

# Real-World Vehicle Emissions: A Summary of the Sixteenth Coordinating Research Council On-Road Vehicle Emissions Workshop

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**ABSTRACT**

The Coordinating Research Council held its 16th workshop in March 2006, with 83 presentations describing the most recent mobile source-related emissions research. In

**IMPLICATIONS**

Mobile source emissions are the largest contributor to urban emission inventories in many locations. Ambient air quality standards have become increasingly stringent, and it is important to understand the role of mobile source emissions on air quality through well-designed studies. This information can provide important input for the formulation of effective air quality management strategies. Going forward, new mobile source emission models released by U.S. Environmental Protection Agency and the California Air Resources Board should be compared with data collected during on-road and air quality studies so that their accuracy might be properly verified.

this paper, we summarize the presentations from researchers who are engaged in improving our understanding of the contribution of mobile sources to air quality. Participants in the workshop discussed evaluation of in-use emissions control programs, effects of fuels on emissions, emission models and emission inventories, results from gas- and particle-phase emissions studies from spark-ignition and diesel-powered vehicles, and efforts to improve our capabilities in performing on-board emissions measurements, as well as topics for future research.

**INTRODUCTION**

The 16th Coordinating Research Council (CRC) On-Road Vehicle Emissions Workshop was held March 28–30, 2006, in San Diego, CA. Nearly 200 representatives from industry, government, academia, and consulting groups from Austria, Belgium, Canada, England, Finland, Germany, Japan, Republic of China, Sweden, and the United

States participated in the meeting. The objectives of the workshop were to present the most recent results from research on the following: (1) in-use vehicle emission control programs; (2) emission measurement methods; (3) U.S. Environmental Protection Agency (EPA) Motor Vehicle Emission Simulator (MOVES) model; (4) vehicle emission modeling and activity data; (5) gasoline and diesel vehicle emissions; (6) effects of fuel on emissions; (7) unregulated emissions; and (8) particulate matter (PM) from mobile sources.

This year's keynote speaker was Dr. James Eberhardt of the U.S. Department of Energy Office of FreedomCAR and Vehicle Technologies (DOE). He addressed emerging emissions challenges from future fuels and engine technologies. The transportation sector consumes roughly two-thirds of the petroleum used in the United States. The resource base for future transportation fuels includes biomass, coal, methane, oil sands, and oil shale. This constitutes an enormous domestically available carbon and hydrocarbon (HC) resource that could be used to produce transportation fuels. He stated that internal combustion engines are the most viable for transportation and that new low-temperature combustion regimes promise high efficiency and low emissions. These need to be investigated so that new emissions problems are not created from future fuel compositions and engine technologies.

There were 54 presentations in 9 sessions, and 29 posters displayed in poster sessions during the workshop. In addition to the many technical workshop presentations, three groups displayed new analytical capabilities and services related to vehicle emissions measurement. Brent Bailey and the CRC staff provided overall workshop coordination, with Steve Cadle of General Motors and Mani Natarajan of Marathon Petroleum Co. serving as workshop cochairmen. Session chairmen were Doug Lawson of the National Renewable Energy Laboratory (NREL), Kevin Black of the Federal Highway Administration (FHWA), Fred Minassian of the South Coast Air Quality Management District, Mani Natarajan of Marathon Petroleum LLC, Hannah Murray of Toyota, Rob Graze of Caterpillar, Alberto Ayala from the California Air Resources Board (CARB), Carl Fulper of EPA, and Chris Tennant from the CRC. The complete workshop proceedings are available from the CRC (3650 Mansell Rd., Suite 140, Alpharetta, GA 30022; phone: +1-678-795-0506; fax: +1-678-795-0509; e-mail: jantucker@crcao.org).

Summaries of the CRC workshops have been published in the *Journal of the Air & Waste Management Association*; the three most recent summaries are found in Vol. 54, pp. 8–23; Vol. 55, pp. 130–146; and Vol. 56, pp. 121–136. This paper summarizes presentations and posters given in each session at the 16th workshop.

### Emission Control Measures

The effectiveness of in-use vehicle emission control programs continues to be an area of research. On-road emissions from a fleet never subjected to any inspection/maintenance (I/M) program in Tulsa, OK, were compared with on-road emissions of a fleet subjected to a mature I/M program in Southern California. The study reported no accumulated, long-term benefit from

I/M in Southern California. Another group has developed a first-generation I/M simulator to estimate the benefits of candidate improvement strategies to the California I/M program.

