REMOTE SENSING MEASUREMENTS OF ON-ROAD HEAVY-DUTY DIESEL NO_X AND PM EMISSIONS

E-56

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Prepared for
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Purpose of the Study

- E-56 was to test whether remote sensing systems were able to reliably measure particulate matter (PM) vehicle emissions.
- Two systems, one from Denver University (DU) and one from Desert Research Institute (DRI) participated in the E-56 study. DU and DRI have each written reports analyzing their own data.
- The purpose of this report is to compare DU and DRI data.
- Three diesel test vehicles were used in E-56:
  - A Ford 250 (F250) equipped with controls that let it be either in a clean or dirty mode. The different modes of the Ford 250 were treated as two separate vehicles.
  - A 1986 Ford Van (Fvan) Club Wagon
  - A 4-cylinder Isuzu.

Three Phases of the Study

- E-56 had three phases:
  - Phase1: A Lab Study where all test vehicles were driven at steady state on a dynamometer at the Colorado Department of Public Health and the Environment (CDPHE) laboratory. Particles were collected and weighed.
  - Phase 2: A Parking Lot Study where the test vehicles were driven similar to the dynamometer drive cycle in Phase 1 and simultaneously measured by both DU and DRI remote sensing equipment.
  - Phase 3: An on-road Ramp Study where the test vehicles were driven similar to the dynamometer drive cycle in Phase 1 and both the test vehicles and other on-road vehicles were simultaneously measured by both DU and DRI equipment on a freeway on-ramp. The test vehicles were all diesel fueled. The majority of the other vehicles on the ramp were gasoline fueled.

Remote Sensing: Gaseous Pollutants & PM

- Remote sensing of gaseous HC, CO, and NO occurs because these pollutants absorb radiation at characteristic wavelengths.
  - Concentrations of pollutants in the tailpipe exhaust plume are measured together with carbon dioxide (CO2).
  - Many measurements are made as the plume disperses.
  - Concentrations of all species decrease at the same rate.
  - The pollutant are expressed as a ratio to the CO2. Pollutants can be expressed as gm per kg of combusted fuel since all the carbon in the combusted fuel is emitted as either CO2, CO, and HC.
- Remote sensing of particulate matter (PM) is more complex because PM both absorbs and scatters radiation. The scattering is a complex function of both size and shape of the particles. In this report, remote sensing PM is expressed as gm per kg of fuel.

DU and DRI Remote Sensing Techniques

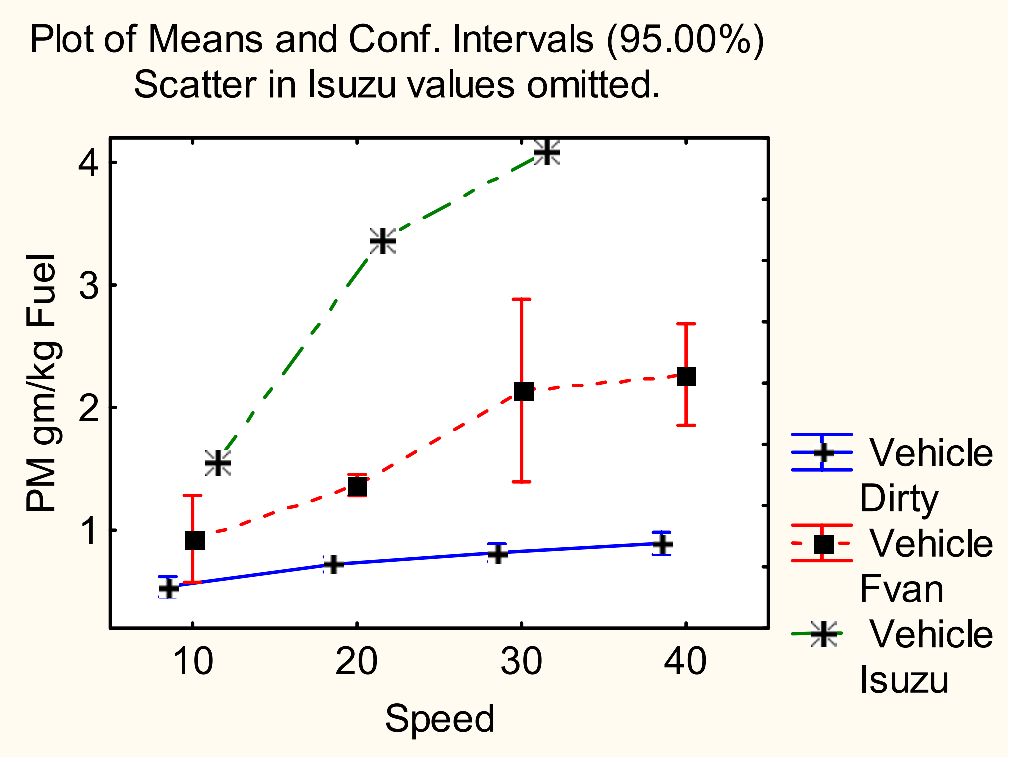
- DU used three different wavelengths of radiation in an attempt to characterize the particulate matter.
    - An IR source at 3900 nanometers (nm) wavelength,
    - A visible laser at 633 nm, and
    - A UV source at 240 nm.
  - The higher energy, shorter wavelength radiation should have shown more scattering from the PM.
  - The UV may have higher absorption due to polycyclic aromatics on the PM.
- DRI used reflected, back-scattered radiation from the particles with a UV laser at 266nm. The technique is called LIDAR.
- Instrument details and theoretical background for the remote sensing techniques are described in the DU and DRI E-56 reports. These are listed in the References Slide at the end of this document.

Phase 1: CDPHE Lab Study

- The purpose of the Lab Study was to:
  - Measure PM mass in gm per kg fuel.
  - Correlate measurements made with an on-board smoke detector (OBSD) with the measured PM mass in the Lab Study.
- The ‘four’ vehicles were operated on a steady state driving cycle for 240 seconds at speeds between 10 and 40 mph on a dynamometer. The load on CDPHE's 48 inch roll electric dynamometer was adjusted to simulate a road load at the grade specified according to known correlations.
- Particulate matter mass was collected for each run and measured by both CDPHE and GM. GM determined the %Volatile in the PM.
- A report of the Phase 1 work has not been written. A telephone conversation with Ken Nelson, CDPHE, was helpful in understanding aspects of the CDPHE Lab Study.

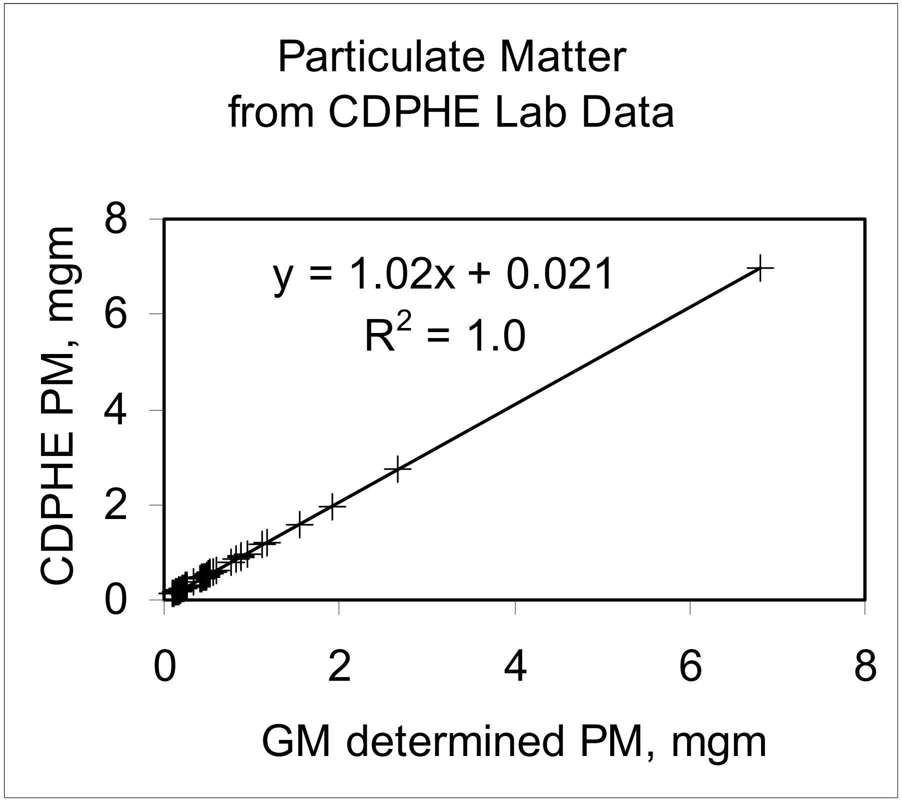
Phase 1: PM/Fuel by Speed and Vehicle

- At 2.8% grade, most similar to the grade in the parking lot (2.0%) and on the ramp (2.2%), average values of PM/Fuel were:
  - Characteristic of vehicle.
  - Linear with speed.
- No difference was seen between the clean and dirty modes of the F250 between 10 and 40 mph under driving cycle conditions with very limited clean mode data.



Phase 1: PM Mass Measurements

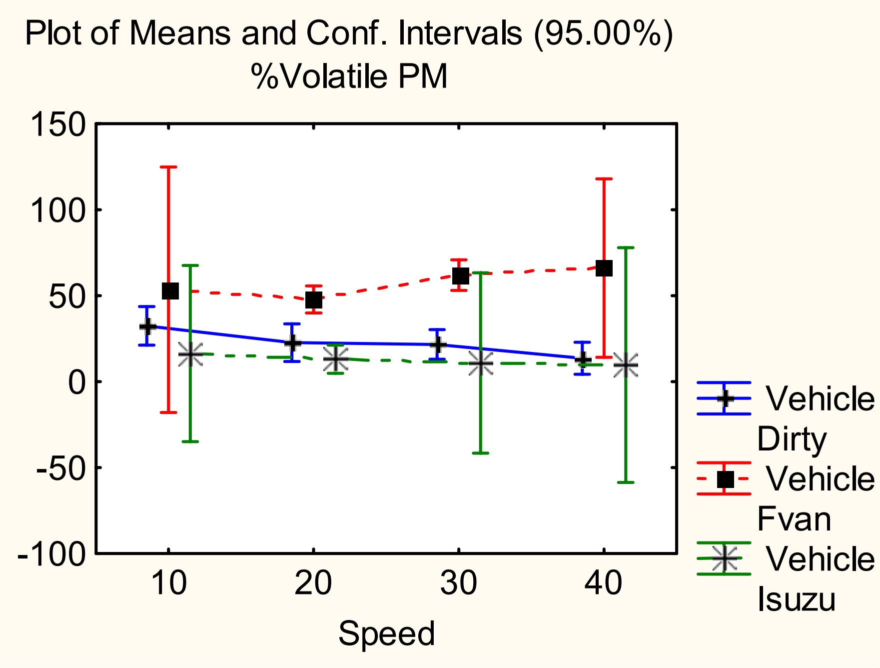
- Particulate matter was collected from a slipstream out of the dilution tunnel.
- Independent mass measurements of PM were made by CDPHE and GM.
- The mass measurements in milligrams (mgm) were in good agreement.
- The GM sample was classified into volatile and non-volatile PM.

