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

E-56

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E-56 Data Analysis.

Summary

This report summarizes the analysis of E-56 data obtained in Denver in February 2001 during a comparative test of two systems, one by Denver University and the other from Desert Research Institute, which were attempting to measure particles in vehicle exhaust plumes by remote sensing.

The two systems, at their then current state of development, were, at best, only able to distinguish particle measurements from a diesel vehicle above 4 grams/kilogram of fuel from those below 2.5 grams/kilogram of fuel. In February 2001, these instruments were not ready for obtaining reliable remote sensing particulate emissions measurements from on-road vehicles.

Background

Fine particles 2.5µm and smaller are suspected of being the major human health risk in ambient air.[1] However, an understanding of the critical parameter in fine particle health hazard is not yet well understood (whether this parameter is related to mass, particle area, or particle composition). Motor vehicles, particularly diesel vehicles, generate fine particles. Recent source apportionment studies indicate that motor vehicle sources dominate the elemental carbon observed on ambient samples taken in urban settings, with emissions from diesel exhaust contributing between 50%and 70% of the elemental carbon mass concentration.[2] Regulations to restrict the amount of fine particle mass emitted from vehicles will result in diesel engine design changes, diesel exhaust after-treatment, and fuel composition changes.[3]

Currently, there is only limited understanding of particle emissions from on-road vehicles. Almost all measurements have been made in the laboratory on individual vehicles under conditions that do not replicate particle formation in the exhaust plume during on-road driving. In laboratory particle measurements, the exhaust is diluted with much less excess air than occurs in the exhaust plume when the vehicle is on the road.[4] To understand fine particle generation from the vehicle fleet, to see how vehicle particle

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[1] For example, see the reanalysis, led by Health Effects Institute, of the two major cohort studies on particulate health effects at http://www.healtheffects.org/Pubs/st-reanalysis.htm

[2] Watson, J.G., E. M. Fujita, J. C. Chow, B. Zielinska, L. W. Richards, W. Neff, and D. Dietrich. 1998. Northern Front Range Air Quality Study (NFRAQS). Final Report Executive Summary, DRI Document No. 6580-685-8750.1F2. Cited by EPA in http://www.epa.gov/ttn/chief/eiip/pm25inventory/newtopmC2.pdf

[3] US EPA rule established a single comprehensive national control program that will regulate the heavy-duty vehicle and its fuel as a single system. The new sulfur standards for highway diesel fuel begin to take effect in 2006. The new emissions standards for heavy-duty vehicles begin to take effect in 2007. http://www.epa.gov/otaq/regs/fuels/diesel/diesel.htm#regs. Additional information at http://www.dieselnet.com/news/9912epa2.html, http://www.dieselnet.com/news/0109epa2.html, Heavy-Duty Engines and Vehicle Standards and Highway Diesel Sulfur Control Requirements

[4] For a discussion of the difference between particle formation in laboratory dilution tunnels and exhaust plumes of diesel vehicles see CRC Project E-43 reports.

generation varies from one vehicle to another, and from diesel to gasoline fueled vehicles, one must be able to make measurements on tens of thousands of vehicles under normal driving conditions.[5] Remote sensing of vehicle exhaust could carry out such measurements if instruments and techniques for making measurements were developed.

CRC Project E-56 requested organizations that were developing remote sensing devices for measuring vehicle exhaust particles to participate in a comparative test (a 'shoot-out') in Denver in February 2001. Two organizations participated in the study. The University of Denver (DU) used opacity measurements, the radiation lost by absorption and scattering, at three different wavelengths, to measure particulate matter (PM) in the exhaust plume. Desert Research Institute (DRI) used back scattered radiation (LIDAR). Each remote sensing instrument suite also had the capability of measuring carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxide (NO), and hydrocarbons (HC). Both DU and DRI have written detailed final reports describing their individual results and the theory behind their instruments.[6,7] This report compares results from DU and DRI.

<u>Discussion of Results</u>

The test had three phases. Phase 1 consisted of three test vehicles (diesel light and medium duty trucks)[8] operated on a steady state driving cycle in the laboratory of the Colorado Department of Public Health and the Environment (CDPHE). Particle mass was measured using a standard dilution tunnel. A sample of the particle mass was collected and analyzed for both volatile PM and elemental carbon. The weight of particle mass from the tailpipe would serve as a standard for the remote sensing measurements carried out under very similar conditions. Particle mass was measured as a function of the vehicle and the vehicle speed operating under conditions simulating a 2.8% road grade. The fraction of volatile PM was determined for a portion of the particle mass. A smoke detector was used to measure PM in the dilution tunnel. All vehicle exhaust emissions in this report are expressed as grams per kilogram of fuel.

