Highlights from the Coordinating Research Council's 27th Real-World Emissions Workshop

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The 27th Coordinating Research Council's Real-World Emissions Workshop was held on March 26–29, 2017, in Long Beach, CA. Co-Chairs, Dominic DiCicco (Ford Motor Company) and Scott Mason (Phillips 66 Company), opened the workshop to more than 240 attendees, representing 12 countries from industry, government, academia, and consulting, which sets a record for the highest attendance for this event. This year's keynote speakers included Jeff Wrona (General Motors) and Daniel Short (Marathon Petroleum Corporation). The workshop comprised 53 presentations in 9 sessions and 28 posters, as well as demonstrations of analytical and technical services by various vendors. Highlights from the workshop sessions are summarized in the following article.

Emission Rates and Inventory

Session Chair: *Henry Hogo, South Coast Air Quality Management District*

Emission rates for light- and heavy-duty vehicles have been established based on certification programs for all pollutants, with a specific focus on nitrogen oxides (NO_x) and particulate matter (PM), with more recent efforts using remote sensing devices (RSD) and portable emissions measurement systems (PEMS). An analysis of newer light-duty vehicles utilizing gasoline direct injection (GDI) engines designed to achieve future greenhouse gas (GHG) reductions has shown a potential to increase PM emissions, especially under cold-start conditions. Early efforts led to additional in-use studies identifying potential pathways for reducing PM, including the possibility for gasoline particulate filters.

Emissions of NO_x and PM from heavy-duty diesel vehicles have decreased dramatically over the past decade as a result of improved diesel fuel, vehicle emission after-treatment technologies, and regulatory requirements, including California's bus and truck rule. More recent studies suggest higher PM emission observations in older fleets with diesel particulate filters (DPFs) than newer fleets, leading to a need for additional studies on the potential for compromised DPF systems. Further, emissions inventories and ozone modeling have mostly relied on the certification emission rates, however, consistently higher volatile organic compounds (VOCs)-to- NO_x ratios observed in ambient monitoring data compared to inventory data implied either an underestimation of VOC emissions, overestimation of NO_x emissions, or both.

The California Air Resources Board's (CARB) EMFAC model summarizes vehicle travel and emissions data for mobile sources, and is continuously updated to reflect the latest base emission and deterioration rates, including the effect of after-treatment technologies incorporated into model-year 2010 or newer engines. Recent studies highlight a potential need to revise the model to account for malfunctions affecting PM emissions. Idle emission rates at varying soak times for vehicles equipped with selective catalytic reduction systems, were also updated. Lastly, chassis dynamometer measurements along with other studies were used to update base emission rates and speed correction factors.

Emissions Control Measures: I/M and OBD

Session Chair: *Susan Collet, Toyota North America Technical Center*

Ambitious governmental targets for light- and heavy-duty vehicle emissions are shown in Figure 1. For light-duty (LD) vehicles, new and innovative technologies are being explored, such as selective catalytic reduction on filter (SCRF) to reduce NO_x and thermoelectric generators (TEGs) to reduce carbon dioxide (CO_2).

Regarding heavy-duty (HD) vehicles, CARB is moving forward with parallel efforts to lower new engine emissions and see that those emissions remain low in-use, during warranty, and throughout useful life. To comprehensively improve NO_x performance in California, a few parallel paths need to be integrated and moved forward together: better hardware and control strategies, consideration of in-use NO_x performance

Figure 1. Light-duty vehicle emissions legislations for European Union, United States, China, Japan, India, and Brazil.