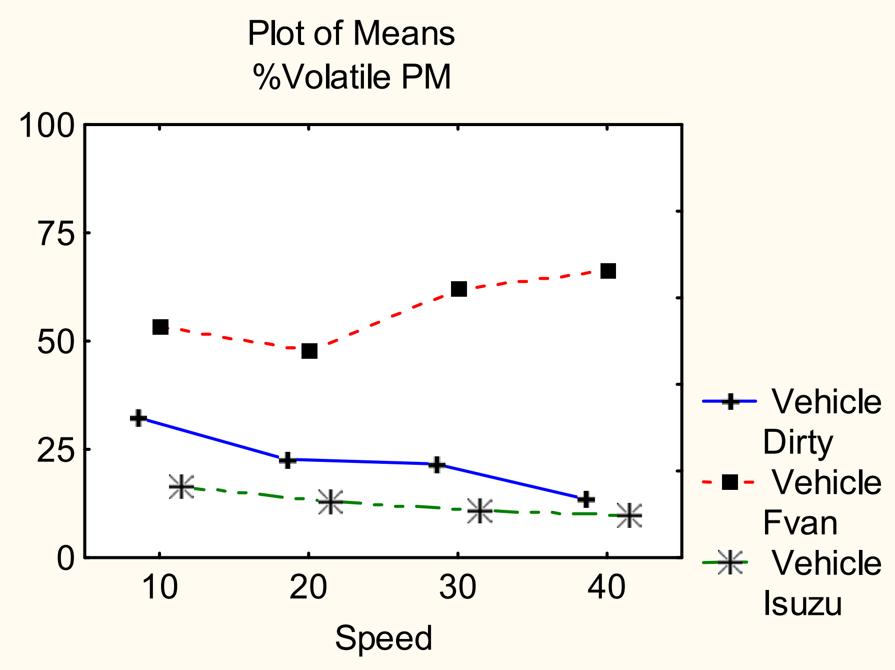


Phase 1: %Volatile PM

- %Volatile PM depended more on the vehicle than on the speed under the driving cycle conditions.
- There was much scatter in the data.
- F250 Clean had too few data points.

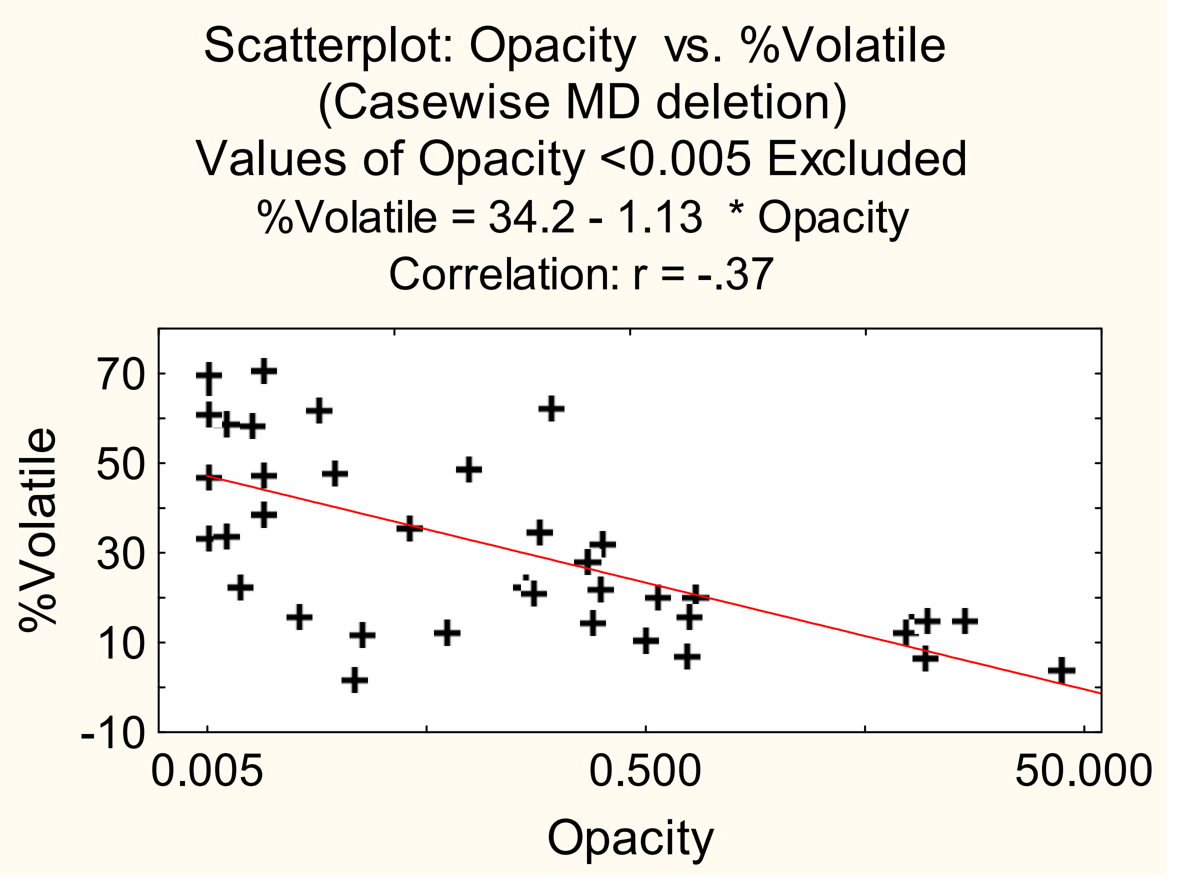
%Volatile Data Points					
Speed	Clean	Dirty	Fvan	Isuzu	Row
10	1	4	2	2	9
20	0	4	2	2	8
25	1	0	0	0	1
30	0	4	2	2	8
40	2	4	2	2	10
Total	4	16	8	8	36



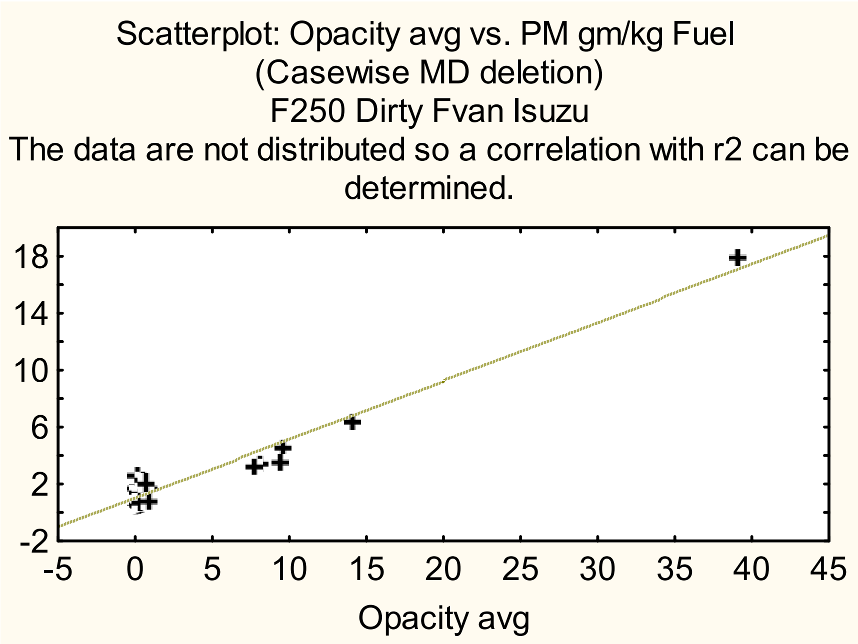


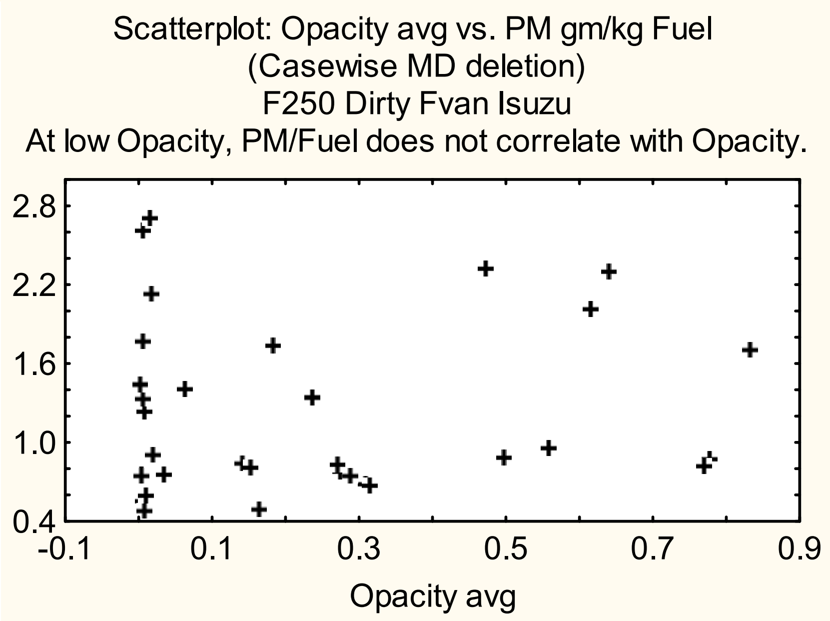
Phase 1: %Volatile and OBSD Opacity

- OBSD opacity increases with decreasing %Volatiles as would be expected since non-volatile PM is more opaque.



