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Project Summary

Heavy Duty Diesel Fine Particulate Matter Emissions: Development and Application of On-Road Measurement Capabilities

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EPA's On-road Diesel Emissions Characterization Facility, which has been collecting real-world gaseous emissions data for the past 6 years, has recently undergone extensive modifications to enhance the facility's particulate matter (PM) measurement capabilities, with a specific emphasis on fine PM or $PM_{2.5}$ (particles less than 2.5 µm in aerodynamic diameter). At present, the facility's capabilities are focused on continuous sampling and analysis, using fast-responding instruments such as the Electrical Low-Pressure Impactor (ELPI), the Tapered-Element Oscillating Microbalance (TEOM), and a particle-bound Polycyclic Aromatic Hydrocarbon (PAH) analyzer, all of which require a dilute exhaust sample. This dilute sample has been drawn directly from the vehicle exhaust via a stack dilution system, and sampled from the ambient exhaust plume via probes in the trailer. Dilute samples have also been collected on filters for chemical and gravimetric analysis. Experimental results indicate that stack dilution sampling does not adequately represent real-world conditions as determined from initial plume sampling. Therefore, future efforts will be directed toward improved plume characterization techniques.

This Project Summary was developed by the National Risk Management Research Laboratory's Air Pollution Prevention and Control Division, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Because of the current level of interest in fine particulate matter and its health effects, EPA has refocused a substantial amount of its research to study emissions sources that produce fine PM. Diesel engines, already under substantial EPA scrutiny for their nitrogen oxides (NO_x) emissions, are also known to emit large quantities of small particles, although it is not known how much of the fine PM in ambient air actually comes from diesel engines, especially those used in heavy duty diesel vehicles (HDDVs).

A number of researchers have collected diesel fine PM data, mostly using engines mounted on dynamometers and, to a lesser extent, chassis dynamometer facilities. These facilities allow for the collection of data under very controlled, repeatable conditions. Many of these conditions are of a steady-state nature, where the emissions are allowed to stabilize before data or samples are collected. Though steady-state tests prove useful for producing repeatable results and comparisons, there is no consensus on how well steady-state tests represent real-world emissions. More transient tests, on the other hand, typically suffer from poor measurement repeatability. Fine PM measurements in particular are problematic because many of the most sensitive instruments cannot follow such rapidly changing conditions. Nonetheless, it is likely that it will take a combination of steady-state and transient tests to fully characterize fine PM emissions from HDDVs.

The Air Pollution Prevention and Control Division of EPA's Office of Research and Development has developed its on-road approach as sort of a reality check for HDDV emissions estimates. By replacing assumptions with measurements, and simulation parameters with real-world operating conditions, the On-road Diesel Emissions Characterization (ODEC) facility provides another dimension to the data currently available for quantifying and characterizing HDDV emissions. Fine PM measurement capabilities have recently been added as an extension of this original purpose. The report describes the facility's fine PM measurement capabilities, and presents data from on-road testing of two truck configurations.

Description of Heavy-Duty Test Facility

The general capabilities of the ODEC facility are shown in Figure 1. Its purpose is to allow emissions testing of heavy-duty diesel vehicles (HDDVs) in a manner that represents the real world as closely as possible. Fully integrated into a Class 8b truck, the facility is designed to be completely self-contained, able to collect several hours' worth of data while traveling along public roadways. A majority of the data are collected in real time by continuous analyzers which allows comparisons between emissions and vehicle operating modes. These data include vehicle parameters, engine parameters, and emissions measurements. Cumulatively, all of these measurements form the core capabilities of the facility, those that remain intact as more task-specific capabilities are added and removed.