In Phase 2 of the study, the same diesel test vehicles were operated at steady speed in a parking lot with a 2% road grade while the vehicles were measured by the remote sensing instruments. Although the vehicles, the speeds, and road grade were the same or very similar to what was used in the CDPHE laboratory, there were two significant differences between Phase 1 and Phase 2. The particles measured in the exhaust plume in the parking lot in Phase 2 were formed under significantly different dilution conditions from

[5] Some Statistical Issues in the Statistical Analysis of Vehicle Emissions, Wenzel, T., Singer, B.C., Slott, R., Journal of Transportation and Statistics. 3:2, 1-14 (Sept 2000)
[6] "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.
[7] "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.
[8] Three diesel test vehicles were used in E-56: A Ford 250 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. The other vehicles were a 1986 Ford Van Club Wagon, and a 4-cylinder Isuzu.

particles measured in the dilution tunnel in Phase 1. The vehicle load in the parking lot did not result in valid remote sensing measurements to be conducted on the dirtiest vehicle tested in Phase 1 by either DU or DRI. At the levels of PM emissions seen from the other test vehicles, below 2.5 gm/kg fuel based on Phase 1 measurements, the correlations between remote sensing measurements in the parking lot and particle mass collected in the dilution tunnel were poor for both DU and DRI instruments. The results from the smoke detector, on-board the test vehicles in Phase 2, measuring exhaust directly, did not correlate with the Phase 1 particle mass. The smoke detector results were not used in Phase 3. Remote sensing NO emissions measured simultaneously by DU and DRI on the same vehicles correlated well ($r > 0.9$). The corresponding remote sensing HC and CO emissions measurements did not correlate well between the DU and DRI instruments ($r < 0.2$). The HC and CO emissions were at low levels, as expected for diesel test vehicles (see Table 1).

In Phase 3 of the study the same diesel test vehicles were operated on a freeway on-ramp with a 2.2% road grade. The test vehicles were driven under conditions as similar as possible to conditions in the CDPHE laboratory and in the parking lot. However, speed and acceleration were higher than in the earlier phases leading to 50% on average higher vehicle load in Phase 3.[9] As a result of the higher load, the dirtiest test vehicle had a plume strength which allowed valid remote sensing measurements to be made. The DRI instrument was better than the DU instruments at distinguishing the higher PM emissions from the dirtiest test vehicle (3.5 to 4.7 gm/kg fuel per Phase 1 mass measurements) from the lower PM emissions from the other test vehicles (less than 2.5 gm/kg fuel).

Simultaneous remote sensing measurements from the DU and DRI instruments were also made on many of the other vehicles on the ramp. CO emissions from vehicles on the ramp were higher than the test vehicle measurements as would be expected from a fleet consisting mainly of gasoline powered vehicles containing a distribution of vehicle ages (see Table 1). With the higher average CO emissions, remote sensing CO and NO emissions measured simultaneously by DU and DRI on the same vehicles correlated well ($r = >0.88$). The corresponding remote sensing HC emissions measurements did not correlate well between the DU and DRI instruments ($r < 0.45$). The HC emissions were at low levels. There were no "Phase 1" PM mass measurements as standards for the other vehicles on the freeway on-ramp in Phase 3. However, inter-instrument correlations of simultaneous PM measurements could be examined. The cross correlations showed that the DRI LIDAR measurements did not correlate with DU opacity measurements. The best cross instrument correlations were between the DU IR and DU visible laser opacities.

A PowerPoint presentation describing the E-56 results is available.[10]

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[9] Vehicle specific power (VSP) is a measure of the vehicle's instantaneous load per mass. Engine-out emissions have been found to correlate very well with this parameter. VSP can be estimate by speed, acceleration, and road grade. "Vehicle Specific Power: A Useful Parameter for Remote Sensing and Emission Studies," J. L. Jiménez, P. McClintock, G. J. McRae, D. D. Nelson, and M. S. Zahniser, 9th CRC On-Road Vehicle Emissions Workshop, San Diego, April 21st 1998

[10] Negative readings are a result of instrument noise or interferences which could not be accounted for properly.

Conclusions and Recommendations

While E-56 data showed remote sensing systems capable of making consistent measurements of fleet NO and CO emissions, the two remote sensing instruments evaluated in the E-56 February 2001 Denver shoot out were not ready for making particulate measurements from the on-road vehicle fleet.

Considering the importance of vehicle particle control, and the desire to monitor in-use equipment for particle control, further studies of remote sensing devices to measure on-road vehicle particulate matter would be worthwhile if continuing instrument development takes place.

Figures

Table 1: Number of Measurements and Average Values of CO, NO, and HC in Phase 2 and 3 in grams pollutant per kilogram of fuel.

		Test Vehicles				Ramp Vehicles	
		Phase 2		Phase 3			
		Pk Lot		Ramp		Ramp	
		N	Avg	N	Avg	N	Avg
DRI	CO	36	7	24	10	436	54
DU	CO	45	12	24	1	436	54
DRI	NO	34	20	24	18	436	7
DU	NO	45	16	24	13	436	6
DRI	HC	35	3	24	2	436	4
DU	HC	45	10	24	-4	436	8

Table 1 includes all values for Phase 1, but only vehicles simultaneously measured by both DU and DRI with valid CO, HC, & NO in Phase 2 .