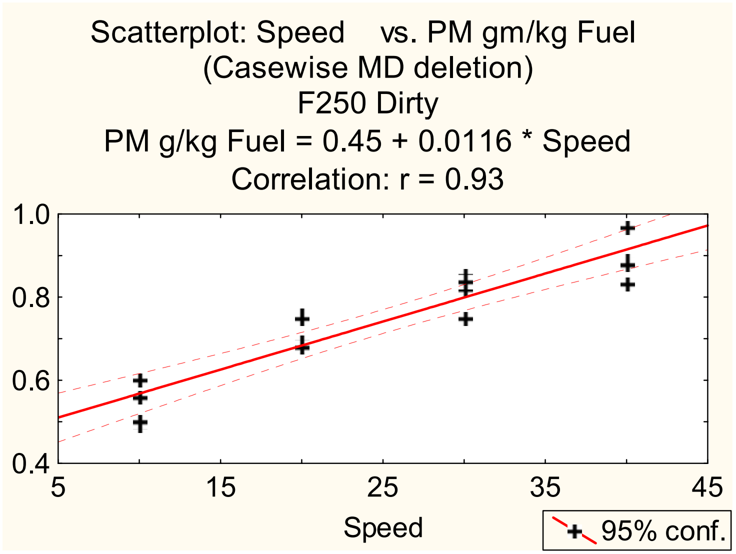
- Two problems with the OBSD opacity data.
  - There were insufficient numbers of high opacity values measured. At low opacity the amount of scatter is too large.
  - The on-board smoke detector (OBSD) was not on-board the vehicle when the Lab measurements were made. It was measuring opacity in the dilution tunnel.
- Due to the poor correlation, no further analysis was made using the OBSD data.

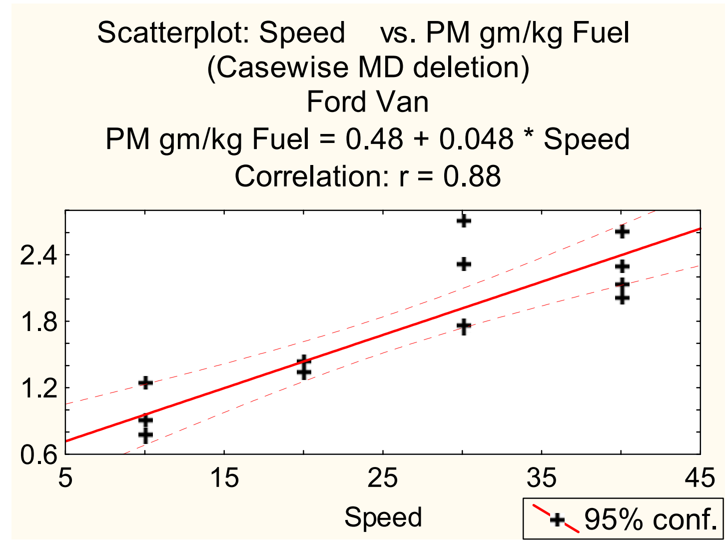


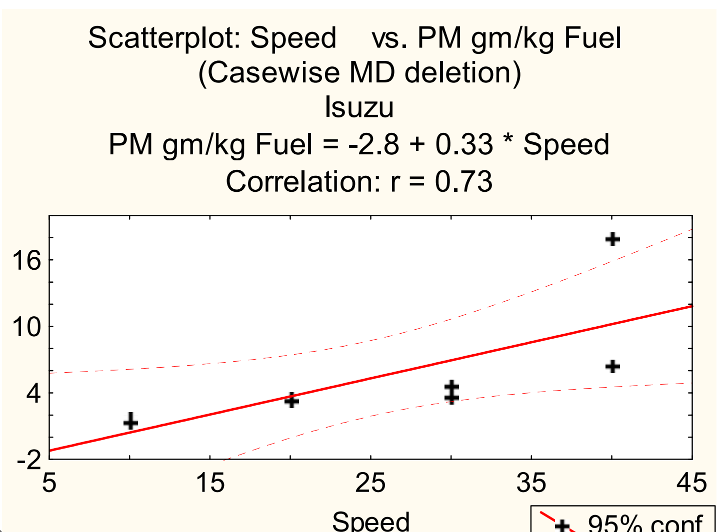


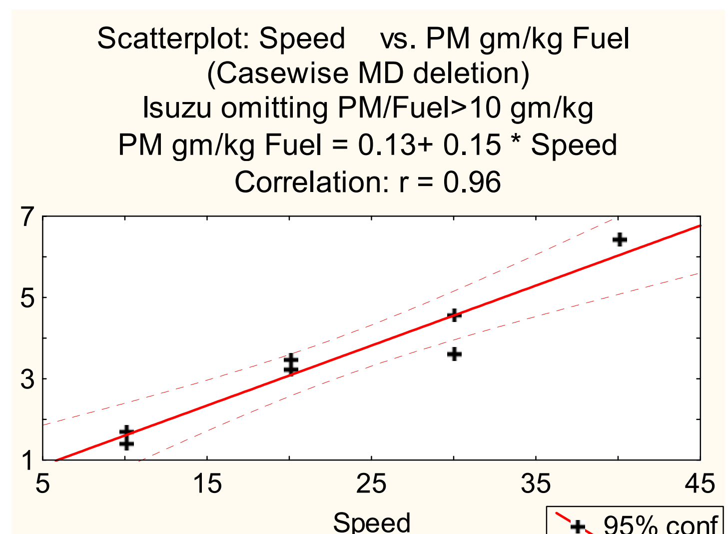
Phase 1: PM/Fuel by Vehicle and Speed.

(Casewise MD deletion means cases with missing data (“MD”) are not plotted)









Phase 1: PM gm/kg Fuel Equations

- Average PM gm/kg Fuel versus Speed data at 2.8% grade equivalent can be represented by linear equations characteristic of the vehicle,
  - y = PM gm/kg Fuel
  - x = Speed (from 10 to 30 mph).
  - These equations were used to estimate Lab Study measurements of PM mass corresponding to remote sensing PM in the Ramp Studies where speed varied from target levels.

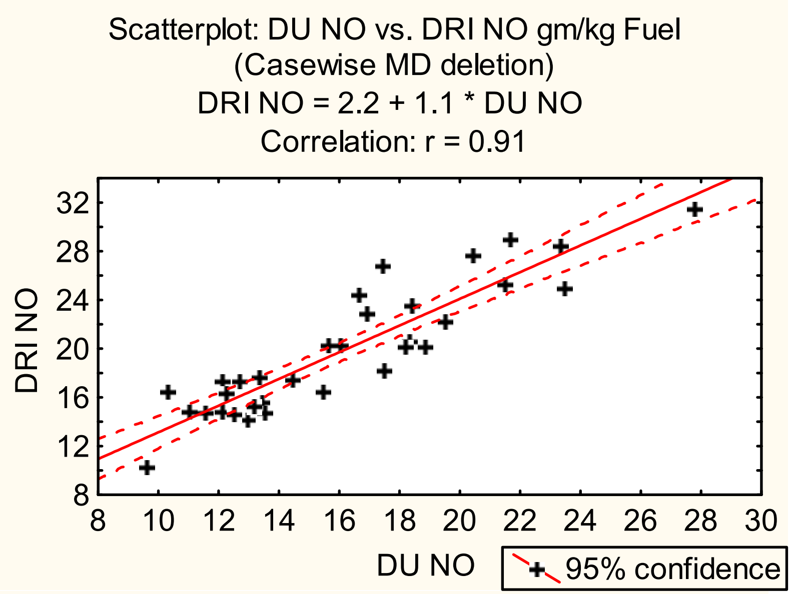
Average of PM/Fuel		
Vehicle	PM/Fuel as f(Speed)	R2
Clean	same as Dirty	
Dirty	$y = 0.0138x + 0.4147$	0.97
Fvan	$y = 0.0605x + 0.2671$	0.98
Isuzu	$y = 0.1266x + 0.4786$	0.94

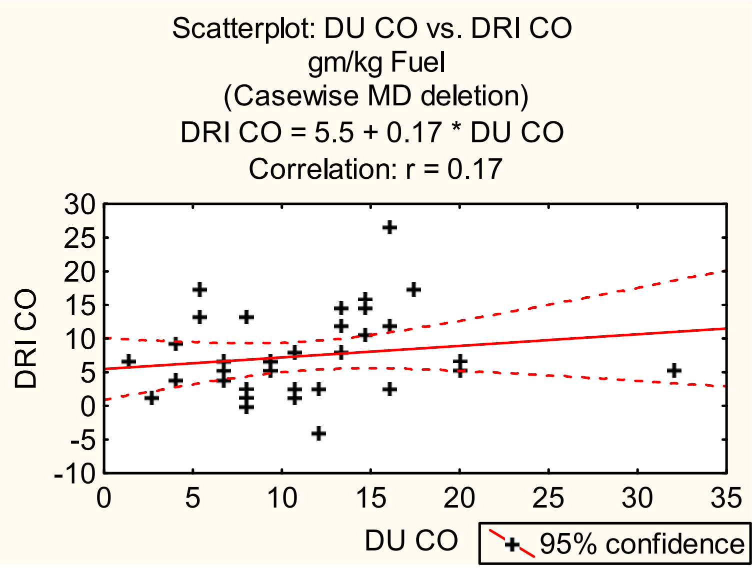
Phase 2: Parking Lot Studies

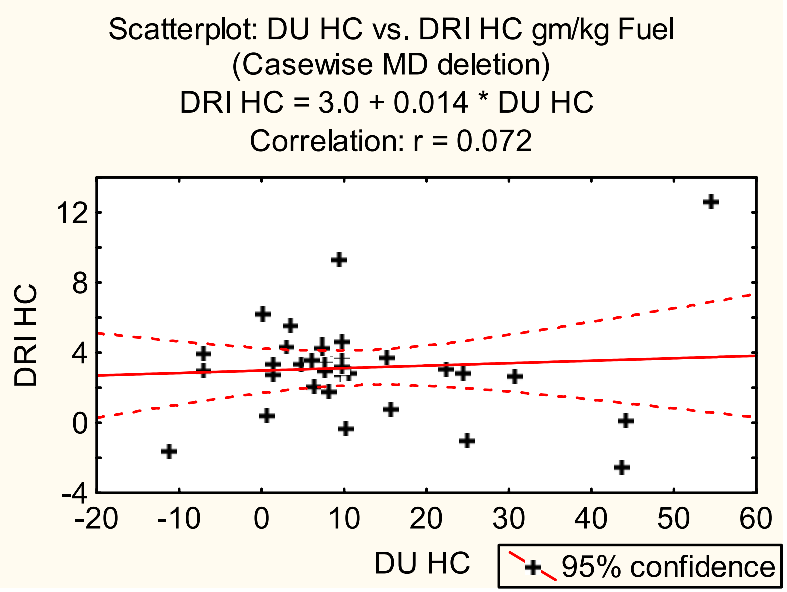
- On the first day of testing (February 21, 2001) “the two remote sensing systems were set up approximately 5 feet apart in a level portion of the parking lot and the measurements were made after the vehicles had approximately reached steady state operations.” (From the DU final report)