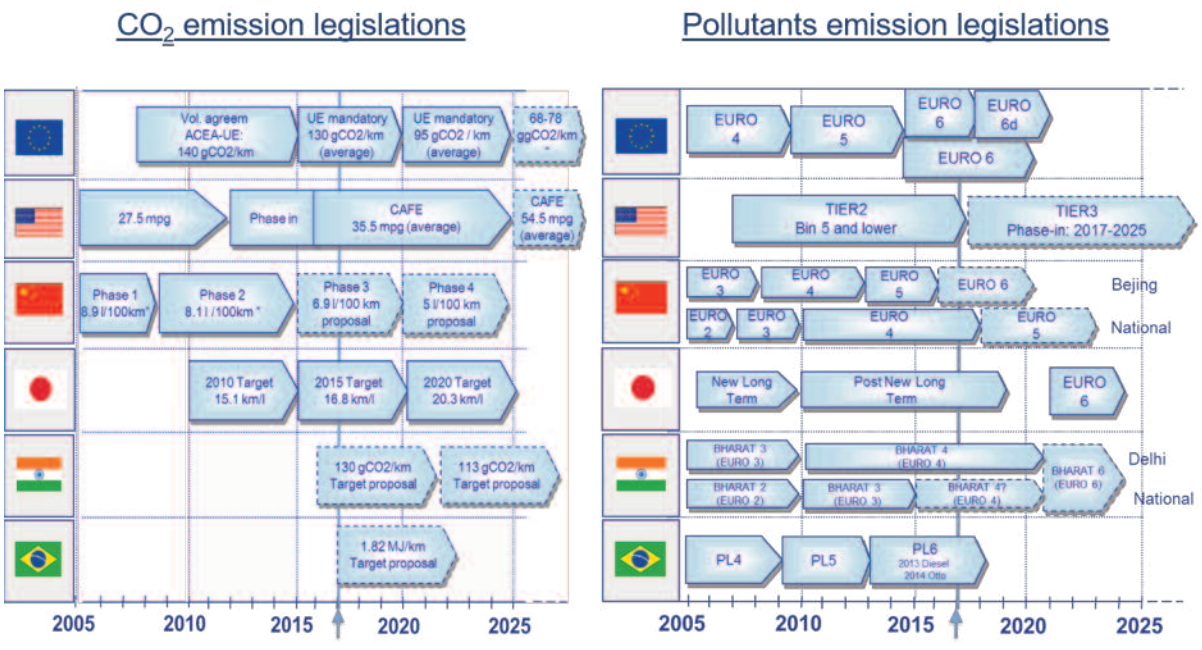


Table 1. CARB's regulatory development plan for heavy-duty vehicle emissions.

Hearing	Action	Implementation
Actions Taken	Optional Low NOx Standards: (50%, 75%, & 90% lower)	Currently Certifying Engines
	Innovative Technology Regulation	Undergoing final administrative steps
2017	Updates to Smoke Opacity Programs	2018
	Warranty Updates	2018 and onwards
	CA Heavy Duty Phase 2 GHG alignment	Paralleling federal program
2019	Low NOx Engine Performance Requirements	2023 and onwards
	Low Load Certification Requirements	
	In-Use Compliance Program (currently NTE)	
	Warranty/Durability/Useful Life Period Definitions	
2020	HD Inspection/Maintenance Program	Post 2020

across duty cycles, expansion of regulatory durability and NO_x emission control throughout HD truck useful life, and identification and remediation of high emitters, as shown in Table 1. CARB also sees a need for a more comprehensive, multi-pollutant HD inspection and maintenance (I/M) program to ensure in-use vehicles have regular inspections and effective emission controls.

It is important to have accurate HD NO_x sensor monitoring. Artificial neural networks (ANNs) can predict arbitrary functions using input/output data, which is useful not only for on-board diagnostics (OBD) monitoring at highway conditions, but also for NO_x production prediction during various modes of engine operation.

Emissions Modeling

Session Chair: *Megan Beardsley, U.S. Environmental Protection Agency (EPA)*

A detailed emissions model predicted second-by-second fuel use and emissions, based on PEMS measurements of Euro 6 vehicles, as shown in Figure 2. A dynamic evaluation of ozone trends in California's South Coast Air Basin found that the rate of decrease in ambient ozone levels was steeper than that estimated by air quality models. California's EMFAC2017 inventory model will include a number of updates, including LD and HD in-use emissions and activity profiles, as well as a new module to estimate GHG emissions.

Data from remote sensing, I/M programs, and tunnel studies were used to evaluate LD vehicles NO_x running emissions rates in Motor Vehicle Emission Simulator (MOVES); however, results from this preliminary evaluation were mixed. Telematics data were used to generate light-, medium-, and heavy-average speed inputs and temporal profiles for MOVES by county and road type that, when finalized, will be used to estimate emissions for EPA's 2014 National Emission Inventory (see Figure 3).