The CARB has initiated a program to evaluate emission benefits that can be obtained by replacing catalytic converters in vehicles that already pass the I/M test but are not as clean as average vehicles in various age groups. Another study also evaluated the ability of remote sensing to correctly identify high-emitting vehicles, and the study has confirmed work reported as early as 1989, with  $\geq 90\%$  failure rates for vehicles tested immediately using the Acceleration Simulation Model test after being measured as high emitters by remote sensing.

One study reported using remote sensing emissions to compare with emissions estimated by the MOBILE6 model. The remote sensing measurements were comparable to modeled levels for newer vehicle HCs and NO emissions. The modeled values were lower for HCs and NO for older vehicles than remote sensing measurements and higher for cars and most light truck CO emissions than remote sensing measurements. A state of New York evaluation reported that on-board diagnostics system failure rates in New York City were 2–4% higher than corresponding I/M data from upstate New York.

Data from the Ontario, Canada I/M program have been examined to show that a significant number of vehicles have intermittent malfunctions, which cause them to fail one test and pass another without repair. More research is needed to quantify the number of such “flipper” vehicles and their impact on the effectiveness of I/M programs. British Columbia's I/M program currently fails light-duty (LD) diesel vehicles for smoke opacity only, and the program has just started to measure nitrogen oxide (NO<sub>x</sub>) emissions from LD diesel vehicles.

Finland is investigating whether unused rail embankments could be used for heavy-duty (HD) freight transport. Modeling results show that for a 122-t truck and trailer combination, fuel consumption and emissions would be reduced 34% and 29–49%, respectively, on the rail embankment, as compared with equivalent transport conditions over a 600-km road distance from Helsinki to Oulu.

### Particle Measurement Methods and Results

In this session, new approaches were outlined for measuring diesel PM (DPM). With the new U.S. HD PM 2007 engine certification standards for PM, emission concentrations could be lower than the detection limits of many currently used methods. The European Particulate Measurement Program (PMP) establishes a solid particle number method to measure the emissions from diesel and gasoline direct injection engines. CARB has found this method to be more precise than gravimetric methods used for trap-equipped diesel trucks. Similarly, CARB also has been investigating laser-induced incandescence (LII) in comparison with gravimetric methods for portable emission measurement systems (PEMS) to obtain actual drive cycle emission data. The comparisons between LII and gravimetric analysis methods have been reasonable for on-road tests but less so in chassis dynamometer testing.

DPM sampling is a challenge because of high temperatures, moisture, and sulfuric acid in the exhaust stream. Laboratory and modeling methods were outlined describing dilution's effect on concentration, temperature, control of volatile species, and stabilizing pressure. Recent work investigating the influence of dilution on the organic component of DPM has shown that dilution conditions will increase the measured concentrations of organic compounds, possibly because of condensation, whereas elemental carbon (EC) concentrations are not affected.

Studies investigating fuels and diesel particle filters (DPFs) provided some interesting findings. Iridium and deuterated HC tracers were used to measure DPM in the exhaust and crankcase emissions from a diesel school bus and associated concentrations inside the vehicle. It was found that in-cabin crankcase PM emissions may exceed the DPM emissions from the exhaust. Results from a separate study on a DPF-retrofitted diesel engine showed that the filters eliminated the coarse exhaust and crankcase DPM fractions, the accumulation mode, and much of the nucleation mode fractions, but the volatile nuclei mode responsible for the generation of the remaining particle numbers and mass remained. A continuously regenerating trap (CRT) combined with an additional sulfur trap provides even greater reductions of the nucleation fraction than the CRT alone.

A microproportional sampling system (MPS) for in-use emissions measurements from spark and compression ignition-powered vehicles was laboratory tested and installed on a truck for testing. Exhaust flow measurements from the MPS, the constant volume sampler (CVS), and engine control module were compared from the dynamometer and in-use measurements. In another project, in-use PEMS results were compared with CVS engine dynamometer test cell and chassis dynamometer data. The results showed that PEMS can measure  $\text{NO}_x$  and carbon dioxide ( $\text{CO}_2$ ) over steady-state and transient tests to within 20% of laboratory equipment measurements.