Phase 2: CO, HC, NO: DU and DRI Correlation

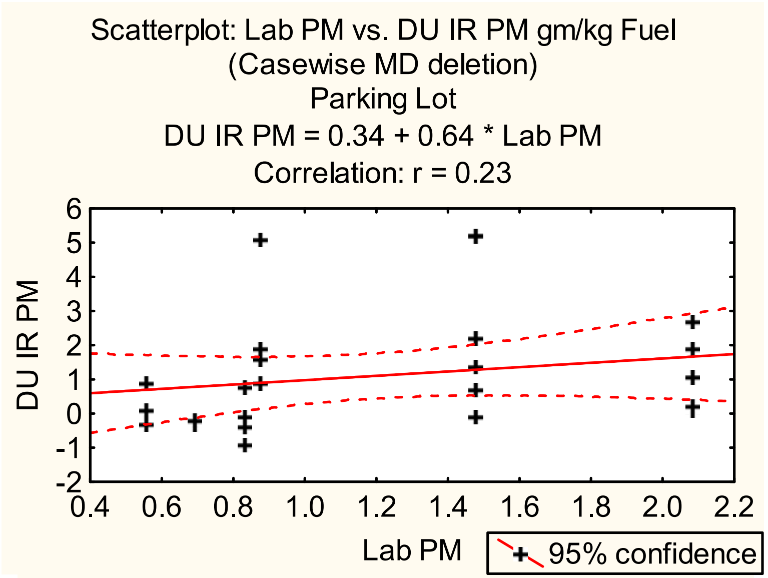
- Correlation between DU and DRI emissions measurements in the Parking Lot Study on the same Test Vehicles shows NO emissions correlated best, CO and HC worse.
- The lower CO correlations in the parking lot compared to the ramp were associated with much lower CO levels than observed on the ramp.

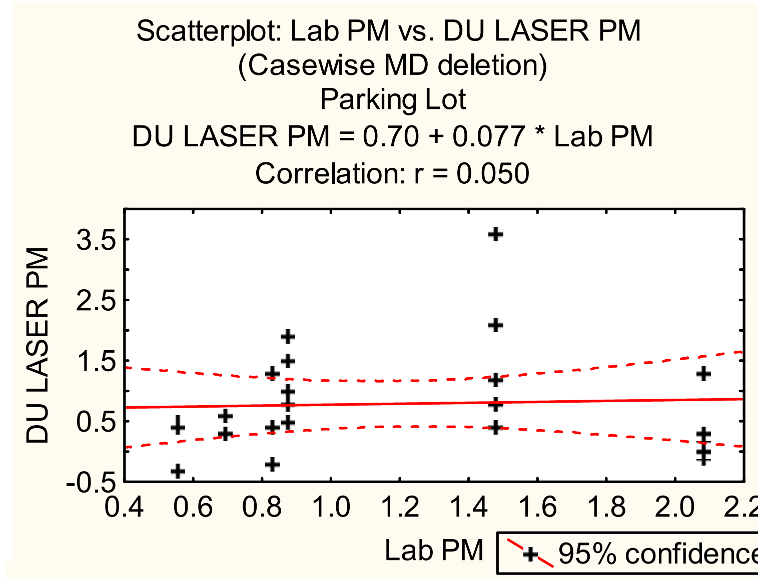


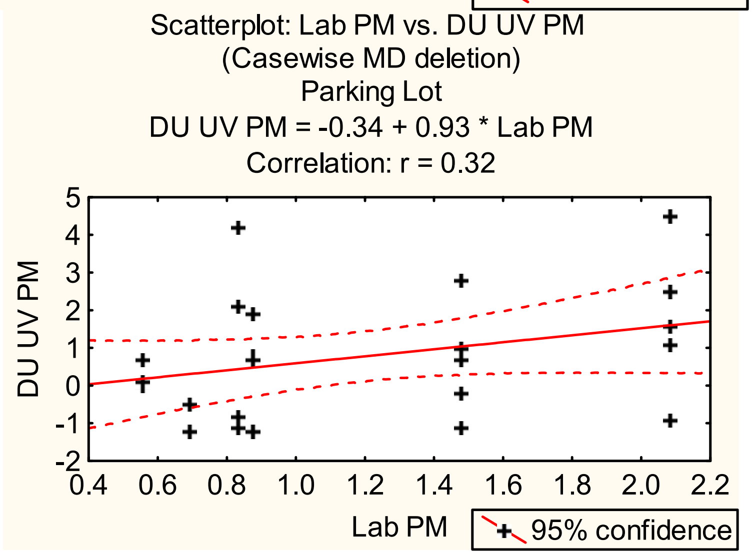


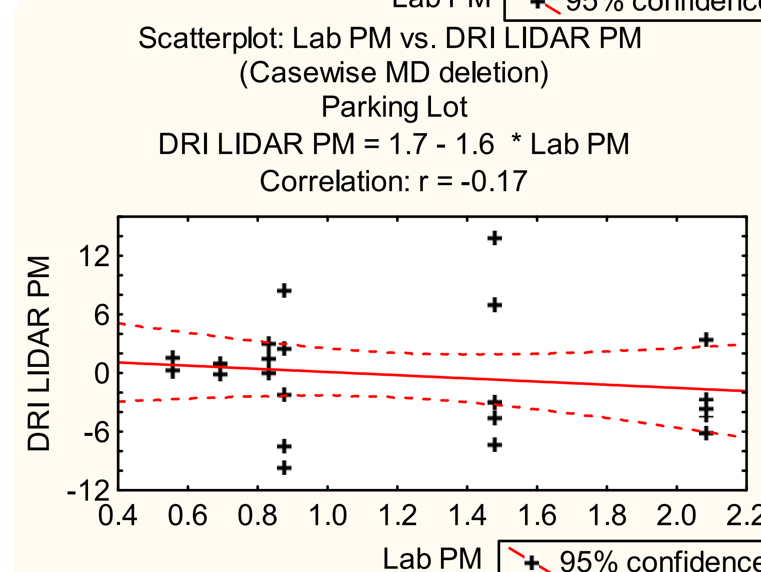


Phase 2: Parking Lot PM to Lab PM







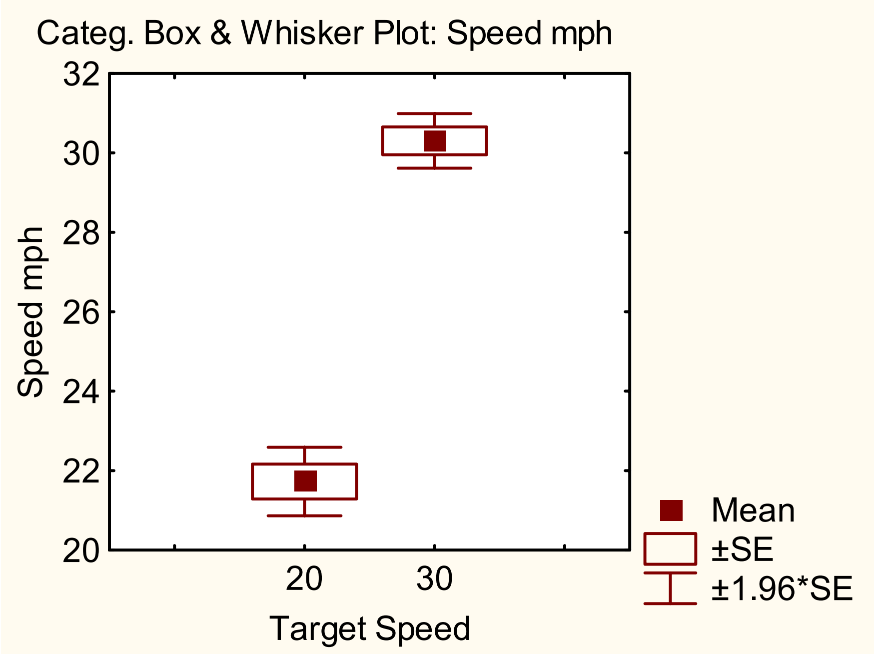


Phase 3: Ramp Studies

- "For the second day of testing (February 22, 2001) the two remote sensors were set up three quarters of the way around a curved uphill on-ramp from northbound University Blvd. to northbound I-25. Traffic volumes are relatively low (300 - 500 light-duty vehicles / hour) and the tightness of the curve limits operating speeds." (From the DU final report)
- The Test Vehicles used in the Lab and Parking Lot studies were examined on the Ramp in real traffic.
- Other Vehicles on the Ramp were measured. Although license plates were not identified in the databases, the times of the Test Vehicles were. This allowed the other vehicles that were measured by both DU and DRI instruments simultaneously to be identified and analyzed.

Phase 3: Test Vehicle Speed and Acceleration

- Measurements in the Lab were under controlled conditions.
  - Load was adjusted to simulate grade, acceleration was zero, speed was controlled at 10, 20, 30, or 40 mph.
- Conditions in the Parking Lot were controlled to be the same as in the Lab so that measurements could be directly compared.
- Speed and acceleration on the Ramp were less well controlled, but speed was slightly higher than target, and acceleration was not zero.

