Highlights

from the Coordinating Research Council's 26th Real-World Emissions Workshop

by Dominic DiCicco, Ford Motor Company; Scott Mason, Phillips 66 Company; Henry Hogo, South Coast Air Quality Management District; Radha Purushothaman, Caterpillar Inc.; Tao Huai and Jorn Herner, California Air Resources Board; Shirish Shimpi, Cummins Inc.; Matthew Thornton, National Renewable Energy Laboratory; Kevin Black, Federal Highway Administration; Susan Collet, Toyota North America Technical Center; Megan Beardsley and Tom Long, U.S. Environmental Protection Agency; and Christopher Tennant, Coordinating Research Council

The Coordinating Research Council's (CRC) 26th annual Real-World Emissions Workshop was held March 13–16, 2016. More than 225 attendees representing 12 countries enjoyed presentations, posters, and demonstrations on topics such as emission measurements and measurement techniques; emission rates, inventory, and modeling; emission control measures; and fuel effects and fuel efficiency at this international forum for vehicle and engine emissions research. Highlights from the workshop sessions are summarized in the following article.

Real-World Emissions Data

Keynote: *Matt Miyasato, Deputy Executive Officer for Science and Technology Advancement at the South Coast Air Quality Management District*

In his keynote presentation, Dr. Miyasato discussed the importance of having sound real-world emissions data and the challenges of significantly reducing nitrogen oxides emissions for future regulations. As on-road transportation sector emissions levels are reduced, instruments capable of measuring these lower levels are needed. There will also be a greater need to collect real-world emissions as enhanced engine after-treatment technologies are deployed to confirm that lower levels are maintained.

Emission Rates and Inventory

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

While high-emitting vehicles may account for a large fraction of light-duty vehicle emissions, total emissions are lower overall. The Volkswagen compliance topic indicates that a segment of European vehicles have higher emissions than previously thought. A study was presented using a dedicated exhaust gas recirculation/gasoline direct injection system that produced reductions in nitrogen oxides emissions, however hydrocarbon emissions were higher.

Correlations were shown between vehicle age, mileage, and emissions deterioration. Mobile source emissions trends across the United States (see Figure 1) show that despite population growth and increased vehicle miles traveled (VMT), emissions have dropped significantly; trends through 2035 will decrease further. Greenhouse gas emissions will decrease until 2035, but without further action will increase afterwards. Activity patterns of selective catalytic reduction (SCR) equipped