Several PEMS units were evaluated by backup generator and chassis dynamometer testing for emissions inventory development. The best PEMS came within 4% of the reference method for  $\text{CO}_2$  and 8–18% of the reference method for  $\text{NO}_x$ . The results for PM were more ambiguous. In another project, the objective was to quantify the response time of a PEMS and to develop an appropriate method for statistical modeling of emission rates. The results showed that for modal and trip level emissions measurements the accuracy may be adequate, and consecutive averages improve predictability of the emission models.

The exhaust of an HD diesel engine equipped with a catalyzed DPF was measured for brake-specific PM emissions using five partial flow sampling systems (PFSSs) and a full-flow constant flow sampler. The work demonstrated the feasibility of using PFSSs both when the PM emission rate is well below 10% of the 2007 PM standard and in the absence of soot. Another project assessed various particle measurement methods during different combustion modes. The results showed excellent correlation for LII and photoacoustic spectroscopy for soot measurement under lean conditions and also showed that soot from

rich combustion is different from that produced during lean combustion.

### Fuel Effects

Changes in federal and state regulations and increasing demand for gasoline and diesel fuel consumption are driving changes in fuel composition. The impacts of these changes on emissions and air quality need to be understood. A study to address volatility parameters and ethanol content on exhaust emissions was carried out using a matrix of 12 fuels and 12 in-use vehicles ranging in certification level from a low emissions vehicle to a super ultra-low emissions vehicle. Overall, the results indicated that  $\text{NO}_x$  decreased with increasing T50 at high ethanol levels but had no effect at other ethanol levels. For high T90 fuels, nonmethane organic gases (NMOGs) and toxics increased with increasing T50 and ethanol levels.

A separate program in Taiwan tested a 4-stroke motorcycle engine without a catalyst, using 13 gasoline blends with varying oxygen, sulfur, and aromatic content on an engine dynamometer. CO and HC emissions were higher at idle than during cruise modes, whereas  $\text{NO}_x$  was lower at idle for all of the test fuels. Increasing sulfur content increased the HC and  $\text{NO}_x$ . Increasing aromatics increased HC emissions, whereas the oxygen and benzene content did not appear to affect the emissions.

Changes in aromatic HC emissions since 1991 were reported in a paper that related gasoline properties with species measured in ambient air. Speciated HCs from on-road vehicles were measured in the Caldecott Tunnel in the San Francisco Bay area in California. After normalizing individual organics to total NMOG mass, it was found that step change reductions in benzene and highly reactive C9+ aromatics coincided with the introduction of California phase 2 reformulated gasoline. Ambient benzene levels showed a strong downward trend since 1991.

The State of Maryland has considered legislation that would ban the use of methyl tertiary butyl ether in gasoline. Modeling results have shown that using 10% ethanol in gasoline will increase total ozone precursors (volatile organic compound [VOC] +  $\text{NO}_x$ ) in the state by as much as 15.8 t on a summer day. This increase is equivalent to about a 7% increase in VOC and  $\text{NO}_x$  emissions from the on-road gasoline motor fleet. The results also showed that switching to a nonoxygenated reformulated gasoline will increase total VOC +  $\text{NO}_x$  emissions by 7 t, which is equivalent to about a 3.2% increase from the on-road gasoline motor fleet.

The CARB Predictive Model simulates the logarithm of  $\text{NO}_x$  and total HC emissions as a quadratic function of seven fuel parameters. An alternative approach was presented, which assumed that vehicles with higher-than-normal average  $\text{NO}_x$  emissions respond differently from normal-emitting vehicles. This alternative approach fits the data better and shows very different fuel parameter responses for normal and higher-than-normal emitters.

An updated life cycle inventory model was used to estimate the energy consumption of biodiesel and petroleum diesel. The results indicated that 99% of life cycle energy consumption for petroleum diesel is fossil energy compared with only 37% for biodiesel. Biodiesel has lower life cycle emissions of CO and PM but higher  $\text{NO}_x$

and VOCs. The results suggest that biodiesel is a promising alternative fuel for diesel but there are some environmental tradeoffs.

### Gasoline Vehicle Emissions

Since the inception of the Clean Air Act of 1970, gasoline vehicle exhaust emissions have been synonymous with emissions as measured by the laboratory Federal Test Procedure (FTP). A comparison of current government tailpipe criteria pollutant standards with the standards of the 1980s and 1990s clearly demonstrates that today's vehicles produce much lower emissions than earlier technologies. As a result, it is no surprise that an increasing body of research focuses away from the traditional laboratory FTP and instead explores emission performance over the full range of vehicle operation; the workshop highlighted a number of programs delving into this area.