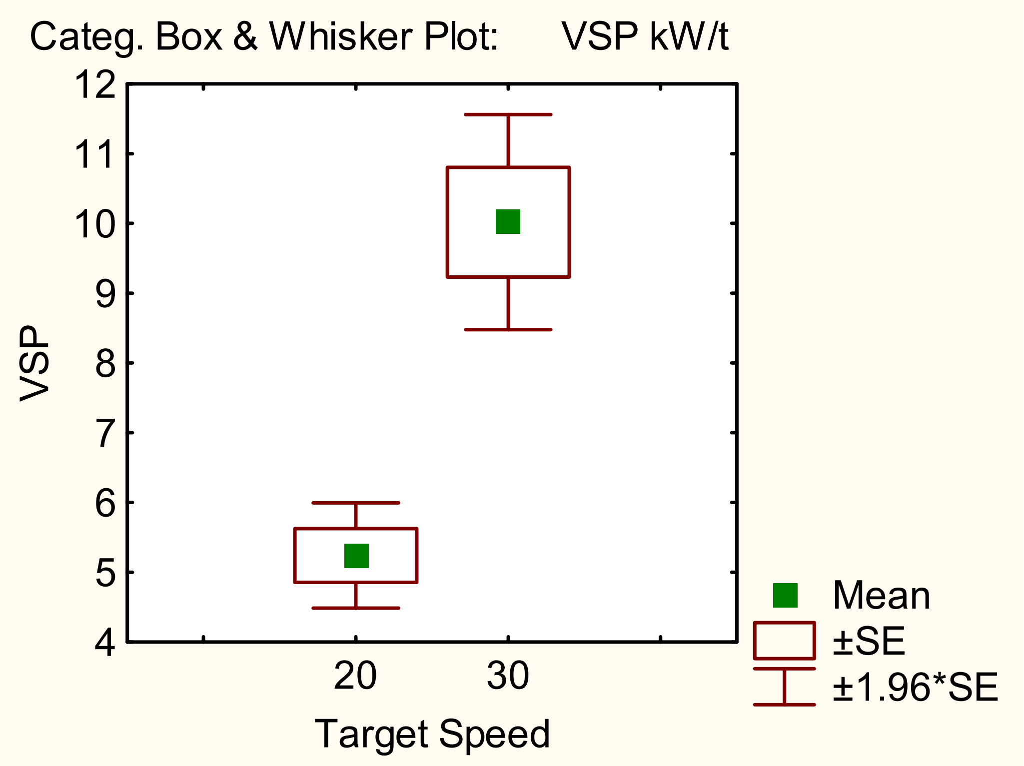


Phase 3: Test Vehicles Target and Actual VSP

- On the Ramp Test Vehicles were under a different load than intended.
- Load can be estimated by Vehicle Specific Power (VSP). VSP was about 50% over target on the Ramp. This could make a difference in comparisons between Ramp and both Parking Lot and Lab studies.

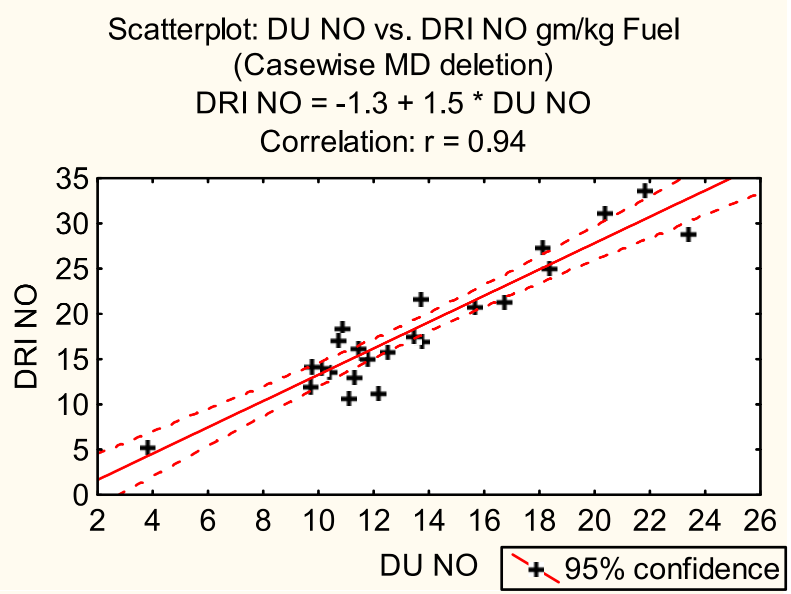
Ramp Target Values		
Speed	Accel	VSP
10	0	2
20	0	4
30	0	6
40	0	9

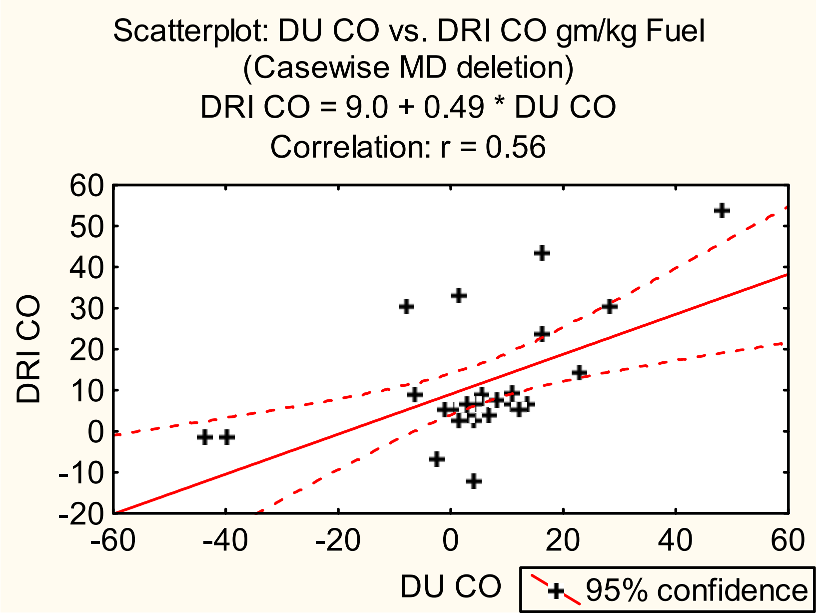
Activity	VSP
Maximum in FTP	23
Average in IM240	8
ASM 5015	6
ASM 2525	5

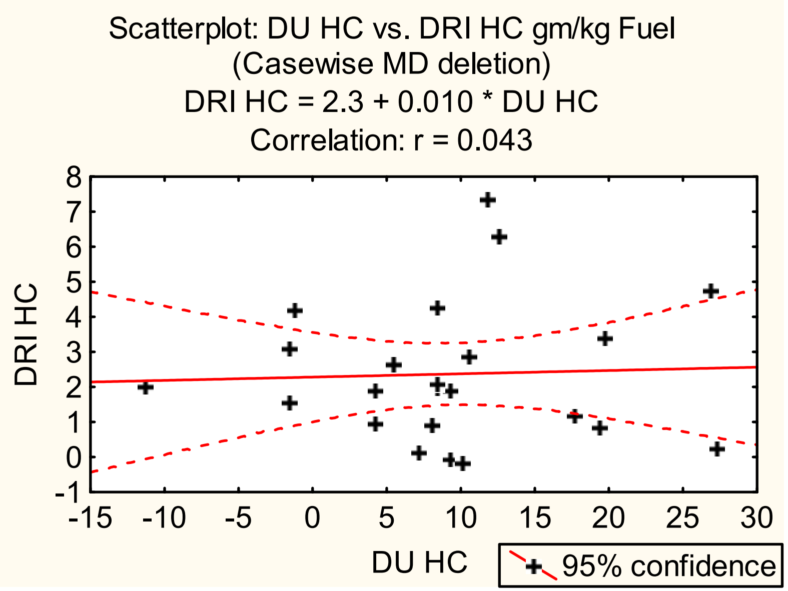


Phase 3: CO, HC, NO: Test Vehicles

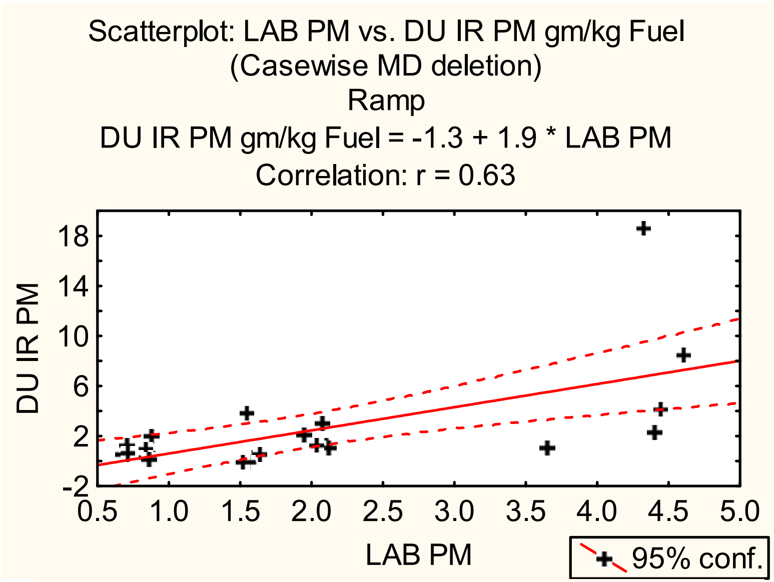
- Correlation between DU and DRI emissions measurements on the same Test Vehicles shows NO emissions correlated best, then CO and least of all HC.
- 3 values of DU HC gm/kg Fuel below -20 were not plotted.