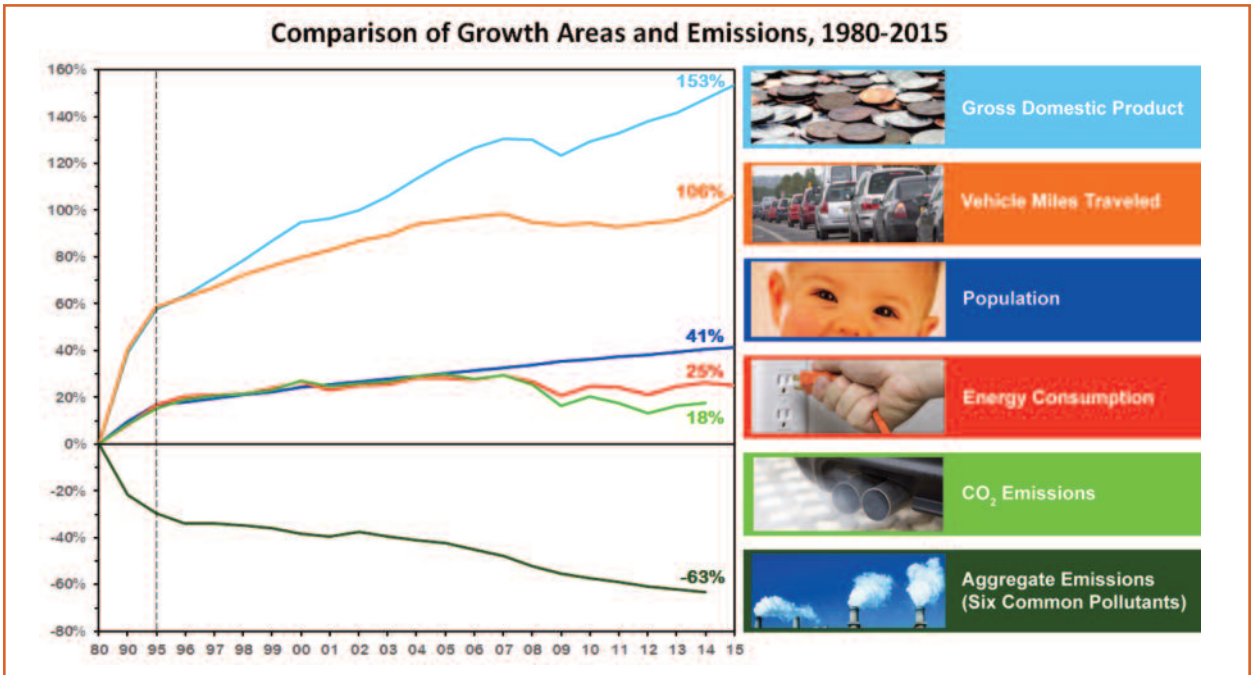

Figure 1. Historical trends in U.S. gross domestic product, population, vehicle miles traveled (VMT), and energy consumption compared to criteria pollutant and greenhouse gas emissions. (Choi, 2016; CRC Workshop proceedings).