Cold temperature emission performance provided a justification for current regulatory action, as well as a backdrop for emission reduction possibilities via partial oxidation catalyst technology. Hybrid electric configurations showed some differences from conventional vehicle configurations at cold (20 °C) and colder (−18 °C) temperatures over a variety of testing cycles; notably, higher speed driving cycles improved fuel consumption during a low-temperature cold start operation. PM emissions data from multiple vehicle configurations: diesel, gasoline, compressed natural gas (CNG), and hybrid, were collected over a variety of driving cycles as the initial part of New York's efforts to develop updated emissions profiles.

To put LD gasoline vehicle emissions data in perspective from an inventory point of view, the session also included individual vehicle owner incentives and activity research. Trips per day measured in Atlanta, GA, are significantly less than estimated in several emission models, indicating a potential reduction in real-world cold start emissions. The session concluded with a big-picture analysis of air quality trends in Southern California, the workshop's location. Of particular interest is the need to accurately characterize emissions from high-emitting vehicles, which will continue to increase in importance as newer vehicles become progressively cleaner.

### Diesel Vehicle Emissions, Models, and Aftertreatment

This session focused on two themes: emissions characterization from multiple generations of on-highway trucks and emissions reduction performance and system diagnostics of aftertreatment devices. Emissions characterization was generally performed using a variety of CVS systems ranging from a conventional laboratory system to a fully portable unit in a semitrailer. Vehicle test cycles ranged from the CARB 4-mode cycle used during the CRC E-55/59 project to a combination of highway (driver speed control) and freeway (cruise control) cycles used in Finland. In addition, on-road HD emissions were measured using roadside remote sensing devices at two Colorado locations.

One study used a consistent driving route with a trailer-based CVS and normal variances in traffic densities to enable a range of realistic driving conditions. The truck model years ranged from 1969 to present, gross vehicle

weight from 15 to 60 t, with no consistency in maintenance. Observations included a wide variation in fuel consumption by truck brands and significant scatter in NO<sub>x</sub> and PM between vehicles that obscured the influence of load and vehicle category. Currently, NO<sub>x</sub> and PM engine emissions are generally considered to be at their lowest historical levels; however, this conclusion is not consistent between cycles or universally embraced by different researchers. Finally, low speed/load operation in high traffic congestion contributes to disproportionately high levels of emissions on a gram per mile basis.

Exhaust aftertreatment results from testing European buses with urea-selective catalytic reduction (SCR) show 85–99% reduction from baseline NO<sub>x</sub> and PM levels; however, ammonia slip remains problematic. One research group reported large reductions in VOC and carbonyl emissions with aftertreatment on CNG and diesel buses versus the diesel baseline. CNG engines properly fitted with aftertreatment systems were reported as equivalent to diesels for ozone-forming potential. A neural network-based unit was shown to detect, isolate, and accommodate aftertreatment failure conditions correctly.

### Off-Road Emissions

As on-road emissions continue to be reduced, off-road emissions become a more significant component of the emission inventory. Researchers are advancing the understanding of the relative contributions of various off-road sources, including those associated with port activities, locomotives, and construction equipment applications. For example, emissions from large 3-MW auxiliary engines in ocean-going cargo vessels fueled by heavy fuel oil or marine distillate oil are now being evaluated. Comparative emissions evaluations are being carried out for various stationary and mobile sources including backup generators, locomotives, and yard tractors. Others have measured emissions from winter equipment used at Yellowstone National Park by using remote sensing devices and PEMS for snowmobiles and snowcoaches, respectively. Four-stroke snowmobile technology has a significant emission advantage over two-stroke units. Large variations in snowcoach emissions were observed with emissions being influenced principally by snow conditions, fuel management technology, and power-to-weight ratio.

The New York State Energy Research and Development Authority Clean Diesel Program and the current effort on inventory refinement and in-use strategy evaluation were discussed. The work has the objective of providing assessments of the in-use performance of commercially available diesel retrofit control technologies to expand energy-efficient diesel emission control technology options for off-road applications in New York state.

EPA's NONROAD emission model is being updated with data from a survey of equipment owners. The estimated emissions of NO<sub>x</sub> and PM in the updated inventory are higher than previous estimated emissions, with NO<sub>x</sub> nonroad emissions increasing nearly twofold in the New York City metropolitan area. The refined inventory results will be used to identify equipment for the demonstration of control technology in a field testing program.