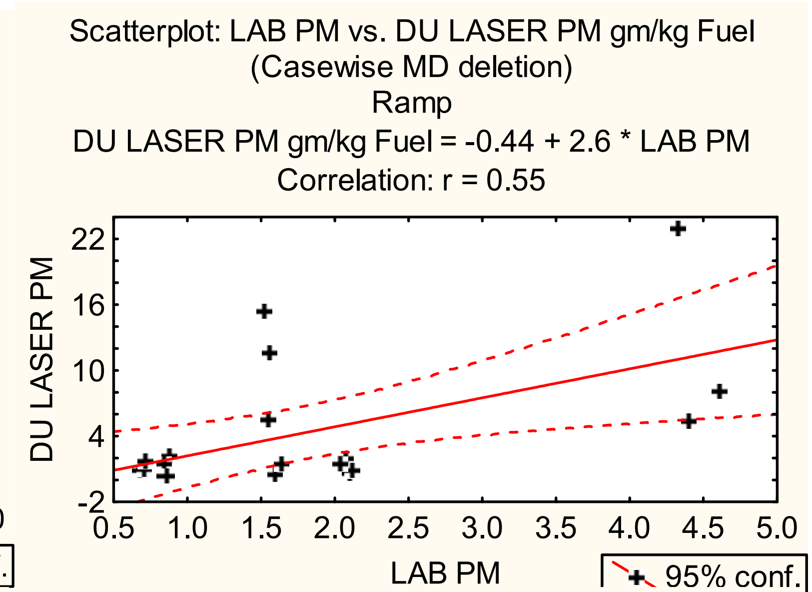


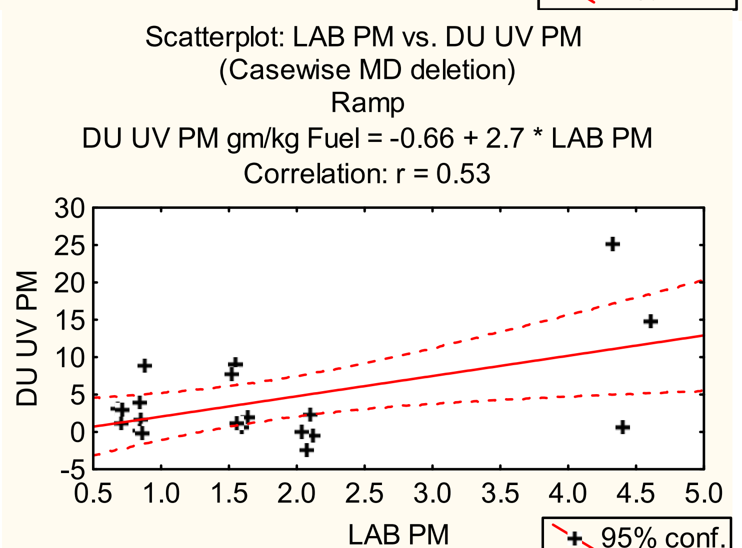


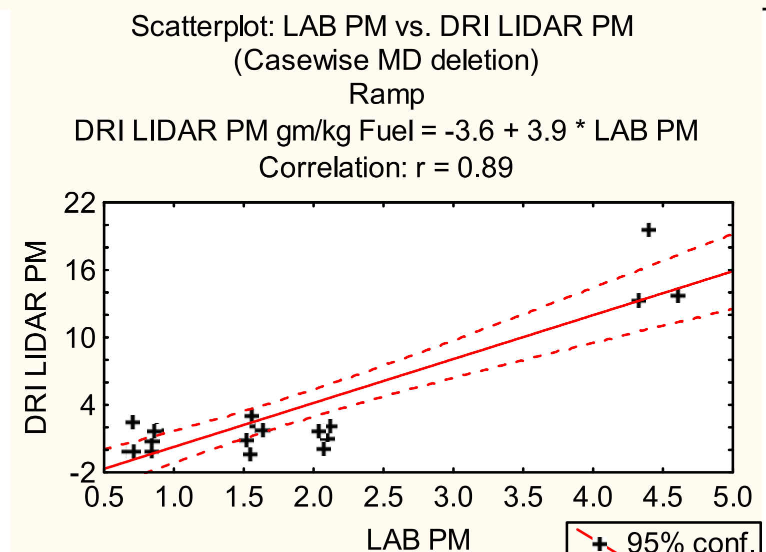


Phase 3: Ramp PM to Lab PM: Test Vehicles



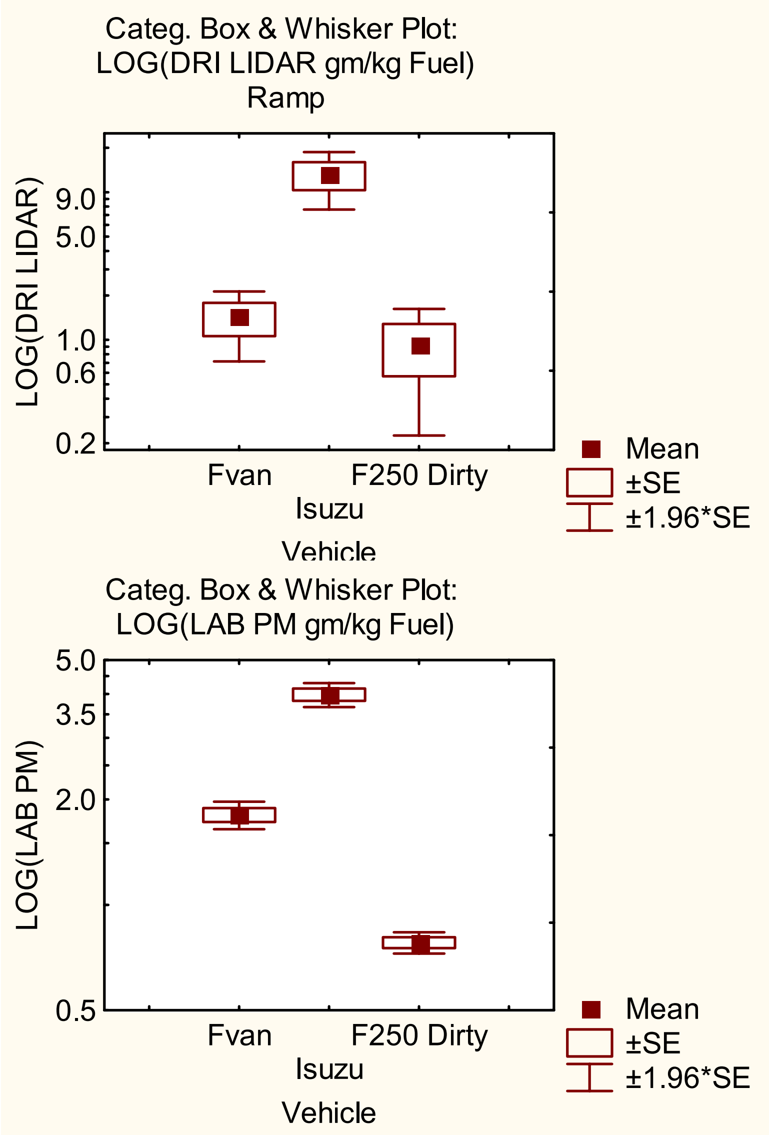






Phase 3: Improved Correlation with Test Vehicles

- The improved correlation from remote sensing PM on the Ramp was due to the high PM emitting Isuzu vehicle. In Phase 2, the plume on the Isuzu was too small.
- The charts on the right show the uncertainty in repeated measurements for the Ramp DRI LIDAR remote sensing measurements and the calculated Lab PM (the latter due to speed variation).



Phase 2 & 3: Test Vehicle PM Summary

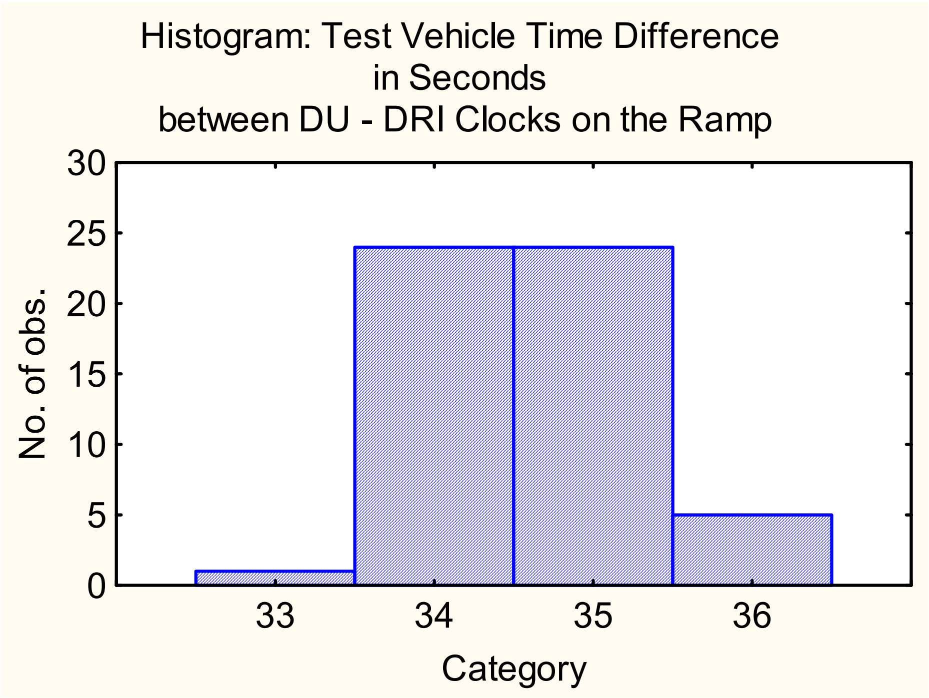
- In the Lab Study, PM, from ‘four’ Test Vehicles operated on a dynamometer, was collected and weighed.
- Average Lab PM for the F250 Clean at 2.8% grade equivalent was too uncertain because only four data points were taken.
- As a PM standard for comparison in the Ramp Study, Lab PM was calculated based on average Lab PM mass by vehicle as a function of speed.
- In the Parking Lot and on the Ramp, PM was measured on the test vehicles using a variety of remote sensing techniques.
- In the Parking Lot only F250 Dirty and the Ford Van could be compared. The Isuzu plume strength was too low in the Parking Lot.
- On the Ramp F250 Dirty, Ford Van, and the Isuzu could be compared. The Isuzu contributed high PM that improved correlation between remote sensing PM and Lab PM mass in the Ramp Study.
- A summary of PM Measurements is shown in Appendix A.

Phase 3: Selecting Other Vehicles on the Ramp using Test Vehicle Times

- In addition to the Test Vehicles operating on the Ramp, other vehicles were also being driven there. The other vehicles were mainly gasoline vehicles and were not subject to the same controlled driving conditions that the Test Vehicles were.
- Data from DU and DRI did not list license plates of individual vehicles. DU and DRI clocks were not synchronized. The DU and DRI instruments were not always operating at the same time. Some of the DU and some of the DRI measurements were not valid.
- In order to estimate which Ramp Vehicles had simultaneous valid measurements by both the DU and the DRI instruments, the time difference in seconds between DU and DRI clocks for the Test Vehicles was used. Vehicles selected for Ramp Vehicle analysis were those with valid measurements on both DU and DRI instruments and having the same time differences on the DU and DRI clocks as the Test Vehicles.