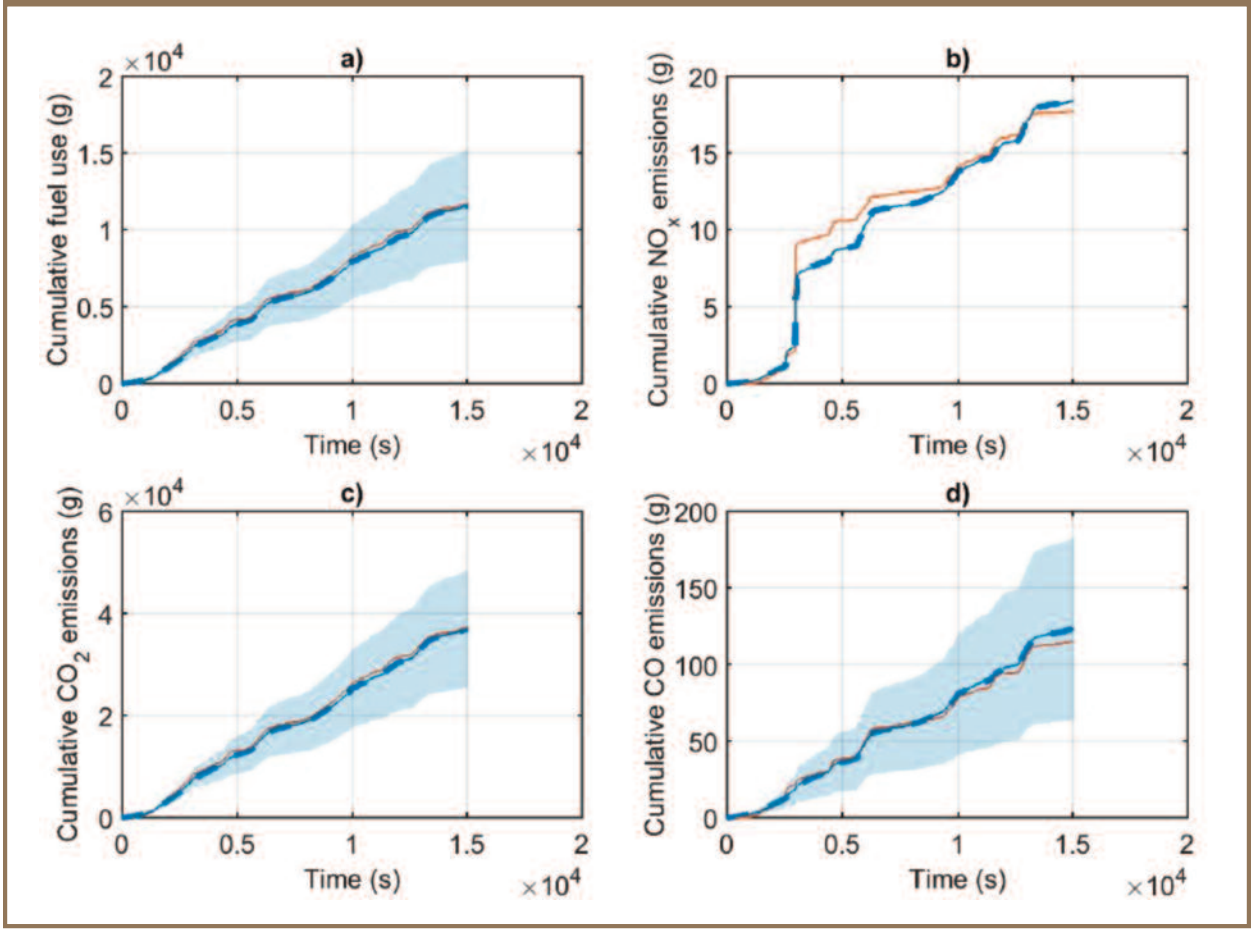
Fuel Effects/Fuel Economy

Session Chair: *Matthew Thornton, National Renewable Energy Laboratory*

The relationship between driver performance and real-world fuel consumption was examined for vehicles in Singapore, which showed that on-road fuel consumption estimated using OBD data is generally higher than the rated fuel consumption. The impact of driving conditions on the formation of secondary PM emissions from GDI vehicles was examined using fuels with different ethanol content.

Comparison of PM emission trends using Tier 2 and Tier 3 certification test fuels showed higher composite PM emission using the Federal Test Procedure (FTP) on Tier 3 fuel. Another study investigated trade-offs between fuel consumption and engine-based strategies to achieve low-engine-out NO_x and improved SCR activity. Another study looked at ultra-low NO_x measurement and emission factors for HD compressed natural gas (CNG) vehicles.

