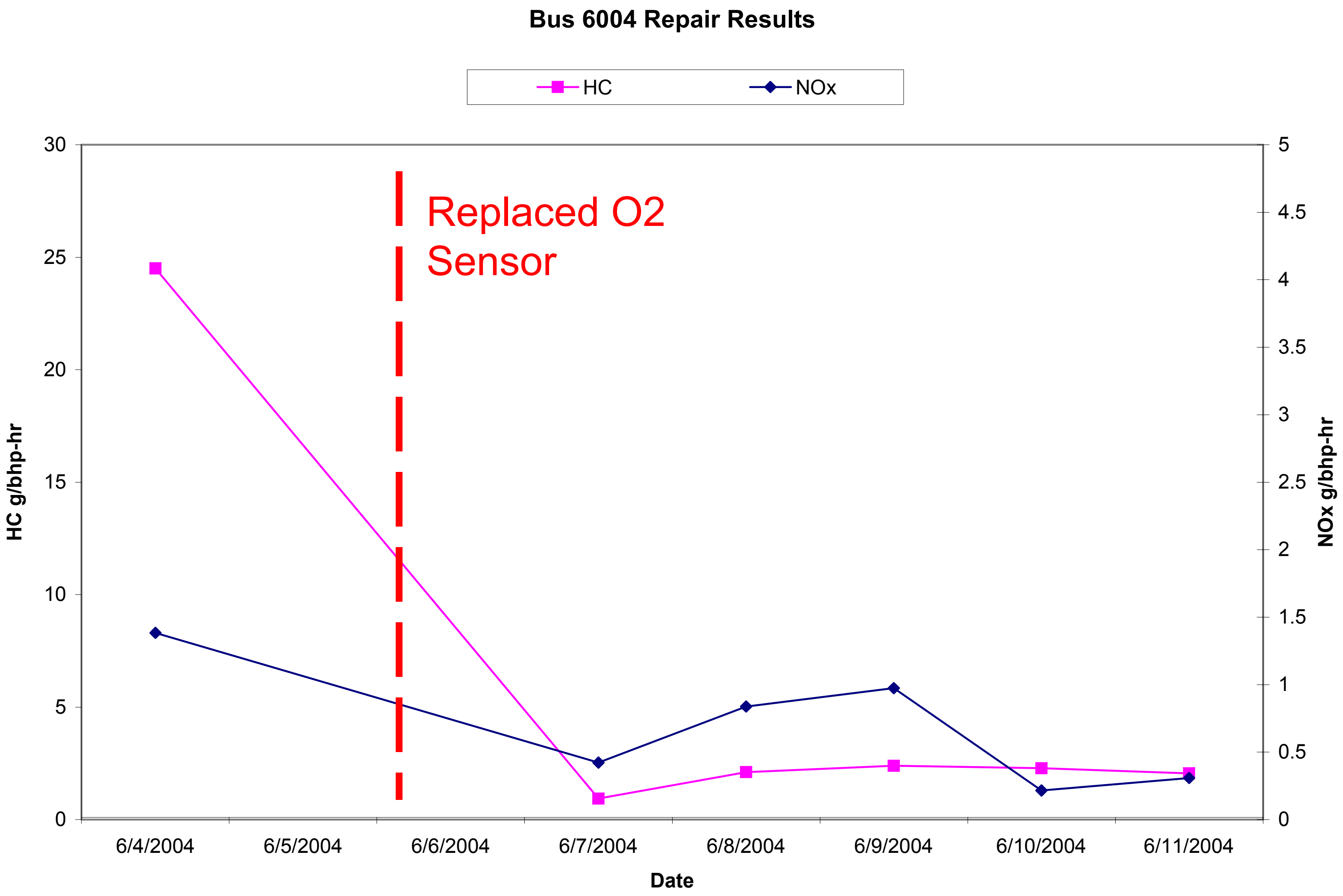
HC Data


HC
g/bhp-hr
35
30
25
20
15
10
5
0
Bus c6002 repaired
Bus c6004 repaired
3 x '98 Certification Level
'98 Certification Level
1984 -1989
2-stroke Diesel
1994 -1995
4-stroke Diesel
'99
'02
'04
CNG