Capabilities added for fine PM characterization included a stack dilution sampling system, plume sampling, and the ability to operate a number of sophisticated fine PM instruments. Of all the instrumentation that is available to measure and characterize fine PM, none of it is compatible with raw diesel exhaust. The ODEC facility follows two approaches to providing dilute samples to the PM instruments: (1) a direct-dilution system that draws samples from the raw exhaust and dilutes them with clean air, and (2) probes that draw naturally diluted samples directly from the truck's exhaust plume. Each is described below.

The design of a direct-dilution system is of considerable importance when sampling fine PM. Several researchers have demonstrated that particle size measurements can be fundamentally altered by changes in dilution ratios, residence times, and physical characteristics of the sampling system. Other considerations that are specific to mobile test facilities include the size of the dilution system, its power demands, and how the raw exhaust is delivered to its inlet.

Based on all of these concerns, the facility currently utilizes the "ejector diluter" system used by David Kittelson at the University of Minnesota in much of his work. This system uses air-powered ejectors to draw in samples and mix them with a rapid flow of filtered air. Using a combination of multiple stages and inlet orifices, the system can deliver dilution ratios as high as 1000:1 while using less than 20 SCFM of compressed air. In designing the system, intermediate stage residence times and dilution ratios are manipulated to create a system that attempts to simulate the real-world dilution of an ambient exhaust plume. The accuracy of this simulation, however, is currently limited by our knowledge of how the plume itself dilutes.

Sampling directly from the plume is possible because the high-dump (elevated) exhaust stack that is most common on Class 8 trucks typically creates a plume that is seldom completely disrupted as it passes along the length of the trailer. Since the ODEC facility's laboratory is already built into the trailer, plume sampling is simply a matter of mounting probes directly behind the truck's exhaust stack, and locating the necessary instrumentation near these probes.

The fine PM instrumentation consists of:

- Electrical Low-Pressure Impactor (ELPI) – uses a cascade impactor and electrical particle detection to provide real-time size classification and quantification of particulate with aerodynamic diameters from 0.03 to 10 μm.
- Polycyclic Aromatic Hydrocarbon (PAH) analyzer – produces real-time measurements of surface-bound PAHs using the principle of photoelectric ionization.
- Tapered-Element Oscillating Microbalance (TEOM) – measures particulate mass in real time by calculating the harmonic frequency change of a vibrating element (where the mass includes collected particulate).
- Aethalometer – uses an optical measurement to calculate the amount of black carbon deposited on a quartz filter tape.
- Condensation Nucleus Counter (CNC) – uses condensation particle growth and optical detection to count particles from 3 nm to 1 μm in diameter.