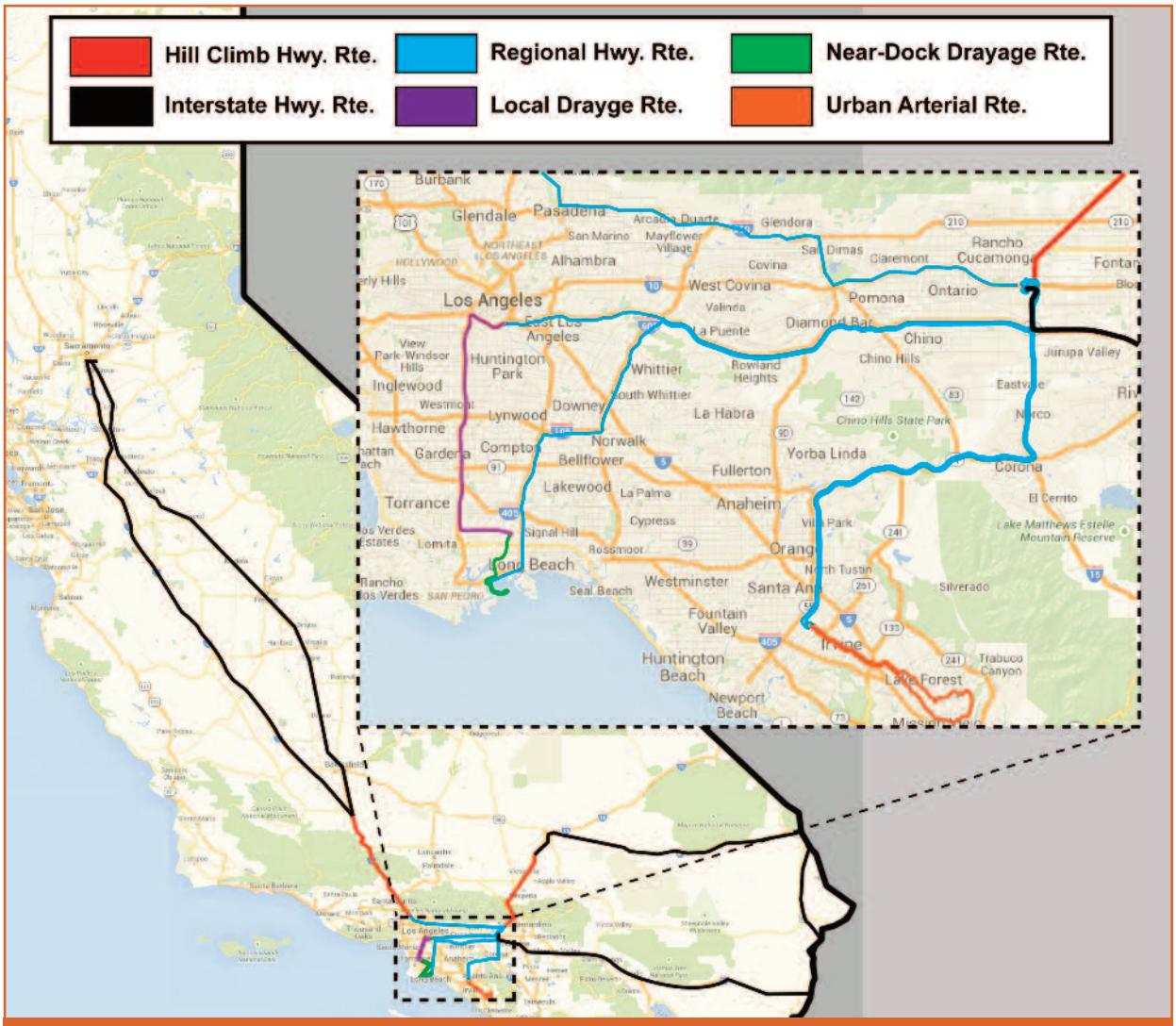

Figure 2. Particle emissions from real-world measurements (Smith, 2016; CRC Workshop proceedings).

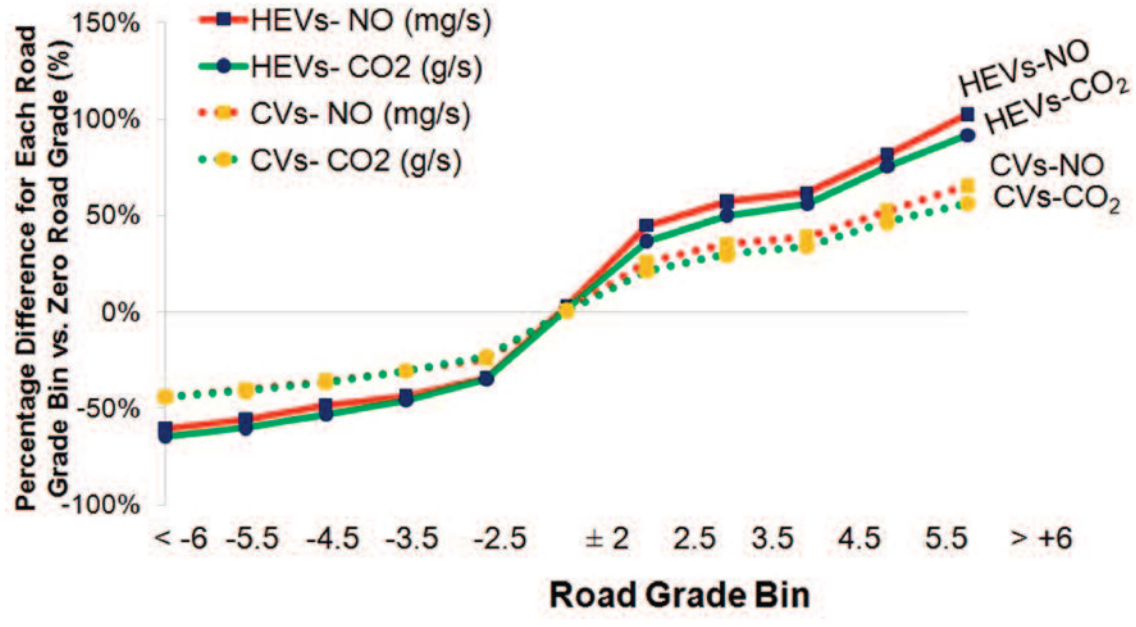

Figure 3. Actual vs. predicted values for emissions and fuel economy (Delavarrafiee, 2016; CRC Workshop proceedings).

Figure 4. Roadside testing and "refail" (Di Genova, 2016; CRC Workshop proceedings).

heavy-duty (HD) vehicles are being studied to identify where the SCR may not be operating effectively, and for comparison to the certification test cycle.

Off-Road Emissions

Session Chair: *Radha Purushothaman, Caterpillar Inc.*

Emissions inventories and measurements from a diverse collection of off-road sources, including construction and mining equipment, marine vessels, and motorcycles were discussed. A model demonstrated using portable emissions measurement system (PEMS) data to quantify emissions from heavy-duty construction equipment. For most cases, the model is 30 percent lower for nitrogen oxides emissions and 50 percent lower for particulate matter emissions, when compared against the California Air Resources Board (CARB) model.

The European Union in-use evaluation method using work-based window for non-road mobile machinery was also explained. The hoteling emissions from tanker ships at ports were studied, showing auxiliary engines emissions were lower, but boiler emissions were significantly higher than previously thought. Repowering a tugboat with a new engine showed emission reductions of 47 percent (nitrogen oxides), 81 percent (particulate matter), and 3 percent (carbon dioxide). Improving black carbon measurements on marine engines using a dynamometer was also described.