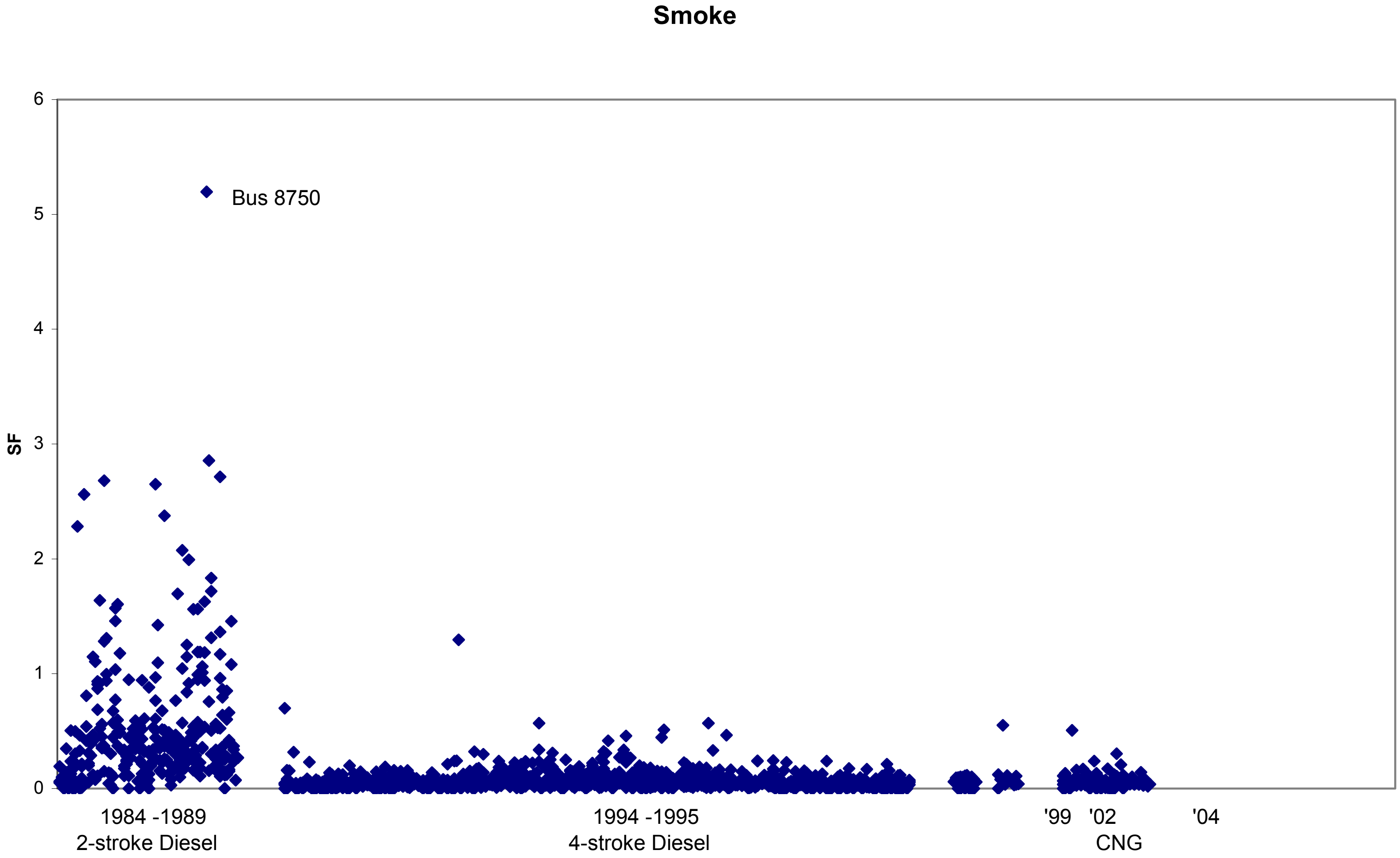
HC Lessons Learned

- Diesel two-stroke and four-stroke as expected, with low nominal HC levels
- CNG buses (specifically ‘99 vintage)
  - Exhibiting lean NOx misfire and excess methane emission levels
  - O2 sensor repairs for several buses show that HC was significantly reduced, with some added NOx benefit
- HC may be a viable surrogate for CNG I/M