Figure 2. Observed (red) and simulated (blue) fuel use and emissions during one trip. Blue shade area shows 25–75 percent of the simulated cumulative values.



A predictive model for the correlation of heat of combustion with diesel fuel composition was evaluated and better test repeatability for net heat of combustion was found than that of the analyses for the same fuels performed by ASTM D4809. The session ended with a study looking at the fuel effects on gaseous and PM emissions on spark-ignited direct-injection (SIDI) in-use vehicles. This study investigated how a range of fuel properties in specifically-blended fuels affect criteria pollutants, fuel economy, and GHG emissions.

HD In-Use Emissions

Session Chair: *Tao Huai, California Air Resources Board (CARB)*

One research team compared in-use transit bus NO_x emissions and concluded that newer model-year buses significantly reduced tailpipe NO_x emissions under real-world driving conditions due to SCR improvements. A HD chassis dynamometer study was designed to check the zero-mile emission rates for model-year 2010 or newer HD diesel vehicles. CARB developed a HD Truck and Bus Surveillance Program to generate surveillance data to not only refine the mobile source emissions inventory, but also identify engine families for confirmatory in-use compliance testing.

EPA examined the MOVES 2014 model and concluded that the real-world NO_x emissions of model-year 2010 or newer vehicles are higher than the standards and current model estimates. On-board NO_x sensors were evaluated to compare with other on-board laboratory grade measurement systems (e.g., PEMS and Fourier transform infrared spectroscopy [FTIR]).

Particle Emissions Measurements: Mass and Number

Session Chair: *Shirish Shimpi, Cummins Inc.*

Focus in this session for the particle mass was on capability of partial flow dilution (PFD) systems to satisfy Tier 3 LD engine regulations and evaluating sampling system parameters. HD engine testing using PFD involved comparing the performance of three PFD units from different suppliers with each other and with the constant volume sampling (CVS) counterpart; differences in PN (particle number) measurement results were within 15 percent.

Recently the measurement of PN in-use emissions has been an area of interest in the European Union and a study evaluated an instrument developed to address the size concerns encountered in-use. Condensation particle counter (CPC) has been the mainstay of PN measurement with one company being the prominent player. Another company has decided

to supply their own brand of CPC to go with their PN instruments, and the measurement performance was tested both in laboratory and over chassis dynamometer tests.

LD In-Use Emissions

Session Chair: *John Collins, California Air Resources Board (CARB)*

LD vehicle emissions have been monitored by RSD for about 30 years. When using historical data to evaluate deterioration as a function of vehicle age, special care must be taken to compensate for changes in fleet composition because each RSD sample campaign captures a new cohort rather than following one longitudinal cohort.

A newly developed laser-based RSD method that looks down on the highway rather than across it showed good sensitivity and accuracy, which could allow monitoring of more driving modes than conventional RSD. Both RSD and PEMS measurements have shown that on-road vehicles emit differently on the highway compared with when measured in the laboratory over standard driving cycles. To overcome this discrepancy, certification tests need to be designed not only in a way that the vehicle is blind to the fact that it is being tested, but also to represent the wide range of operating conditions encountered in the real world. To represent on-road conditions while maintaining laboratory accuracy and reproducibility, a method to generate chassis dynamometer cycles from on-vehicle, on-road activity measurements has been developed, although current methods do not yet incorporate road grade.

In addition to aging more slowly, modern technology vehicles have different proportions of emissions from cold-start, warm-start, and hot-running exhaust than older technology vehicles. Counterintuitively, start emissions from lukewarm engines after moderate soak times are on average higher than start emissions from fully cold engines. The California emissions model EMFAC 2017 has been updated to reflect the new emission profiles from modern (LEV II) vehicles. Finally, while primary emissions of PM in the exhaust continue to be reduced, emissions of some volatile and semi-volatile gas phase species can lead to formation of tens of times more secondary PM, which the emission models need to address as another source of PM.

Method Developments in Emissions Measurements

Session Chair: *Tom Long, U.S. Environmental Protection Agency (EPA); Kevin Black, Federal Highway Administration (FHA)*

Real-time nonmethane organic gas (NMOG) measurements using FTIR were within 5 percent of the traditional method, which subtracts methane, oxygenates, and acetaldehyde from total hydrocarbons in post-processing. By using gas chromatography-mass spectrometry (GC–MS) to develop new recipes, FTIR can then be employed to perform real-time quantification of new or unexpected exhaust species. CARB has developed a portable roadside plume capture system to screen for high emitting in-use vehicles, which emit disproportionately large amounts of NO_X and black carbon (e.g., 48 out of 610 vehicles contributed to 50 percent of total NO_x emissions, as shown in Figure 4). Among a variety of alternate particle neutralizers to Krypton 85, it was observed that Po-210 produced a similar PN at high concentrations

Figure 3. Weekday average speeds by hour for light-duty passenger vehicles on urban unrestricted roads.