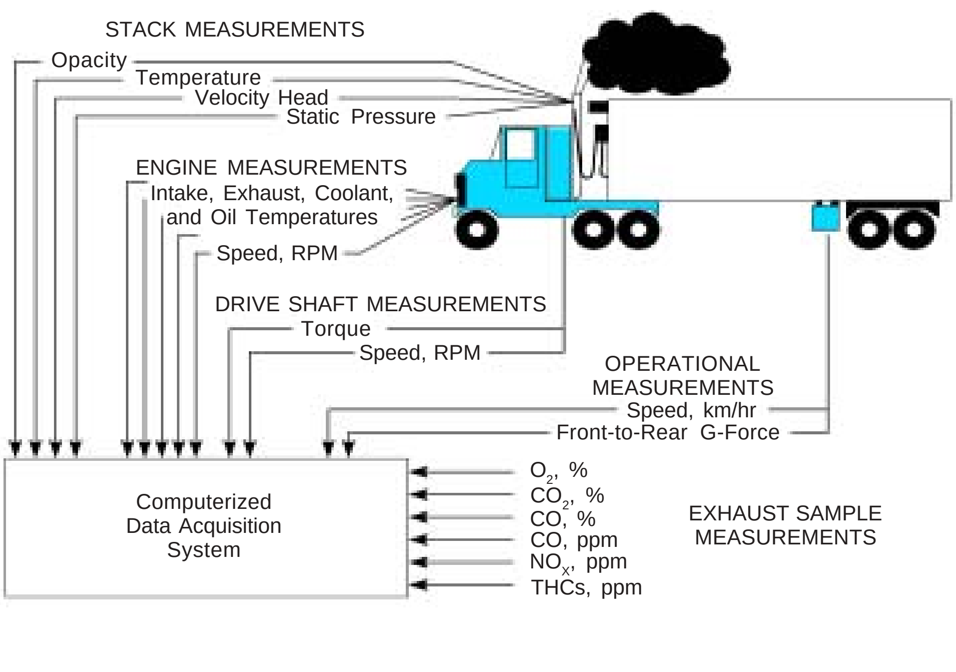

Figure 1. On-road Diesel Emissions Characterization Facility

Fine PM Emissions Data

Each technique used for fine PM sampling (direct-dilution and plume sampling) has its advantages and disadvantages. For direct-dilution, the advantages relate to the ability to control the dilution process: a well-designed system should maintain a steady dilution ratio and introduce little or no background to the dilute sample. This minimizes variability due to factors unrelated to the source concentrations, and allows straightforward calculation of those concentrations. The main disadvantage is that this artificial dilution may not accurately simulate real-world plume dilution, and the fine PM measurements may be biased as a result.

Plume sampling, however, uses some of the most realistic dilution conditions attainable, thus providing considerable confidence in the representativeness of the data, especially the size distribution data (which is most sensitive to the dilution schedule). Unfortunately, because of widely varying dilution ratios, the currently available plume data can only provide snapshots of the PM emissions.

Figure 2 shows some snapshot particle size distributions, as measured by the ELPI, for a truck at a typical highway speed (65 mph), as determined by stack dilution sampling and plume sampling. The bars represent the bin data recorded by the ELPI software, where each curve is a best-fit lognormal distribution profile (or bimodal-lognormal, if it provides a better fit). The ~100 nm peak is typical of the accumulation mode for diesel exhaust, where the leftward skewness (represented as a tail in the best-fit curve) varies quite a bit with operating conditions and dilution technique. The data represented here would indicate that the skewness may be a result of some bias introduced by the direct-dilution sampling system.

Of the fine PM instrumentation used in this study, the ELPI gave the most useful data for quantifying mass emissions. It measures total PM mass concentration in terms of equivalent aerodynamic diameter (i.e., “unit density spheres”or u.d.s.), based on its impactor cut points and stage counts. In general, the highest mass emissions are the spikes that correspond to some identifiable event in the truck’s operation (e.g., pulling off from a stop, changing gears). The lowest emissions correspond to low power conditions such as low-speed/zero-grade tests, with emissions generally increasing with increased power demand. So, the on-road tests have identified two primary contributors to PM emissions, operating transients and power demand.