Effect of Maintenance



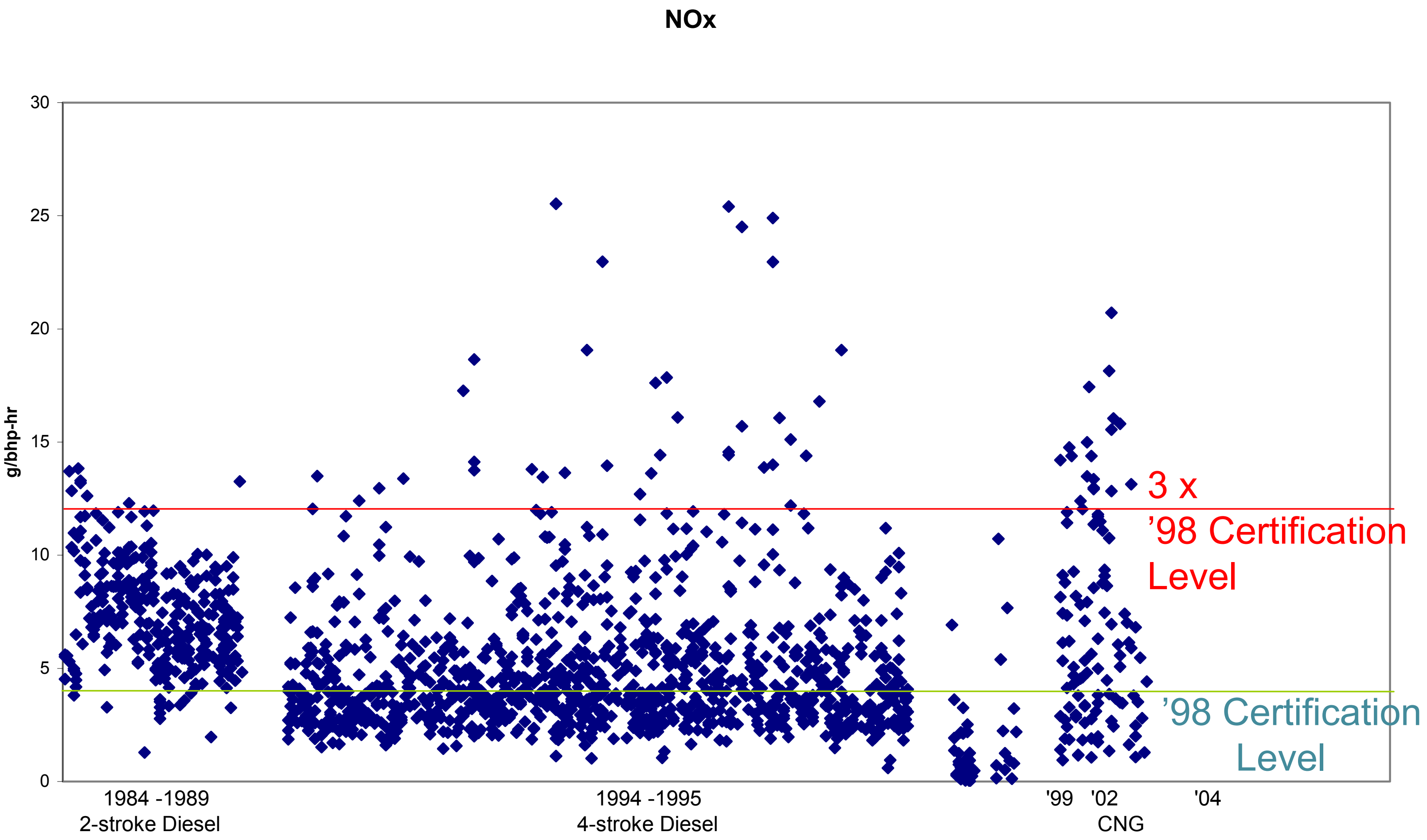
Smoke Data


Smoke
6
5
4
3
2
1
0
SF
Bus 8750
1984 -1989
2-stroke Diesel
1994 -1995
4-stroke Diesel
'99
'02
'04
CNG

Smoke Lessons Learned

- RSD unit uses UV for smoke factor determination
- Results as expected, with DPF-equipped 4-strokes and CNG showing very low smoke, and two-stroke buses higher
  - 2-stroke Bus 8750 flagged for further analysis, OBD scan and Opacimeter test. No failure determination yet for this bus
  - The few outliers in ‘94-’95 bus group will have DPF modules inspected for damage