CARB presented emissions from 20 red and green sticker off-highway motorcycles; larger two-stroke motorcycles exceeded CARB's off-road motorcycle hydrocarbon limits. In general, important advances in the understanding of off-road emissions and, most importantly, potential options for reductions of various air and climate pollutants were presented.

Particle Emissions: Real-World Measurements

Session Chair: *Tao Huai, California Air Resources Board*

Four studies were presented that evaluated the impact of diesel particulate filters (DPFs) in reducing particulate matter emissions from on-road heavy-duty vehicles. The University of Denver confirmed that DPF decreases particulate emissions via the on-road heavy-duty vehicle emissions monitoring system (OHMS). A field evaluation in two Latin American cities concluded that solid particle number is more sensitive than opacity for particle emissions of DPF-equipped vehicles. CARB and West Virginia University found that the particulate matter emissions of DPF-equipped vehicles are more than 50 percent lower than the 0.01 g/bhp-hr standard. CARB also concluded, for parked regenerations, that DPF prevents approximately 99 percent of engine-out particulate emissions (see Figure 2).

In the light-duty presentations, Southwest Research Institute identified engine start-up (i.e., cranking, especially under cold-start conditions) may be a significant source of particle

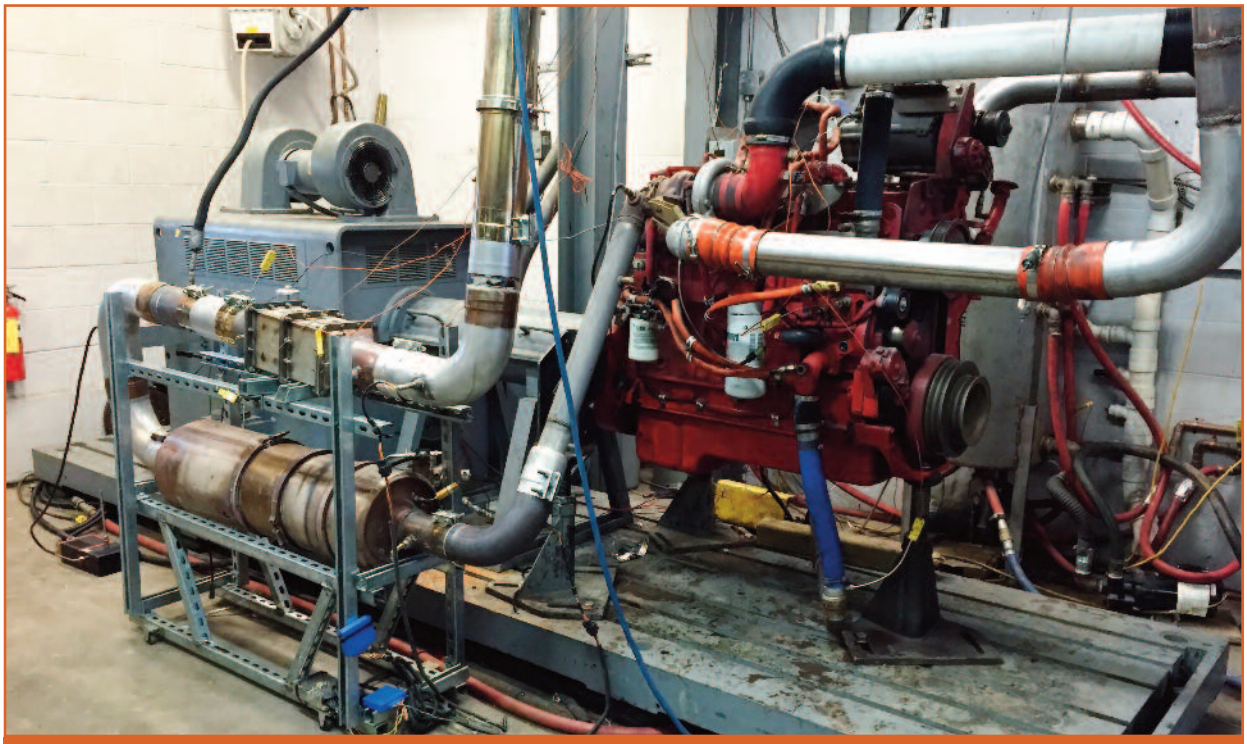

Figure 5. West Virginia University, Center for Automotive Fuels, Engines, and Emissions (WVU-CAFEE) Engine Testing Laboratory equipment, including an ammonia reduction catalyst with a three-way catalyst (Pradhan, 2016; CRC Workshop proceedings).

emissions. CARB showed that a model-year 2015 vehicle with improved gasoline direct injection (GDI) engine technology reduced its particulate matter (PM) emissions by 50 percent, while increasing fuel efficiency compared to earlier model-year GDIs. The agency also demonstrated that human driver deviation from chassis dynamometer cycle traces can be quantified to reduce test-to-test variability.