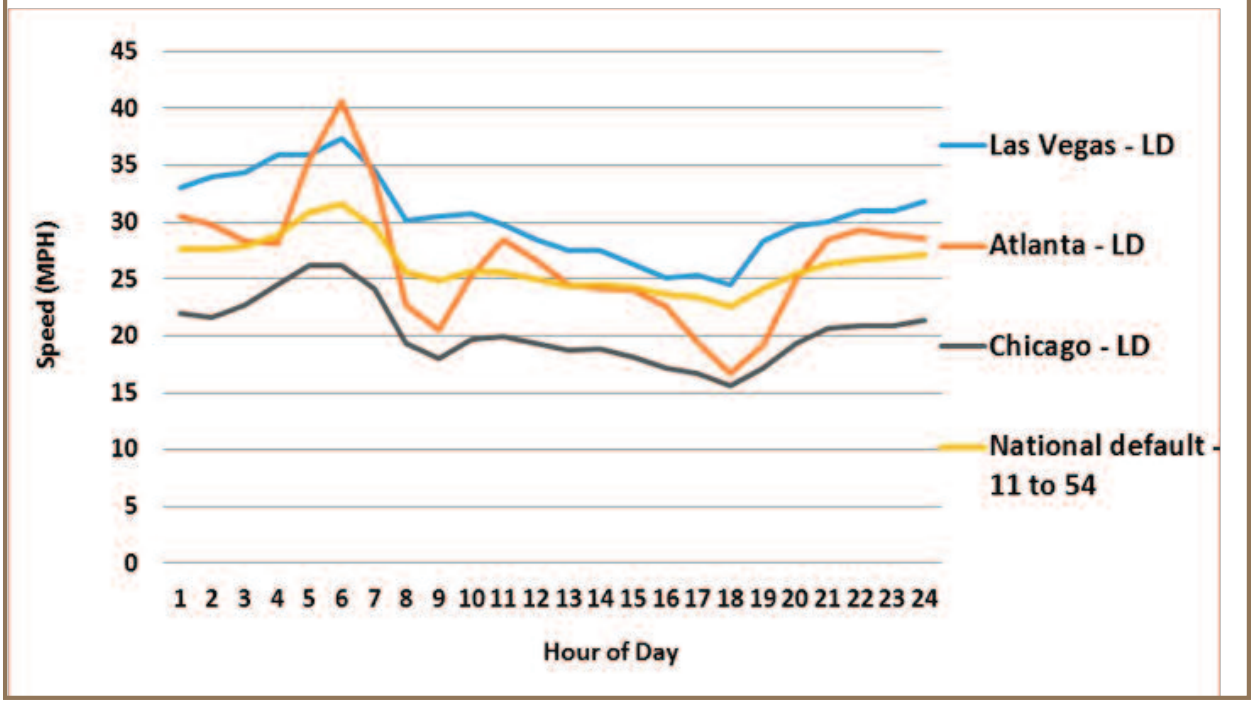
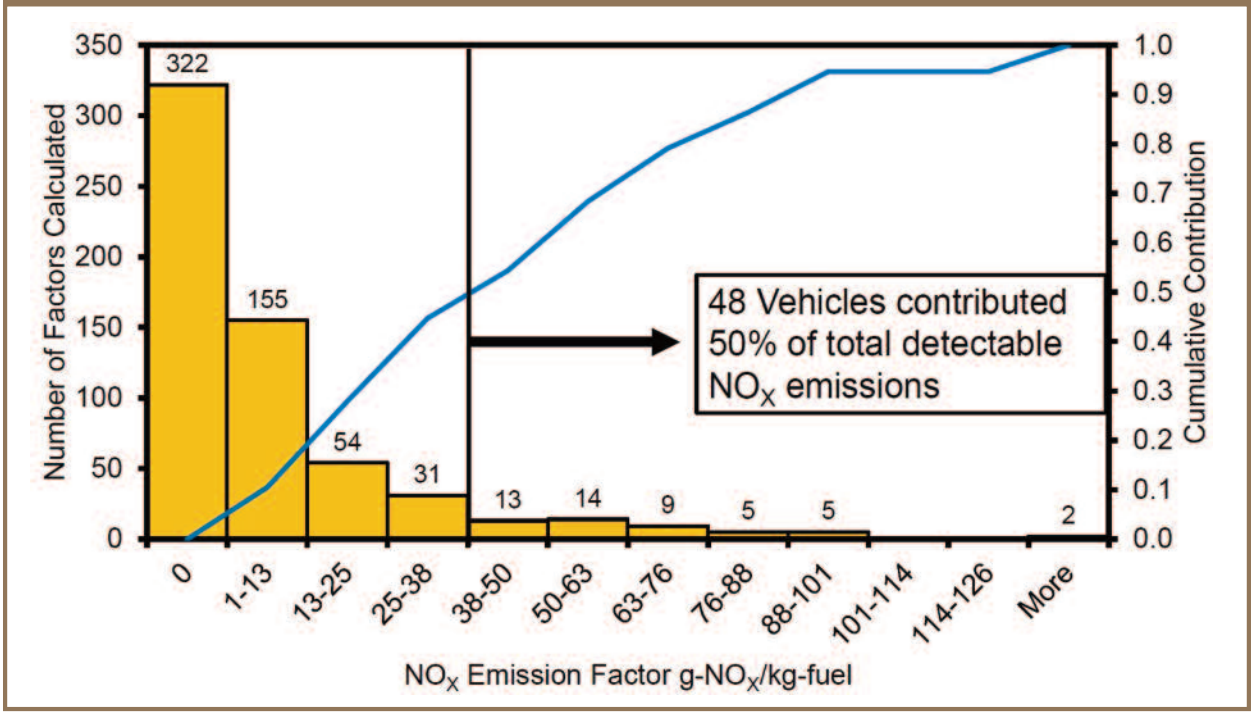