NOx Data

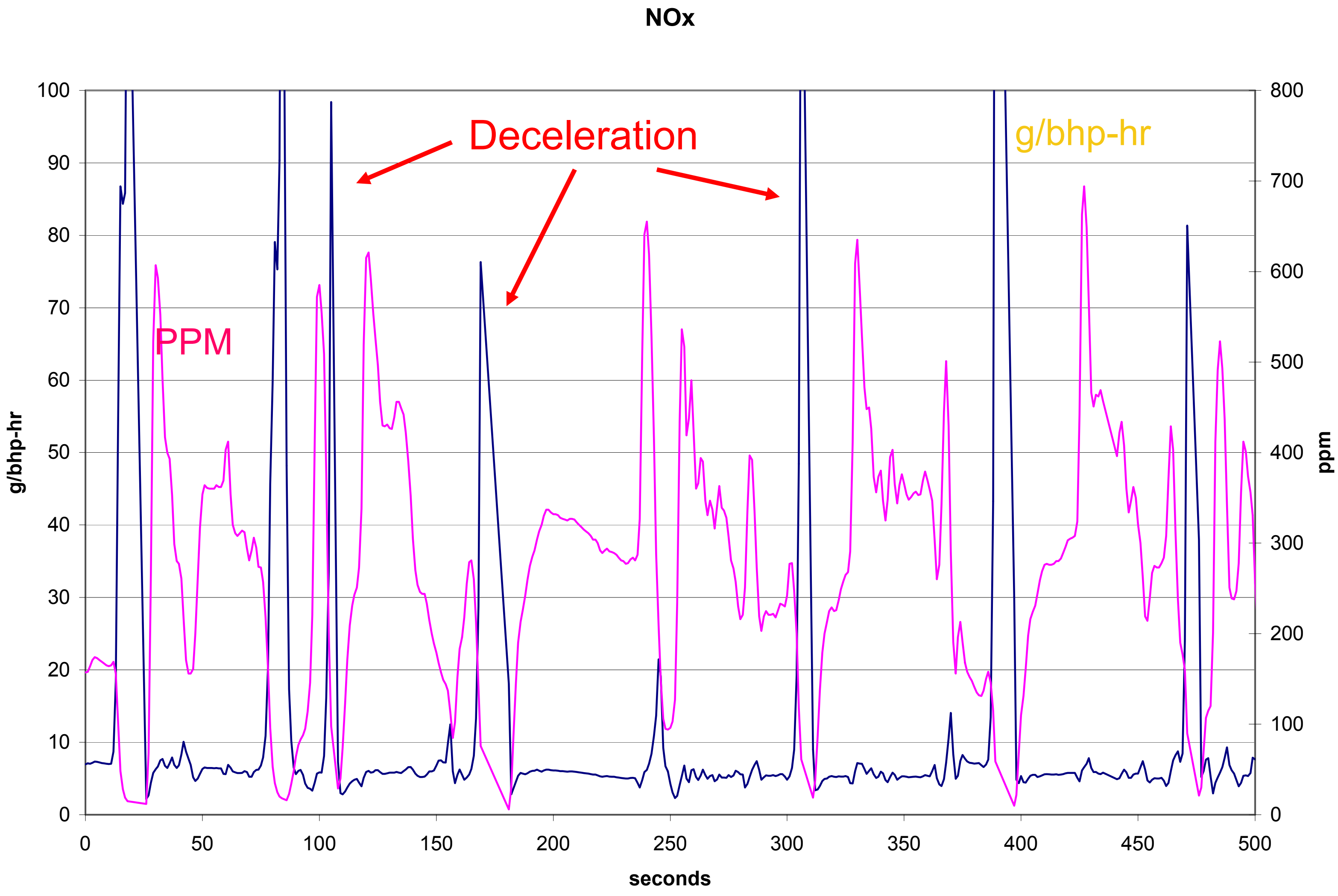

NOx
g/bhp-hr
30
25
20
15
10
5
0
1984 -1989
2-stroke Diesel
1994 -1995
4-stroke Diesel
'99
'02
'04
CNG
3 x
'98 Certification
Level
'98 Certification
Level