### Emissions Modeling

Staff from EPA described their efforts in developing a new approach for modeling evaporative emissions within the new MOVES model. New areas of interest are development of a new permeation test procedure, a better understanding of new fuels' permeation rates, especially for ethanol/gasoline mixtures, and other nonfuel emission sources (e.g., upholstery). Early data indicate that ethanol permeation effects might be relatively large; however, this effect is not included in EPA's MOBILE6 model.

EPA is working on including uncertainty estimates in the new MOVES model. The model will propagate input uncertainties into output uncertainties by the Monte Carlo sampling methodology. EPA is investigating different ways to handle uncertainties for data gaps on emission rates, fleet, and activity inputs (e.g., vehicle miles traveled [VMT], populations, speeds, spatial and temporal allocations, etc.). Many challenges in calculating input uncertainties remain to be solved, and EPA will continue to inform model users on the results of its research.

MOVES will allow users to use mobile source activity data at three different scales (microscale, mesoscale, and macroscale) and will have activity estimates generated through vehicle-specific power (VSP) bin distributions and different driving schedules. EPA will update annual sales and VMT growth and will add activity components related to start and evaporative emissions.

EPA is also evaluating the effect of cold temperature on mobile source emissions from a number of studies. Analyses to date suggest that the MOBILE6 model seriously underestimates HC emissions at low temperatures. In the future, EPA will be evaluating the latest data, including data from the extensive in-use Kansas City, MO, LD gasoline vehicle emissions program.

### PM

The Kansas City Gasoline Vehicle PM Emissions Study (CRC E-69), funded by EPA, DOE/NREL, FHWA, and CRC, was summarized at the workshop. The study objective was to expand the data available on LD vehicle PM emissions, as well as other regulated and unregulated emissions. Data collection began in 2004 and concluded in 2005, including spark-ignition vehicle testing in summer and winter. Approximately 500 vehicles of various types were recruited from the in-use Kansas City fleet and tested on a chassis dynamometer using the Unified Driving Cycle (LA-92), with additional testing by PEMS. Regulated emission rates were higher in winter than in the summer. Using a definition of two standard deviations above the mean, 13% of the cars were high emitters (all pollutants considered). Overall, one-fifth of the cars produced ~75% of the total PM. The PM from high emitters had a higher ratio of organic carbon to EC than that from normal emitters. Measured fuel economy correlated well with most official vehicle ratings but was lower for some categories (especially for hybrids and older vehicles). There are ongoing efforts to incorporate these data, as well as HD in-use data (from the CRC E-55/59 project) into EPA's new MOVES model, although more analysis is needed for continuous PM data measurements. In addition, upcoming projects in evaluating PM and other pollutants from

near roadways and from 2007- and 2010-compliant HD diesel engines were presented in this session.

### Future Research Priorities

When the first CRC On-Road Vehicle Emissions Workshop was held in 1990, the main underlying question was why urban ambient concentrations of HC, CO, and NO<sub>x</sub> had not decreased as much as expected in response to the progress that had been made in reducing emissions from new vehicles. The general consensus was that in-use mobile source emission control programs had not been as effective as previously thought. The workshop concluded that the answer must come from better measurements of in-use emissions from LD vehicles.

Since that time, a great deal has been learned about emissions from the in-use fleet. Remote sensing and on-board measurement tools have been greatly improved and have been used to characterize fleet emissions. The on-board tools have been used to obtain both in-use emissions data and to greatly improve activity data. Tunnel studies and dynamometer studies have continued. New driving cycles have been developed to better represent how vehicles are driven in the real world, and new evaporative emission tests have been developed to provide a better measure of these emissions from newer technology vehicles. Our understanding of the impact of fuel composition has greatly improved through laboratory studies. Changes in fuel composition have been implemented to reduce emissions. Emission inventory models, which at that time underpredicted actual, in-use vehicle emissions, have been modified several times and have better performance in predicting in-use fleet emissions. Much of the original underprediction was because of a lack of information on high-emitter vehicles, although that certainly was not the only deficiency. The high-emitter problem has increased the focus on in-use emission control measures, such as I/M programs and on-board diagnostics.