Center for Environmental Research and Technology, University of California, Riverside researchers found that the largest amount of PM is generated from very slow or fast speeds, and suggested engine technologies and higher vehicle speeds could be important considerations for inventory models.

Particle Emissions: Measurement Techniques

Session Chair: *Shirish Shimpi, Cummins Inc.*

It was noted that challenges to gravimetric PM measurement still remain as regulated levels have decreased by two orders of magnitude in 30 years. The CRC E99 project identified improvements that can still be made within the current measurement procedures. The need for measurement with real-time PM instruments continued to be expressed with comparisons to gravimetric PM measurement. A novel filter holder was introduced that enables measurements of real-time as well as gravimetric PM in a single device.

Ultrafine particles and the challenges to their definition and characterization were also discussed. A measurement technique demonstrated the ability to provide highly detailed characterization of individual ambient and emissions particles in real-time and in-situ by the use of an array of advanced instruments and methods. PM sensors were shown to be capable of detecting on-board diagnostic (OBD) failures.

Emissions Measurements: Laboratory

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

The accuracy of hydrocarbon measurements using traditional flame ionization detector (FID)-based methods was discussed along with an alternative method proposed using a Fourier Transform Infrared Spectroscopy (FTIR) for improved hydrocarbon measurement accuracy when methane levels are high. The measurement of semi-volatile exhaust species from gasoline vehicles using raw proportional sampling were compared to the semi-volatile exhaust emissions trends relative to nonmethane hydrocarbon and PM emissions.

Examination of the increasing importance of nitrogen dioxide (NO2) emissions and nitric oxide (NO)/NO2 ratios in diesel exhaust led to an evaluation of higher toxicity of NO2 compared to NO. The development of a nitrogen oxides