NOx Lessons Learned

- NOx measurements appear accurate, with weight of readings for each bus type at or near the certification standard for that engine
  - 2-stroke buses show higher NOx than 4-stroke buses
  - Ultra low NOx of ’99 CNG buses typical of lean misfire O2 sensor failure (see HC data)
  - ‘04 CNG NOx similar to diesel, with greater variability

- Some of the high NOx readings on 4-stroke diesel and ‘04 CNG appear to be artifact of test method
  - See PEMS data for NOx, which illustrates spike in NOx gm/bhp-hr upon deceleration
  - Illustrates need for more control over bus mode during sampling

NOx PEMs Data



Initial Results Over-all

- Over 1500 readings for ~400 buses over a two-week period
  - Data collection is automated
  - Very little post-processing required
- Demonstrated accuracy and ease of use with RSD equipment makes it useful for I/M screening and emissions inventory data collection
  - Can rapidly screen entire fleet(s)
  - Can flag outliers for maintenance action
  - Can demonstrate effectiveness of maintenance action on individual vehicles
- More control of vehicle mode needed during data collection
  - In general want to collect data during vehicle acceleration
  - For permanent I/M programs, can control with physical installation of equipment and/or procedures/training
  - For road-side data collection programs, need to choose collection site carefully
  - Could also be facilitated with more exact vehicle speed sensing

Next Steps (on MBTA Project)

- Use PEMs and Chase Measurements to get detailed emission signature for each bus type
  - Determine whether 2-stroke diesel and CNG show same NOx spikes on deceleration that would flag false failures

- Further evaluate effect of maintenance action on outlier results (2-stroke, CNG)

- Determine best indicator for I/M by engine type
  - 4-stroke diesel: NOx
  - CNG: HC
  - 2-stroke diesel: Smoke or CO?

Matching Fleet Emissions

2. EPA RSD Cross-Border Development Program

August 04

Cross Border Phases

Phase 1	3 Weeks	2004
Goal: Fleet Baseline & RSD Correlation		
Phase 2	9 Months	2005
Goal: Screening Application Development		
Phase 3	On-going	2006
Goal: Enforcement Demonstration Program		

Cross-border Pilot

Phase 1

Location:	Nogales, Arizona
Sponsors:	USEPA, ADOT, ADEQ, ESP
Duration:	Phase 1, 3-weeks
Timetable:	Oct./Nov. 2004
Goals:	1. Fleet Characterization (baseline) 2. Test Comparison (RSD, PEMS, Chase)

Portable Emissions Analyzer

“Correlation”

<u>In-Use Testing:</u>

- Recruit Vehicle
- Install Analyzer
- Trace a Few Miles
- Remove Analyzer

Mobile Chase Laboratory

"Correlation"