Although research has provided a much better understanding of LD gasoline vehicle in-use emissions today than in the past, there remains a need to continue work in this area. The in-use fleet emissions need to be monitored to determine the impact of new technology vehicles that meet stricter emission standards and to help evaluate the effectiveness of I/M programs and on-board diagnostic equipment.

In-use evaporative emissions testing still requires that vehicles be brought into the laboratory to undergo several days of testing. The cost and time required to perform these tests have greatly limited the number of vehicles that have been tested. Hence, the understanding of the number and emission rate of high evaporative emitters remains limited as does the knowledge of the in-use performance of enhanced evaporative emissions-equipped vehicles.

The relative importance of nontailpipe emissions as compared with exhaust emissions remains an area of large uncertainty. EPA and CARB mobile source emission models traditionally have estimated that nontailpipe emissions are responsible for roughly half of the total HC emitted from the LD spark-ignition fleet, whereas on-road and source apportionment studies suggest that nontailpipe emissions are not that important. A need exists to

design and conduct a study that conclusively addresses this issue.

Interest in understanding near-roadway and on-roadway exposures has increased because of several studies that have reported health impacts of household residents decreasing with distance from major roadways. This has increased the need for modal models capable of simulating microenvironments. A major limitation is the availability of large amounts of modal data to help construct and validate the modal emissions models. It is anticipated that modal exhaust emission data will be generated in laboratory chassis dynamometer studies, in on-road emissions studies using portable emissions measurement systems, and, perhaps, with remote sensing studies.

Although several modal emissions models exist, probably the most significant efforts have been expended on EPA's new emissions model, MOVES. The model remains under development. The initial version that calculates emissions of greenhouse gases was released in 2005. An updated version that will include the criteria pollutants is expected to be released late in 2006. The model uses VSP bins for various classes of vehicles. It is expected that the VSP bins will be updated frequently as new data are generated. Hence, the challenge will be to obtain sufficient information on the in-use fleet to populate these bins.

Given that MOVES is a totally new model, there clearly will be great interest in evaluating its performance and understanding how various factors, such as fuel effects, ambient conditions, evaporative emissions, and so forth, are handled. PEMS are expected to play an increasing role in providing data for models such as MOVES and to improve understanding of in-use emissions and activity under various ambient conditions. Several studies have been done comparing their performance for HC, NO<sub>x</sub>, CO, and CO<sub>2</sub> with conventional measures, generally with encouraging results. A variety of methods have been used to obtain an estimate of PM mass. To date, no PEMS system has been validated to give mass measurements comparable to filters for low-emission vehicles. Thus, the development and validation of PM PEMS capability remains an important challenge. Considerable work is going on in this area.

The emissions of air toxics remain an area of interest. Given the low concentrations of these species in exhaust, most analytical methods for air toxics can only provide average emission rates over an entire cycle or major portion of the cycle rather than real-time modal concentrations. Because many of the air toxics are HCs, their emissions can be estimated by assuming that they are proportional to the HC concentration. As fuel compositions change, the proportionality must be adjusted. Other air toxics, however, are not emitted in proportion to the HC concentration. Examples of such species are those coming from the consumption of motor oil. Correct modal modeling of these species will require the development of new methods to obtain modal data.

The health effects community has been very interested in the effects of ambient PM for several years. Although it is generally accepted that PM can cause health effects, it remains a matter of considerable debate as to what properties or components of PM are the causative

agent. Some researchers feel that nanoparticles are worse for health than larger particles and suggest that particle number or surface area is a better measure to use than particle mass. Others think that the composition must play a role. At this time both vehicle and ambient standards in the United States are mass based. Hence, mass measurements are required, but it is prudent to continue to measure particle number and surface area, as well as composition of the PM. The state of California has taken a head start in this area by exploring the merits of the European PMP work.

A significant fraction of the PM mass from mobile sources is semi-VOCs. Thus, the amount of mass collected on a filter is a function of the sampling conditions including dilution ratio, temperature, and concentration of the semivolatiles. Because of this, PM mass is operationally defined. Confounding the issue is that filters can adsorb a small amount of gaseous material, whereas at the same time, they can lose volatile species collected previously on the filter during non-steady-state vehicle or engine operation. In addition, the dilution systems both adsorb and desorb material making the background significant but difficult to characterize. Overall, the measurement of PM from low-emission vehicles is challenging. Standard procedures are in place for certification testing, but PM as currently measured using gravimetric methods may not accurately represent PM as measured in ambient atmospheric dilution processes. Hence, it is not clear how laboratory or current certification results apply to on-road emissions. To the extent that it is necessary to accurately measure these low PM emission rates, it will be necessary to continue to develop improved methods in a coordinated effort to revise the emission certification protocols.