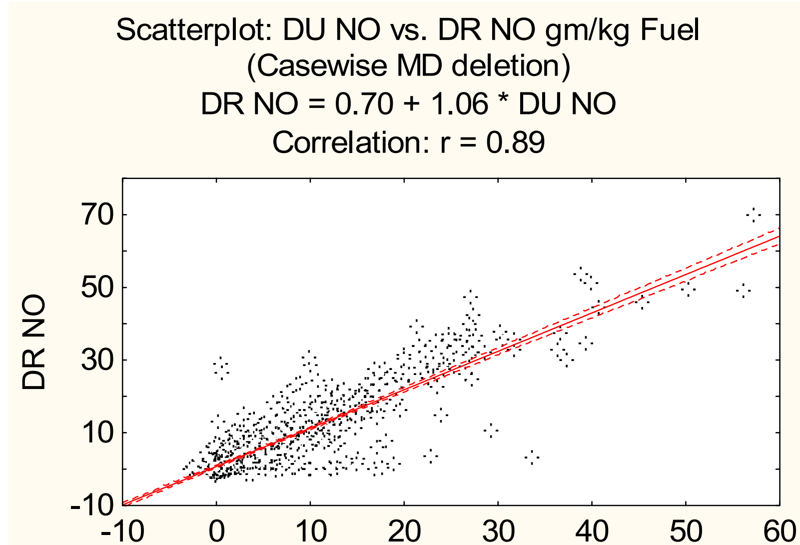
Phase 3: Times for Matched Test Vehicles

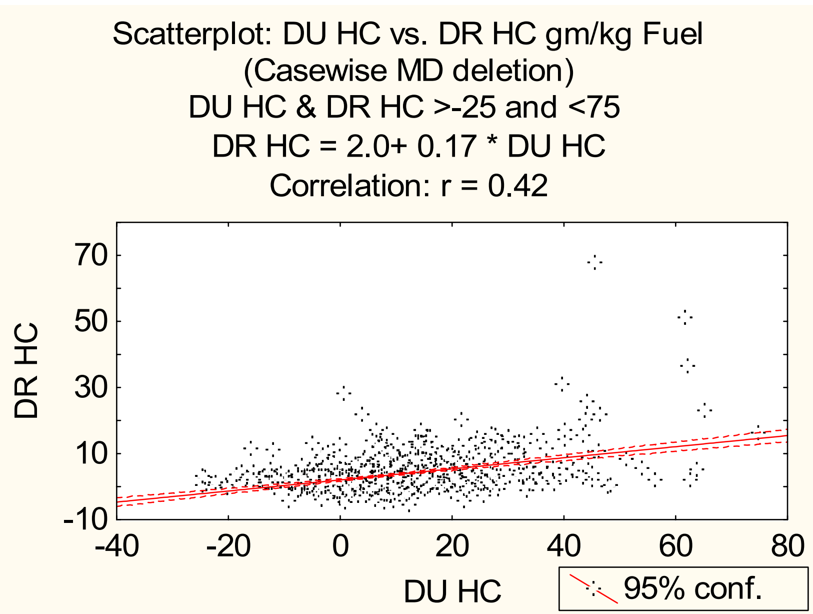
- Although DRI and DU clocks were not synchronized, test vehicle times on the Ramp were identified by both DRI and DU. The difference in clock times for the Test Vehicles was used to match vehicles measured by both DU and DRI on the Ramp.
- There were 826 matched vehicle records on the Ramp with (DU clock - DRI) clock time difference = 34 seconds and 1075 matched vehicle records with time difference = 35 seconds.

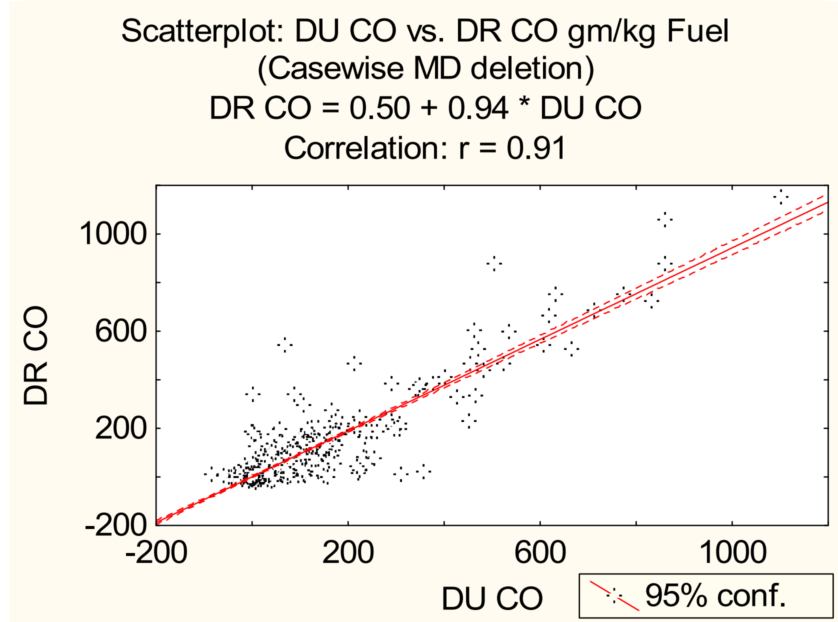


Phase 3: NO, CO, HC - All Vehicles on the Ramp

- Vehicles 34 or 35 seconds apart on DU and DRI clocks were mainly gasoline vehicles.
- Good correlation was seen for NO and CO. The CO levels were higher than for the diesel Test Vehicles, as expected.







Phase 3: NO, CO, HC: Test and All Ramp Vehicles

- Differences between Ramp Vehicles and Test Vehicles on the Ramp measured by both DU and DRI:
  - Ramp Vehicles were mainly gasoline vehicles; Test Vehicles were all Diesel.
  - Ramp Vehicles were not held to the speed and acceleration targets that Test Vehicles were.
- As expected, NO emissions on the Ramp. were higher for Test Vehicles; CO and HC emissions were higher for all Ramp Vehicles

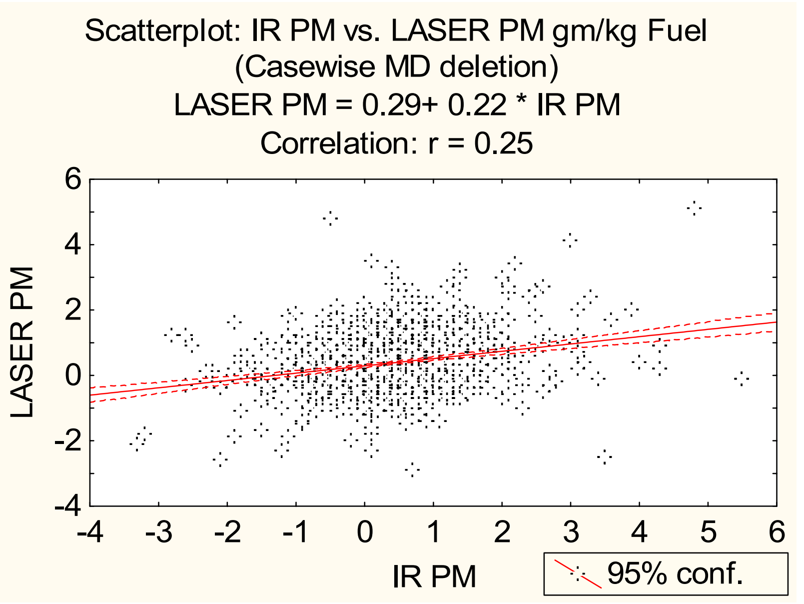
RAMP	NO Emissions	gm/kg Fuel	
Vehicles		Valid N	Mean
Ramp	DRI NO	741	6.2
Ramp	DU NO	741	5.2
Test	DRI NO	25	17.7
Test	DU NO	34	8.1

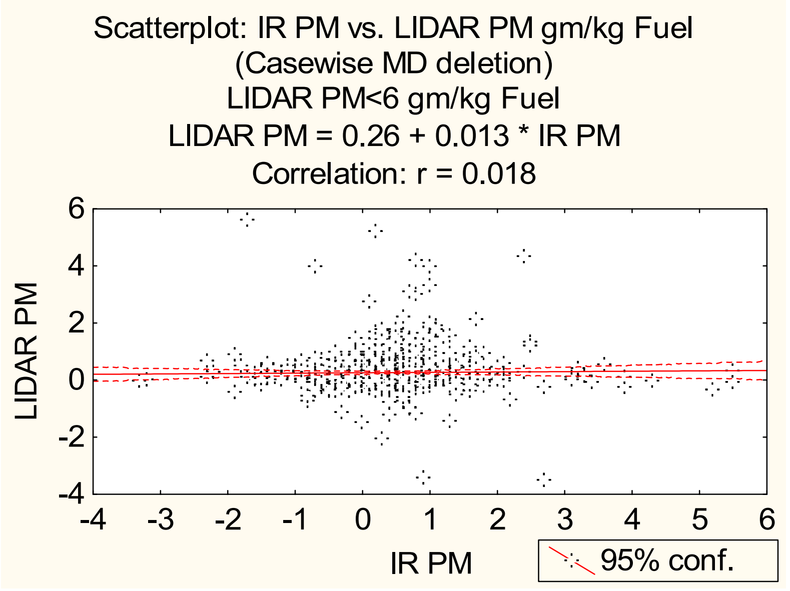
RAMP	CO Emissions	gm/kg Fuel	
Vehicles		Valid N	Mean
Ramp	DRI CO	796	48.8
Ramp	DU CO	796	51.3
Test	DRI CO	29	10.4
Test	DU CO	34	4.4

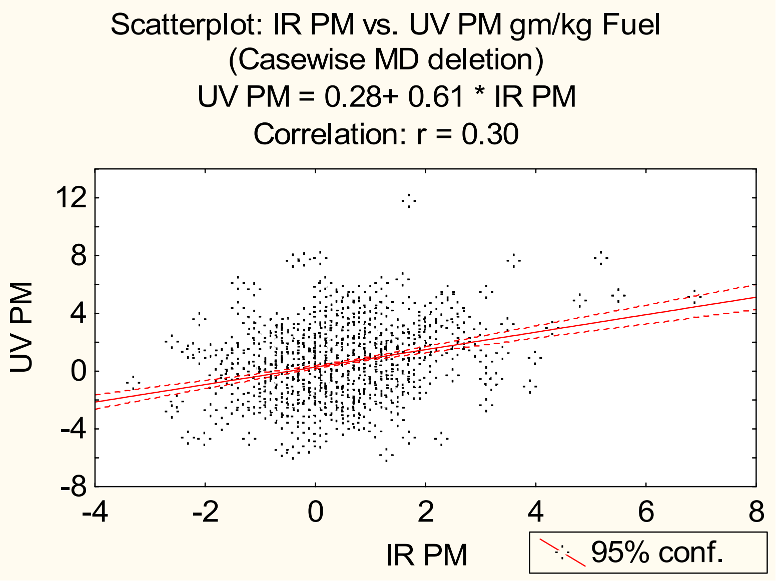
RAMP	HC Emissions	gm/kg Fuel	
Vehicles		Valid N	Mean
Ramp	DRI HC	791	3.6
Ramp	DU HC	791	11.4
Test	DRI HC	27	2.1
Test	DU HC	34	1.2

Phase 3: PM - All Vehicles on the Ramp

- Vehicles 34 or 35 seconds apart on DU and DRI clocks were mainly gasoline vehicles.
- Correlation for different DU PM measurements were low.
- Correlation between DU and DRI PM measurements was near zero.