Chasing the Polluters

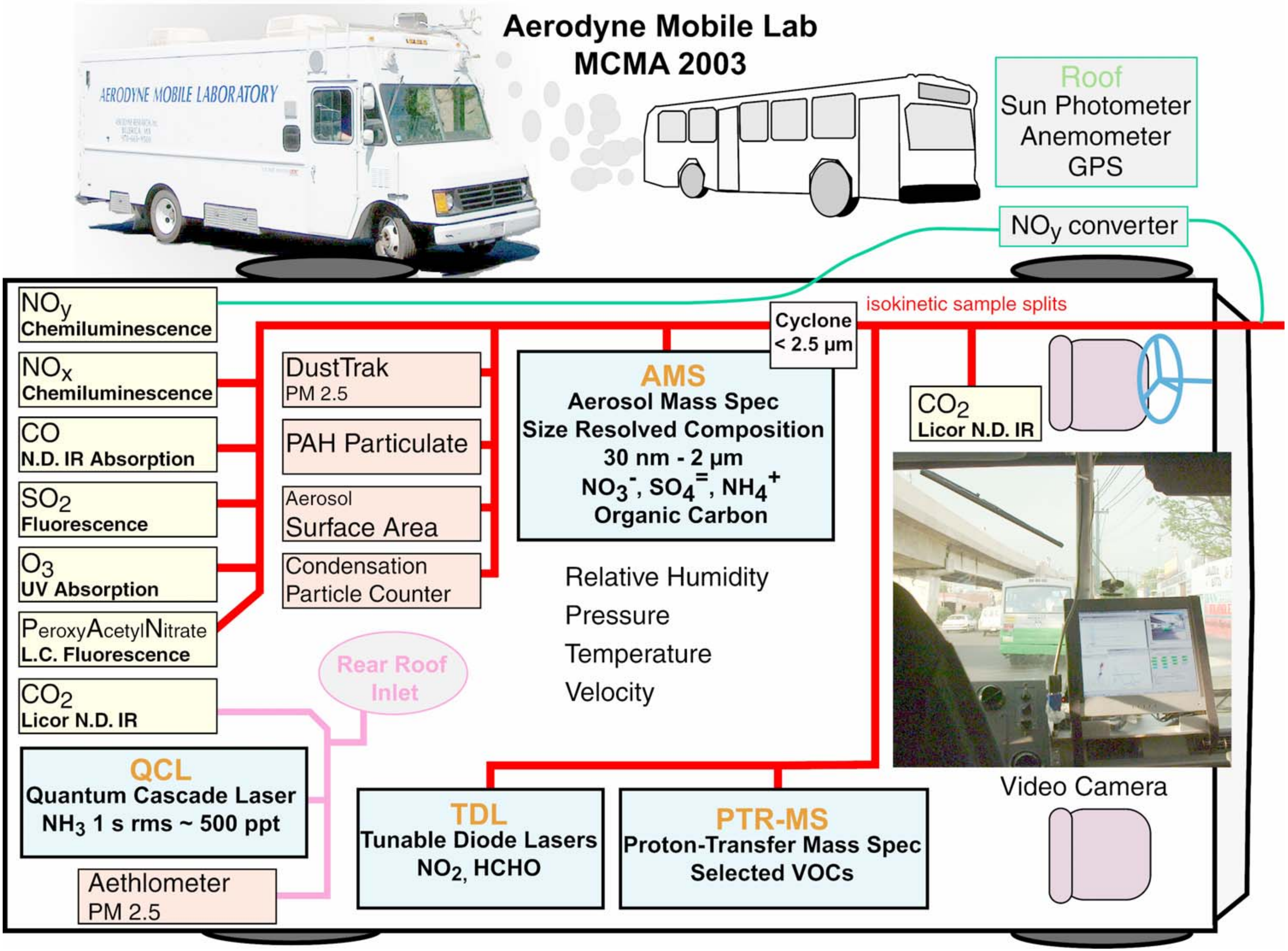
Researchers used a van equipped as a mobile laboratory to collect pollution data in the streets of Mexico City

1. GET THE PLUME
the van falls behind a vehicle

2. SMOKE IN
A pipe connected to a pump sucks exhaust into the van

3. ANALYZE THAT
Special Instruments identify types and concentrations of pollutants and store those data on a central computer

Aerodyne Mobile Lab
MCMA 2003



Roof
Sun Photometer
Anemometer
GPS

NO_y converter

isokinetic sample splits

Cyclone
< 2.5 µm

NO_y
Chemiluminescence

NO_x
Chemiluminescence

CO
N.D. IR Absorption

SO_2
Fluorescence

O_3
UV Absorption

PeroxyAcetylNitrate
L.C. Fluorescence

CO_2
Licor N.D. IR

DustTrak
PM 2.5

PAH Particulate

Aerosol
Surface Area

Condensation
Particle Counter

AMS
Aerosol Mass Spec
Size Resolved Composition
30 nm - 2 µm
NO_3^-, $SO_4^=$, NH_4^+
Organic Carbon

Relative Humidity
Pressure
Temperature
Velocity

CO_2
Licor N.D. IR

Video Camera

Rear Roof
Inlet

QCL
Quantum Cascade Laser
NH_3 1 s rms ~ 500 ppt

Aethlometer
PM 2.5

TDL
Tunable Diode Lasers
NO_2, HCHO

PTR-MS
Proton-Transfer Mass Spec
Selected VOCs

Performance Summary

What it took to get where we are…for LDGVs.

- Technology (HW & SW) – Ready [NH_3, Cold, Unmanned]
- Matching Laboratory Analyzers - Done
- Matching Inspection Results - Done
- Matching Fleet Emissions – Done

What it will take to get where we want to go…for DVs.

1. Technology (HW & SW) – SF Ready [NO_2, SO_2 Begun]
2. Matching Laboratory Analyzers - NO done [SF Begun]
3. Matching Inspection Results – NO done [SF ?]
4. Matching Fleet Emissions - ? [MBTA Begun, EPA Pending]