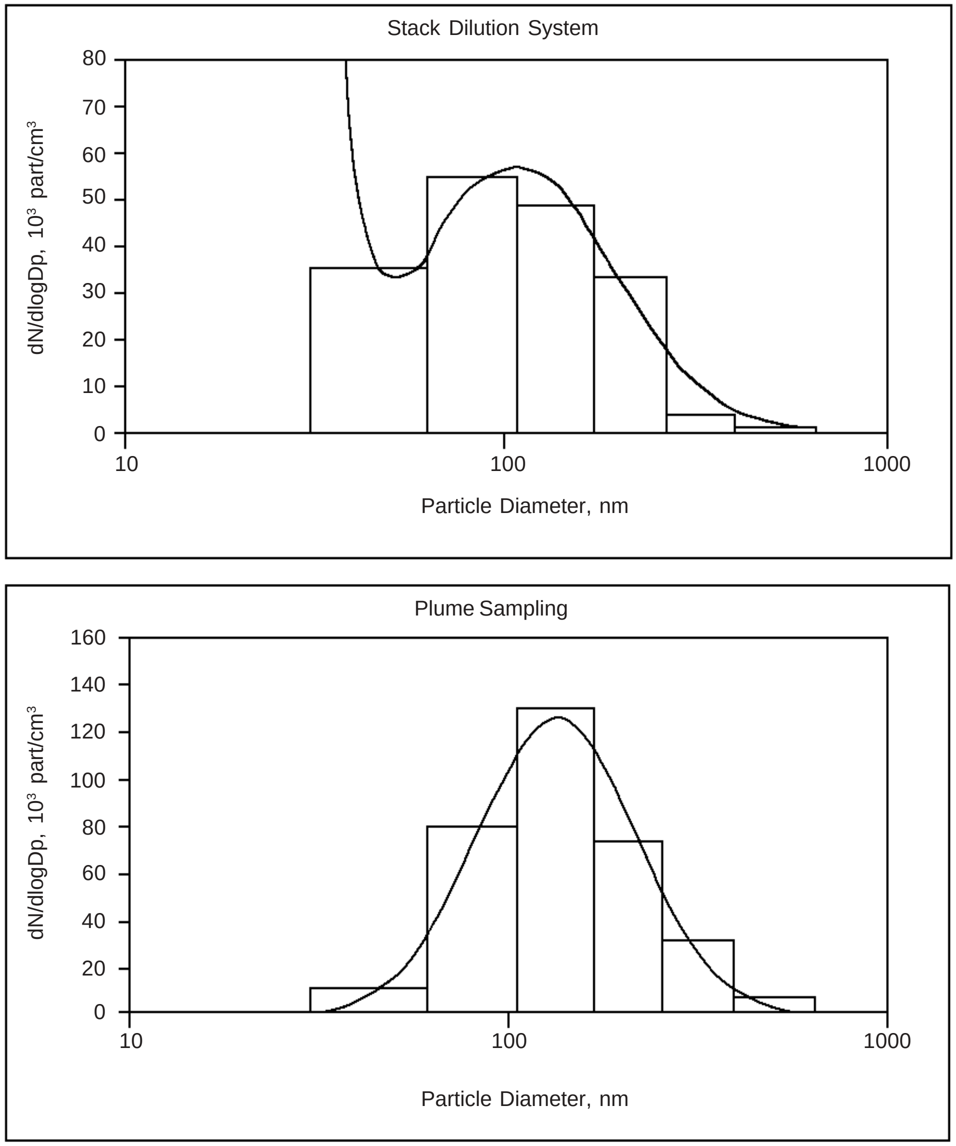

Figure 2. Particle Size Distributions for 105 kph (65 mph) operation.

Plume Dilution Characterization

One challenge of designing a dilution system that will not bias fine PM measurements is knowing the process that the system is simulating. For on-road trucks, the plume dilution process is poorly understood, so any dilution system design is based on little more than an educated guess. Therefore, this project has attempted to characterize the plume dilution process for Class-8 trucks.

Since dilution schedule is a function of dilution ratios and residence times, the project has measured both of these parameters at various points in the truck plume. Dilution ratio is measured using one or more gaseous tracer species which is (are) not directly affected chemically by the dilution process. Concentrations of this species are continuously measured in the raw exhaust, in the plume, and possibly in the background air away from the plume. The dilution ratio is a measure of how much background air has mixed with the raw exhaust at the point where the plume is sampled.

The total residence time at any point in the plume can also be measured using a gaseous tracer. For these measurements, the tracer (propane) is injected into the exhaust at high concentration, so that it causes an easily identified spike at the plume sampling location. It is not necessary to measure exhaust and background concentrations, but it is necessary to characterize the response time of the plume sampling system. This response time is subtracted from the delay time (from the injection of the measurement spike) to get a residence time measurement.

