The 2018 Critical Review focuses on the historic and more recent developments and trends relating to on-road vehicles in some detail. The review covers the major advances in engine design, control technologies, and fuels that have made it possible to reduce emissions and fuel use despite sustained growth in on-road vehicle miles travelled. The full-length review appears in the June 2018 issue of the *Journal of the Air & Waste Management Association* (JA&WMA). A brief summary follows.
Globally, 1.3 billion on-road vehicles consume 79 quadrillion BTU of energy, mostly gasoline and diesel fuels, emit 5.7 gigatonnes of carbon dioxide (CO₂), and emit other pollutants that are responsible for an estimated 200,000 premature deaths annually. In the 20th century, the vast majority of the exponential growth in global vehicle stock and vehicle miles traveled (VMT) occurred in the United States and Europe. However, most of the current growth in vehicle stock and fuel consumption is shifting to China and the rest of Asia (see Figure 1). Petroleum-based fuels remain the predominant transportation energy source globally.

Despite the emergence of a variety of alternative fuel and electric drive vehicles in the last two decades, the share of onroad transportation energy from fuels other than gasoline or diesel is currently trivial. Growth in demand for fossil fuels for transportation has been mitigated, but not eliminated, by improvements in vehicle fuel economy. In 2009, the U.S. Environmental Protection Agency (EPA) found that six greenhouse gases (GHGs) endangered public health and welfare, leading to more stringent fuel economy and new GHG standards effective starting in 2012. In the last decade, fuel economy and GHG emissions of the U.S. light-duty vehicle (LDV) fleet have improved significantly (see Figure 2). Fuel economy standards in many other countries are leading to concurrent improvements. However, consumer interest in heavier vehicles, most notably in the United States and China, offset potential reductions in energy use. EPA announced on April 3, 2018, that it will revise the LDV GHG emission standards for the 2022 to 2025 model years, which could slow the development and diffusion of more energy efficient vehicle technologies.

**Technology-Forcing Standards**

Beginning with the 1970 U.S. Clean Air Act, the United States implemented aggressive standards that forced the deployment of relatively new technologies and led to emissions reductions from gasoline and diesel vehicles that comprise the vast majority of the onroad fleet. The three-way catalyst (TWC) is one of the most important emission control technologies of the 20th century and is responsible for a greater than tenfold decrease in gasoline vehicle emissions of carbon monoxide (CO), oxides of nitrogen (NOₓ), and volatile organic compounds (VOCs). Effective TWC operation depended on phasedowns of gasoline lead and sulfur content and computer-controlled fuel injection for more precise control of air/fuel ratio. The air quality benefits of reduced CO, NOₓ, and VOC emissions are indicated by the virtual elimination of CO and nitrogen dioxide (NO₂) air quality nonattainment areas in the United States and a general trend of decreasing ambient ozone (O₃) ambient concentrations. Ongoing evolution of the TWC and its applicability to a wide variety of fuels used in stoichiometric engines worldwide promise to accrue ongoing health benefits into the foreseeable future.

![Figure 1. Global annual sales of new onroad vehicles.](image-url)
Because fine particles are a major contributor to health effects from the transportation sector, expanding application of diesel particulate matter (PM) controls is a priority. The suite of post-combustion controls now commonly used in the United States and Europe for new diesel engines, including diesel oxidation catalyst (DOC), diesel particle filter (DPF), and selective catalytic reduction (SCR) for NOX, are likely to be among the most important environmental technologies of the 21st century. The ability of these technologies to reduce real-world emissions requires the use of low-sulfur diesel fuel. The real-world effectiveness of these technologies has been validated empirically using many measurement methods. Some questions remain regarding the long-term durability of these technologies, emissions from DPF regeneration, SCR effectiveness related to low exhaust temperature, and the potential for SCR ammonia slip.

**Emerging Challenges**

Gas direct injection (GDI) engines introduced commercially in LDVs in the last 10 years are more energy efficient, but have higher exhaust particle emissions than the port fuel injection (PFI) gasoline engines that they displace. Thus, they may require mitigation with a gas particle filter (GPF) to achieve increasingly stringent particle mass emission standards in California and particle number standards in Europe.

There is growing recognition that vehicle emissions of higher molecular weight VOCs contribute to the formation of secondary organic aerosols (SOAs). Thus, it is important to continue research on organic particle formation and development of targeted prevention options, most likely related to more efficient control of releases of SOA precursors, as well as consideration of control of ambient peroxy radical precursors.

A key issue that has emerged in the last decade in Europe and elsewhere is a widening disparity regarding real driving emissions (RDE) compared to laboratory-based measurements of emissions. Although manufacturer cheating could be a contributing factor, the European-type approval procedure is clearly a key factor. In Europe, only one low power demand driving cycle (NEDC) has been used for type approval and a new replacement cycle (WLTC) is only a small improvement. In the United States, fuel economy rating and emissions certification are based on multiple cycles that represent a much wider range of vehicle operating conditions and, therefore, are more accurate with regard to real-world fuel economy and emissions. The planned use of portable emission measurement systems (PEMS) in Europe and China to measure RDE should lead to improved conformity between real world and official values. As hot stabilized emissions decrease, the relative importance of cold start emissions may increase.