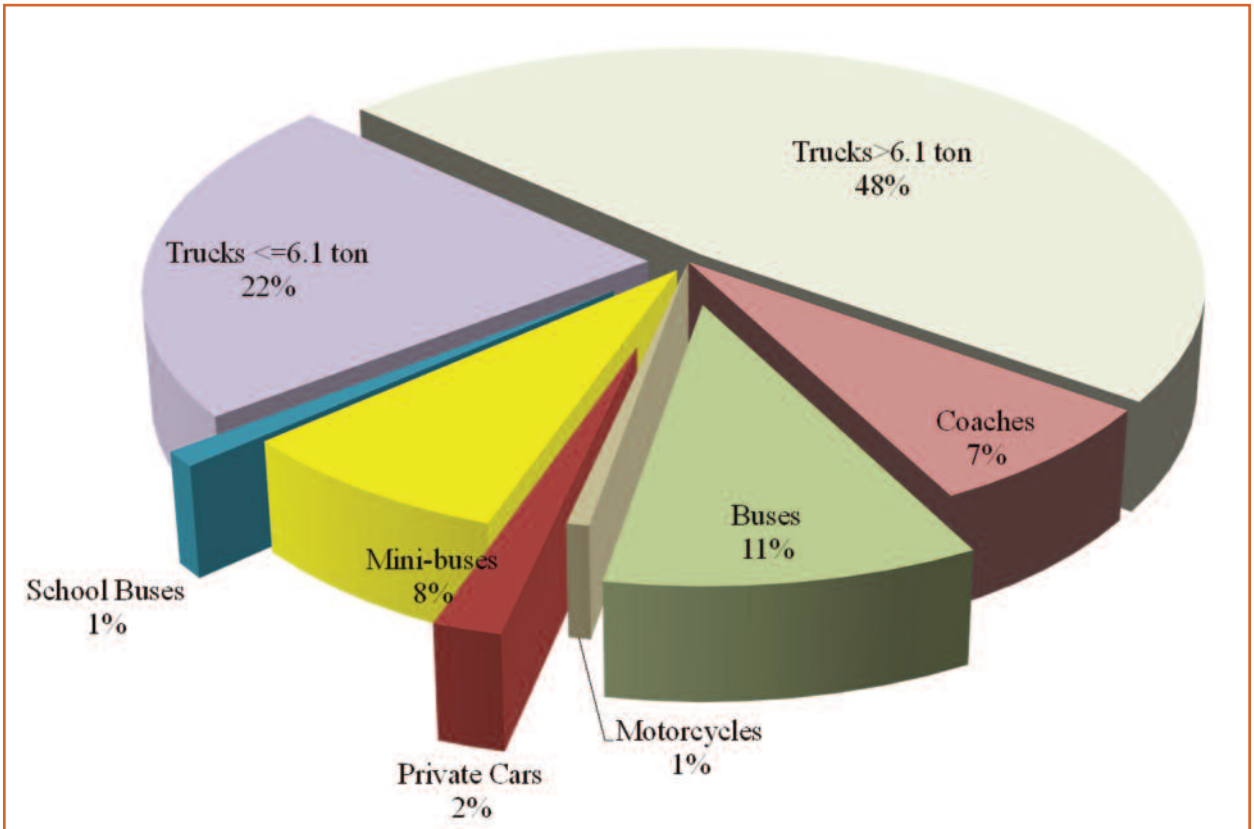

Figure 6. Hong Kong PM vehicle emissions, 2013 (Wong, 2016; CRC Workshop proceedings).

(NOx) sensor, based on solid state electrolytes, demonstrated sensitivity to NOx from 0 to 2,000 parts per million (ppm) measurement ranges and temperature stability are reached by the sensor housing design. PM mass measurement uncertainty was examined, noting that there is a noticeable difference between robotically-weighed and manually-weighed filters.

A real-world HD refuse truck driving cycle was developed using a Markov chain method, demonstrating construction of statistical estimation cycles from the transition probability matrix of the data. This approach takes into account vehicle speed, acceleration, and tractive load demand for close representation of real-world driving pattern. In the development of a preconditioning protocol to stabilize NOx and particle number (PN) for Euro 6 engine certification, it was shown that three preconditioning cycles are required to stabilize brake-specific NOx and PN emissions.

Fuel Effects and Efficiency

Session Chair: *Kevin Black, Federal Highway Administration*

Studies presented examined effects involving a range of fuels (diesel, gasoline, compressed natural gas [CNG], and electric) among vehicle classes (passenger cars, trucks, and buses). Measured (actual) emissions and fuel economy were compared with the vehicle's certified values. For most vehicles, actual emissions are higher than certified rates and actual fuel economy can be higher than the certified value by as much as 16 percent. Hybrid-electric cars, compared to gasoline cars, exhibited greater variability between actual and predicted values for emissions and fuel economy. A possible cause for this is that hybrids are more sensitive to road grade as illustrated in Figure 3.

A hybrid electric truck study showed that although these vehicles exhibited lower fuel consumption, they emitted more NOx. The cause for the higher NOx emissions may be related to the relationship between engine, vehicle, and transmission characteristics and could be reduced through an optimization of the system. The comparison of emissions from diesel and CNG buses for regulated and greenhouse gases showed that diesels demonstrated greater fuel economy while CNG buses emitted less NOx, PM, and nitrous oxide, but more carbon monoxide and mercury. A biodiesel-blended fuels study reported DPF-equipped vehicles exhibited higher emissions during DPF regeneration than during non-regeneration operation.

Emission Control Measures, I/M, and OBD

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

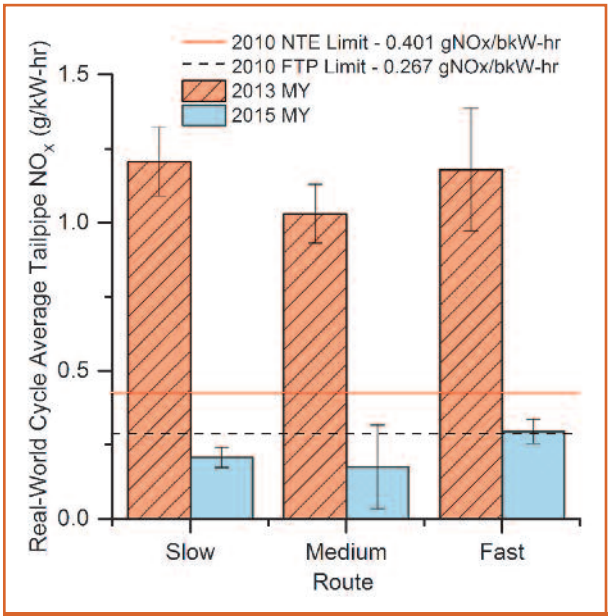

Figure 7. On-road NOx vehicle emissions (Kotz, 2016; CRC Workshop proceedings).