Figure 3 summarizes the plume dilution ratio measurements from 3 days' on-road testing. The sampling locations are identified at "2m" and "11m" to indicate the distance from the exhaust stack in meters. The data show little speed dependency at speeds as low as 35 mph, but the value and variability of the dilution ratio turn up sharply at lower speeds. The data show reasonable run-to-run and day-to-day repeatability at both the 2m and 11m plume sampling locations. At highway speeds (55-65 mph), the total residence times are around 0.1 second at the 2m location, and 1.7 seconds at the 11m location.

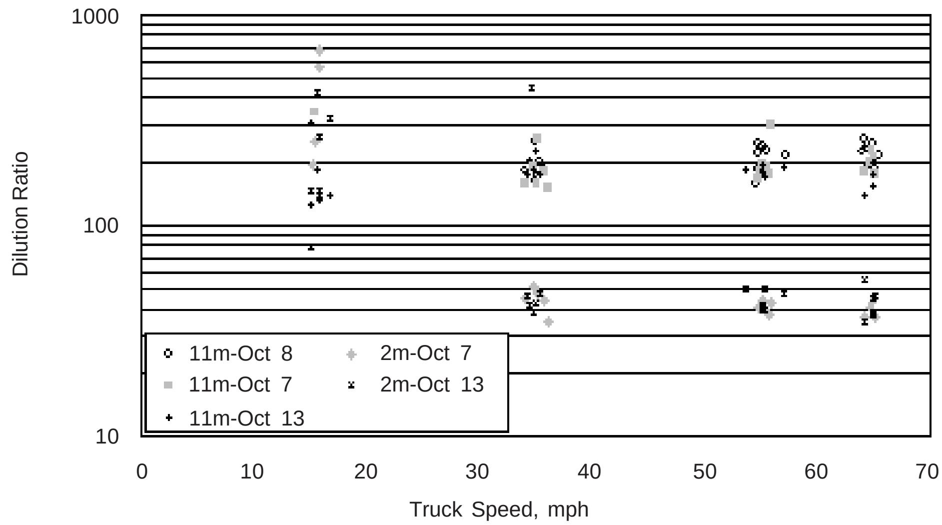

Figure 3. Plume Dilution Ratio Measurements.

Conclusions and Recommendations

The following conclusions were reached from the testing conducted thus far in the research program:

- Although the stack dilution system was designed and operated according to currently accepted practice, the character of the fine PM emissions do not reflect real-world conditions as found in the plume sampling.
- The overall process of cooling and dilution of the exhaust plume in the flow field of the moving tractor-trailer is poorly understood, and should be studied further.
- Although carbon dioxide (CO_2), NO_x, and/or propane tracers have provided all of the dilution schedule data so far, a truly unique tracer is needed to eliminate the problems with atmospheric background and contributions from other vehicles.
- A comparative evaluation of the currently utilized fine PM instrumentation is needed before proceeding with future emissions testing.

The report has presented descriptive details of the ODEC facility and fine PM data from that facility. Since fine PM measurement capabilities were added only recently to the facility, these results represent work in progress. The following refinements should be considered regarding future work:

- Per the third conclusion, above, it is recommended that the use of a unique tracer be implemented in conjunction with current testing activities.
- Plume delay times should be characterized to a higher resolution, especially at the 2m location, where the delay was measured as a single sampling interval (0.1 second) using the 10 Hz data rate. Measurements should also include the 6m and 8m locations, and possibly some plume sampling behind the trailer.
- It may be well worth the investment to upgrade one or both ELPI units by adding the filter stage option that is currently offered by the manufacturer.
- If the TEOM is to provide any useful on-road data at all, the source of the negative readings must be identified and either eliminated or characterized (i.e., for data correction).
- It is recommended that the various options be explored to improve the time resolution of the aethalometer.

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The complete report, entitled "Heavy Duty Diesel Fine Particulate Matter Emissions: Development and Application of On-Road Measurement Capabilities," will be available at http://www.epa.gov/ORD/NRMRL/Pubs or as Order No. PB2002-100140; Cost: $36.00, subject to change, from:

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