Particle number measurements are even more sensitive to sampling conditions because of the presence of semivolatile material. No standard methods exist for quantifying the particle number that includes the particles formed from the semivolatiles. The most reliable measurements today are probably those obtained on or next to roadways. Given the complexity of the factors affecting the formation of PM from semivolatiles and their relatively short lifetime in the atmosphere, the best approach may be to characterize total emissions of the semivolatiles and model the PM formation and loss in the atmosphere.

In 2007, HD diesel engines must meet new stringent PM standards in the United States. To meet these standards, particle traps will be required. Because blow-by emissions are included in the PM standard, it is expected that blow-by controls will be implemented as well. This introduction poses some short- and long-term research needs. In the short term, it is desirable to characterize the emissions from these new technology vehicles. The Advanced Cooperative Emissions Study (ACES) will perform a comprehensive characterization of the exhaust emission from four engines. One of the engines will be used for a long-term animal exposure health study. Over the long term, it will be necessary to monitor the in-use performance of these vehicles. Because catalyzed traps increase the fraction of the NO<sub>x</sub> that is emitted as NO<sub>2</sub>, it will be of interest to include NO<sub>2</sub> in future in-use studies and to evaluate the influence of that increased NO<sub>2</sub> on ambient

ozone levels. In California, verification of traps requires meeting an NO<sub>2</sub> limit. The very large reductions in PM from these engines mean that the current on-road fleet of heavy-diesels will likely dominate the on-road diesel emissions for a long time. Hence, it will be important to continue to monitor their emissions as well.

In 2010, the HD engines must meet stringent NO<sub>x</sub> standards in the United States. At this time it is not clear what technology will be used to meet those standards. One possibility is urea-selective catalytic reduction (SCR). Some LD manufacturers have also expressed an interest in using urea-SCR for diesels to meet the LD NO<sub>x</sub> emissions standard. There undoubtedly will be interest in monitoring in-use emissions performance of this new technology. European experience with these systems is likely to be helpful in this regard.

As the on-road fleet has reduced its emissions, off-road emissions have grown in relative importance. Characterizing these emissions is challenging given the tremendous variety of sources and their activity patterns. It is expected that the development of PEMS systems will help considerably in this regard, at least for the larger vehicles. Unfortunately, as noted above, there remains a need to validate PM capability for PEMS. Although work is currently being conducted in this area, improving the off-road database is expected to be an important research need for many years.

National security, petroleum prices, and global warming issues are increasing interest in alternative fuels and advanced powertrains that have improved fuel economy. Ethanol and biodiesel use are being mandated. Emissions from flex-fueled E85 vehicles have been studied for some time, but fewer studies have been done on emissions from in-use vehicles using biodiesel blends. Although the growth of biodiesel in the United States is expected to be slow, consideration will have to be given to monitoring its effects on the in-use fleet. Use of alternative liquid fuels such as coal-to-liquids and gas-to-liquids is further off but will need to be studied before being introduced in any significant volume. Offerings of hybrid vehicles are increasing and, thus, their presence in the in-use fleet will continue to grow. Their long-term emissions performance will need to be monitored. Long term, new engine technology, such as homogeneous charge compression ignition, may significantly change engine-out emissions.

Although many studies have explored the impact of fuel composition on vehicle emissions, most of these

studies have been performed on properly functioning vehicles. It is desirable to also know the impact of fuel composition on high-emitting vehicles. Unfortunately, high-emitting vehicles tend to have highly variable emissions making the study of fuel effects very difficult.

When considering fuel and vehicle technology options, it is important to take a holistic view of the environmental impacts. Well-to-wheel studies have examined energy use, global warming gas emissions, and emissions of criteria pollutants for a large number of vehicle/fuel options. These studies account for emissions and energy associated with fuel extraction (i.e., oil and gas operations, coal mining, etc.), transportation, fuel processing, fuel dispensing, and the use phase of the fuel. As components of this system change and data are improved, it will be necessary to revisit these analyses to ensure that we understand the total impact of the entire process.

We look forward to discussions of many of these issues at the 17th CRC On-Road Vehicle Emissions Workshop, which will be held in San Diego, March 26–28, 2007.

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