Phase 3: PM - Test and All Ramp Vehicles

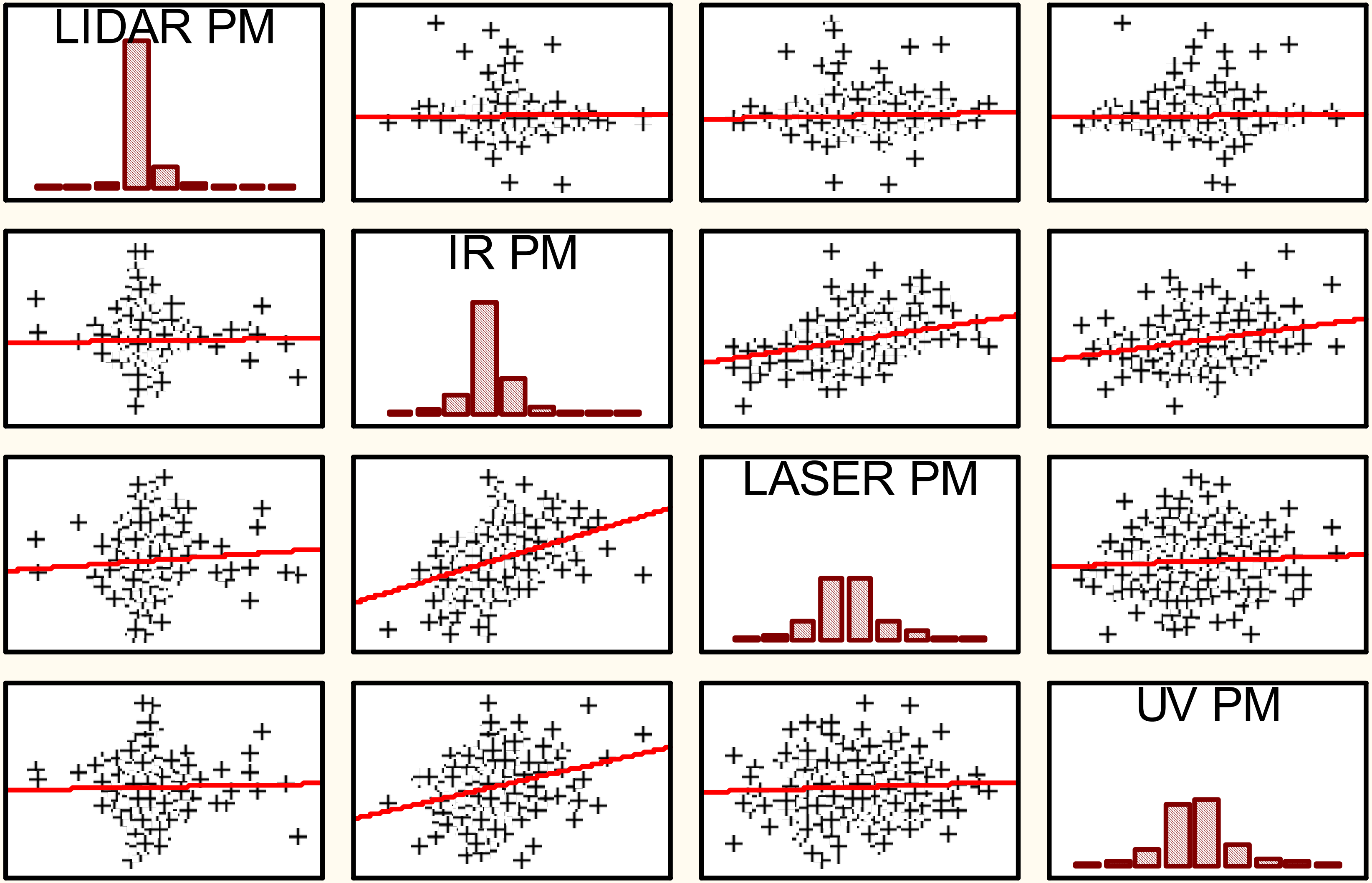
- Differences in PM on the Ramp between Ramp Vehicles and Test Vehicles measured by both DU and DRI simultaneously:
  - Ramp Vehicles were mainly gasoline vehicles; Test Vehicles were all Diesel.
  - Other Vehicles were not held to the speed and acceleration targets that Test Vehicles were.
- As expected, PM emissions measured on the Ramp were higher for Test Vehicles.

RAMP PM Measurements, gm/kg Fuel				
Vehicles	Investigator	Technique	Valid N	Avg. PM
Ramp	DU	IR	1161	0.36
Ramp	DU	LASER	1153	0.38
Ramp	DU	UV	1126	0.50
Ramp	DRI	LIDAR	846	0.37
Test	DU	IR	35	1.83
Test	DU	LASER	35	6.22
Test	DU	UV	35	2.62
Test	DRI	LIDAR	30	2.84

Phase 3: Correlation between PM Remote Sensing Techniques: All Vehicles on Ramp

- Simultaneous valid PM gm/kg fuel measurements were made by DRI (LIDAR instrument) and DU (IR, visible LASER, and UV instruments). The DRI instrument relies on back scatter, and the DU instruments rely on absorption and scattering at different wavelengths.
- Correlations between the measurement techniques are shown in the next chart in a Matrix Plot. The distribution of values are shown for each in a histogram. To find the correlation between two data from two measurement techniques, select the graph at the intersection of the row of one technique histogram and the column of another technique histogram.
- In the Matrix Plot, flat horizontal lines indicate no correlation such as between DRI LIDAR and DU IR.
- Highly slanted lines indicate a good correlation, for example between DU IR and DU LASER.

Correlations (RAMP RSD OFFSET.sta) for valid PM measurements



Conclusions: Remote Sensing PM 2001

- The particulate matter remote sensing techniques may have promise but currently lack sensitivity at PM levels below the level of about 4 gm/kg Fuel.
- If further experiments are to be conducted, more high PM emitters should be used in the vehicle selection.

References

- "Measurement Of Diesel Particulate Emissions By UV LIDAR Remote Sensing In Denver, Co, February 21-22, 2001," by R. Keislar, P. Barber, H. Kuhns, C. Mazzoleni, H. Moosmüller, N. Robinson, and J. Watson, Desert Research Institute, August 2002, prepared for The Coordinating Research Council.
- "Opacity Enhancement of the On-Road Remote Sensor for HC, CO and NO," by D. H. Stedman and G. A. Bishop, University of Denver, February 2002, Final Report for E-56-2, Prepared for the Coordinating Research Council.
- Data from the Colorado Department of Public Health and Environment Laboratory Study and measurements of particulate matter by General Motors, available from the Coordinating Research Council.

Appendix A: Summary of Test Vehicle PM Measurements

- The PM measurements from the Lab Study that were used to compare with remote sensing measurements in the Parking Lot and Ramp studies are shown in the Table below.
- The remote sensing measurements in the Parking Lot and Ramp studies are shown in the next two slides.

PM Measurements in the Lab Study, gm/kg Fuel				
Vehicle	Target Speed	LAB PM	LAB PM	LAB PM
		Mean	SteDev	N
Fvan	20	1.6	0.0	5
Fvan	30	2.0	0.1	5
Isuzu	20	3.5	0.2	5
Isuzu	30	4.4	0.1	5
F250 Dirty	20	0.7	0.0	4
F250 Dirty	30	0.8	0.0	5

Test Vehicle PM Measurements in the Parking Lot Study

- PM measurements on vehicles in the Parking Lot that could be compared with similar measurements from the Lab Study were only obtained on the Ford Van and the F250 in the Dirty mode.

PM Measurements in the Parking Lot Study					
Vehicle	Speed	DU IR	DU LSR	DU UV	DRI LDR
		Number of measurements			
Fvan	10	5	5	5	5
Fvan	20	5	5	5	5
Fvan	30	5	5	5	5
Dirty	10	5	5	5	3
Dirty	20	5	5	5	2
Dirty	30	5	5	5	4
All Groups		30	30	30	24

PM gm/kg Fuel in the Parking Lot Study									
Vehicle	Speed	DU IR	DU IR	DU LSR	DU LSR	DU UV	DU UV	DRI LDR	DRI LDR
		Mean	SteDev	Mean	SteDev	Mean	SteDev	Mean	SteDev
Fvan	10	2.3	1.6	1.1	0.6	0.6	1.1	-1.6	7.4
Fvan	20	1.9	2.0	1.6	1.3	0.6	1.5	1.3	8.9
Fvan	30	1.2	1.1	0.3	0.6	1.8	2.0	-2.6	3.6
Dirty	10	0.2	0.6	0.3	0.4	0.9	1.1	0.8	0.8
Dirty	20	0.0	0.6	0.4	0.2	-0.3	0.6	0.5	0.7
Dirty	30	-0.2	0.6	0.5	0.5	0.7	2.3	1.6	1.3

Test Vehicle PM Measurements in the Ramp Study

- PM measurements on vehicles on the Ramp that could be compared with similar measurements from the Lab Study were only obtained on the Ford Van, the Isuzu, and the F250 in the Dirty mode.

PM Measurements in the Ramp Study, gm/kg Fuel					
Vehicle	Target Speed	DU IR	DU LSR	DU UV	DRI LDR
		Number of Measurements			
Fvan	20	5	5	5	5
Fvan	30	5	5	5	4
Isuzu	20	1	1	1	1
Isuzu	30	4	4	4	3
F250 Dirty	20	4	4	4	3
F250 Dirty	30	5	5	5	5

PM Measurements in the Ramp Study, gm/kg Fuel									
Vehicle	Target Speed	DU IR	DU IR	DU LSR	DU LSR	DU UV	DU UV	DRI LDR	DRI LDR
		Mean	SteDev	Mean	SteDev	Mean	SteDev	Mean	SteDev
Fvan	20	1.0	1.7	7.0	6.5	4.2	4.0	1.5	1.3
Fvan	30	1.8	0.8	1.5	0.7	0.1	1.7	1.3	0.9
Isuzu	20	1.1	0.0	4.8	0.0	-1.4	0.0	5.9	0.0
Isuzu	30	8.4	7.3	10	9	12.3	10.4	16	4
F250 Dirty	20	0.8	0.3	1.6	0.8	2.0	1.4	0.8	1.5
F250 Dirty	30	0.9	0.7	1.1	0.9	2.9	3.7	1.0	0.8