Figure 4. Measured NO_X emissions factor distribution for heavy-duty vehicles entering the California Department of Food and Agriculture (CDFA) Inspection Station in Truckee, CA.



and less error than other alternatives at low concentrations when measured with a scanning mobility particle sizer (SMPS).

While the measurement technologies provide the framework for examining the vehicle activities producing emissions, understanding the pattern of vehicle activities is also important for emission controls. Vehicle activity data describing operating modes, such as idling, accelerating, decelerating, and cruising, can be collected in multiple ways, including telematics (indirect, behavior-based) and traditional "drive cycles" (direct, laboratory-based). Several studies discussed using trip-based real-world activity data to improve our understanding of fleet characteristics and reveal the correlation between idle activity and a vehicle's vocational use (e.g., passenger, commercial, etc.).

Acknowledgment

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Long, "extended" idling activity can be associated with increased NO_x emission, where an "extended idle event" was defined as a continuous activity segment within a trip with second-by-second vehicle speed less than 5 mph, total duration more than five minutes, and total distance less than one mile.

Off Road

Session Chair: *Radha Purushothaman, Caterpillar Inc.*

Research on emissions reduction technologies and measurement methods for locomotive and marine vessels were included. Different black carbon measurement methods were compared on a large marine engine using three different types of fuels. Fuel used for testing affects the black carbon emission rates and the various measurement methods exhibited low uncertainties, except those instruments requiring high dilution had poor agreement. Various measurement methods were utilized to estimate the NO_x control efficiency and fuel flow on a locomotive engine with a new SCR based after treatment retrofit system. Initial evaluation performed in the railyard showed a 93-percent NO_x control efficiency.

Emissions from ocean-going vessels were compared with a scrubber system running on high- and low-sulfur fuel. The scrubber system reduced the sulfur dioxide (SO_2) emissions by 96–100 percent without a reduction in sulfate PM, thus, using a scrubber with high-sulfur (compared to low-sulfur) fuel led to more sulfate PM formation. Exhaust particles from a large marine diesel engine were characterized across four different fuels with varying sulfur levels. Irrespective of the fuel used, 70–80 percent of the particles formed were volatile, and increasing the fuel sulfur and ash content led to larger particles as well as higher total number of particles.

Next Workshop

The 28th Real-World Emissions Workshop is scheduled for March 18–21, 2018, in Orange County, CA. **em**