Studies described field measurement programs and emerging control technologies. One field measurement program metric discussed the California Smog Check station "refail" rate, meaning vehicles which failed their Smog Check initially, were repaired and then passed, then later failed again within a year. Roadside test data showed, for the first time, a reduction in the refail rate of 1976–1995 vehicles (see Figure 4).

Another field measurement program described information from vehicle owners participating in data gathering programs through their insurance providers, allowing the review of the operations on a per trip basis across a far greater number of vehicles than prior studies. Preliminary analysis shows patterns consistent with Motor Vehicle Emission Simulator (MOVES) model default values. HD trucks with SCR show exhaust temperature effects on NOx emission rates across all operating modes, and the representativeness of cycles could be evaluated based on engine power demand and after-treatment temperatures.

Another HD study involving a 2011 engine showed negligible NOx emissions degradation after 115,000 miles, and also found that manufacturers appeared to be scaling back thermal management during off-cycle low-load applications while still achieving lower certification values. A promising pathway to lower NOx and ammonia for off-road dedicated natural gas vehicles uses an ammonia reduction catalyst with a three-way catalyst (see Figure 5). Meanwhile, CARB is funding research to investigate reducing NOx emissions to levels significantly lower than existing standards, with a final report expected by the end of 2016.

Emissions Modeling

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

This session included evaluations of EPA's MOVES model and other emission inventory modeling for mobile sources. MOVES2014a includes corrections that led to a small decrease

in brake wear particulate emissions, and the model can now estimate hydrocarbon species and toxics from nonroad equipment. Researchers investigating how MOVES2014 models ethanol-gasoline blends suggested that additional research is needed on ethanol blends (>10 percent) and disputed the default parameters found in the fuel blends in MOVES2014.

Light-duty vehicle emissions on high-speed driving cycles were used to construct speed correction curves for speeds of 75 mph for updating California's EMFAC model. Plug-in electric hybrid vehicles tested under real-world conditions showed emissions that are generally quite low. PEMS measurements from a large database of vehicles illustrated the impact of Hong Kong's high congestion and steep road grade on emissions (see Figure 6). Analysis of Hong Kong's modeling needs suggested creating customized emissions modeling that combines elements of different existing approaches.

Emission Measurements: In-Field

Session Chair: *Jorn Herner, California Air Resources Board*

This session described on-road vehicle emissions data measured from Minnesota, California, North Carolina, London, and Hong Kong. Although studies focused on NOx emissions, carbon dioxide, carbon monoxide, hydrocarbon, and opacity data were also shown. A major theme was the observation of on-road emissions factors higher than their certification levels, by as much as a factor of ten for NOx. However, some of the most recent HD diesel vehicles tested (e.g., 2015 buses in Minnesota) emitted less NOx than the standards (see Figure 7).

Another common topic was the use of not-to-exceed (NTE) criteria in evaluating on-road emissions. The NTE approach utilizes only 10 percent of on-road data, and although alternative approaches that allow for closer to half of data to be used, such as the Moving Average Window and Work-Based Window, may be preferable, they also may miss as much as 90 percent of total NOx emissions. Many presentations compared 1-Hz PEMS data, including cold starts, to predictions from large-scale emissions models such as MOVES. Results highlighted the need for more PEMS data across various driving types to populate the model databases, and also discussed advances in PEMS technology that will allow for smaller systems.

Student Poster Competition

Twenty-five posters were presented at the workshop. Tom Long led the organizing committee in reviewing student posters and awarded the top effort to Jiacheng Yang (University of California, Riverside), who presented "Impacts of Dimethyl Carbonate on Emissions from a Heavy-Duty Engine." **em**

Workshop proceedings are available upon request from CRC (https://crcao.org). The 27th CRC Real-World Emissions Workshop will be held March 26–29, 2017, in Long Beach, CA.

In Next Month's Issue…

NESHAPS

The National Emission Standards for Hazardous Air Pollutants (NESHAPS) are ever changing and evolving. This issue will explore recent trends in NESHAP rulemaking, highlight the resulting impact it has had on industry, and try to predict future rulemaking initiatives.

Also look for…

EPA Research Highlights

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