Emission factor models such as the Motor Vehicle Emission Simulator (MOVES) are typically based on a relatively small number of driving cycles. However, with the growing availability of data on real-world driving cycles, it is now possible to assess inter-cycle variability as a contributing factor to variability and trends in mean emission rates. Mean emission rates based on sampling of a large number of cycles are likely to be more accurate than emission rates estimated based on a limited number of default cycles.
Inspection and Maintenance
Evaporative emissions from the crankcase and from fuel tank venting are effectively controlled with well-established technologies in conventional vehicles. However, the shift from emission test-based to onboard diagnostic (OBD) check-based inspection and maintenance (I/M) programs in most states may be leading to unacceptably high rates of both false positive and false negative outcomes. Validation is needed that OBD checks are a sufficiently robust indicator of either tampering or failure of emission control systems. The institutional and technical approach to I/M for heavy-duty vehicles has generally not kept pace with the changes in emission control technologies in any country, and requires incorporation of measurement methods relevant to the lower emissions of modern diesel vehicles.

The Volkswagen scandal was discovered because of measurements with PEMS made in a research program, not because of I/M programs. Given that there was a heavy-duty diesel engine NOX emissions scandal (NOX defeat devices installed on heavy-duty diesel engines) in the United States more than a decade prior to the Volkswagen scandal, the threat of penalties is not sufficient to deter cheating. The EU approach to developing RDE regulations means that manufacturers will not know exactly under what conditions their vehicles will be tested. Because methane is a potent greenhouse gas, shifts from liquid fuels to natural gas may offer marginally reduced GHG emissions only if fugitive emissions from natural gas production, transport, and distribution are appropriately managed. Shifts to hydrogen from steam reforming of methane would offer little marginal benefit.

Challenges in Managing Future Consumption and Emissions
As older vehicles are removed and cleaner, more fuel-efficient new vehicles enter the fleet, the average emission rate (g/mile) will decline substantially for many non-GHG pollutants (see Figure 3). However, without other interventions, the growth in vehicle stock, vehicle miles traveled (VMT), and fossil fuel consumption and concomitant GHG emissions could increase. Shifts from transportation fossil fuels to electric drive vehicles will lead to substantial GHG emissions reductions only if the power generation fuel mix is decarbonized. The attempt at the latter in the United States, the Clean Power Plan, is threatened with roll-back under the current political administration. With the forecast continued use of fossil transportation fuels, CO2 emissions would inevitably increase.

Although technological solutions to reducing emissions and fuel consumption rates of vehicles continue to provide

Figure 3. Trends in U.S. national average NOX emissions rates for gasoline-fueled passenger cars for calendar years 2015 to 2050 and ages 0 to 30 years, estimated using MOVES2014a with default inputs.
remarkable benefits, the demand for travel is an integral part of trends in vehicle energy use. Land use patterns, demographic factors, economic factors, design and operational factors, and societal values affect demand for transportation, mode choice, energy use, and emissions. Some of these factors, individually, may provide only small potential for reducing energy use and emissions, but in combination, coupled with technology-based solutions, could be part of an integrated approach to energy and emissions management.

**Disruptive Technology: Autonomous Vehicles**

Currently, it is difficult to predict how full adoption of autonomous vehicle (AV) technology will affect energy use or whether emissions of GHGs, criteria pollutants, and air toxics will be higher or lower. The net effect depends on a number of factors, including whether such vehicles ultimately will increase or decrease VMT. It is possible that adaptive management could mitigate against large increases in energy use via pricing or cordonning schemes. Given the wide range of potential results, it is critical to promote integrated and iterative consideration of energy, emissions, exposure, and health impacts along the AV development and deployment path.

**Research Needs**

The regulatory emission factor model used in the United States, MOVES, needs to account for some newer technology vehicles, such as hybrid electric vehicles (HEVs) and plug-in HEVs. MOVES also does not explicitly account for some of the trends in conventional LDV technology, such as from PFI to GDI. As emission rates generally decrease, the omission of

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**Trends in Onroad Transportation Energy and Emissions by H. Christopher Frey**

**Tuesday, June 26**

9:00–11:45 a.m.

**Connecticut Convention Center, Hartford, CT**

Following the review presentation, a panel of invited experts will critique the presentation and offer their own views on the topic. This year’s invited discussants are: **Alberto Ayala**, Executive Director, Sacramento Metropolitan Air Quality Management District; **Susan Collet**, Executive Engineer, Toyota Motor North America; **Rashid Shaikh**, Director of Science, Health Effects Institute; **Eric Stevenson**, Director of Meteorology, Measurement and Rules, Bay Area Air Quality Management District; and **Michael P. Walsh**, Independent Consultant/Board Member, International Council on Clean Transportation.

**Join the Discussion**

Comments also will be solicited from the floor and from written submissions to the Critical Review Committee Chair. The Chair will then synthesize these points into a Discussion Paper that will be published in the October 2018 issue of JA&WMA. Comments should be submitted in writing to Samuel L. Altshuler, Critical Review Committee Chair, at altshule@pacbell.net by no later than July 31, 2018. The full-length review will be published in the June 2018 issue of JA&WMA.

**Get Involved**

Get involved with the Critical Review Committee and help further our scientific understand by attending the Annual Meeting of the Critical Review Committee on Tuesday, June 26, 2018, at 3:00–4:00 p.m.

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such sources of variability may lead to biases in emission estimates. The effect of vehicle weight and payload needs to be addressed adequately in the development of vehicle emission factors and requires further characterization. The role of ambient conditions, and auxiliary loads such as air conditioning, are also inadequately characterized.

More research on organic particle formation and development of targeted prevention options is needed. Methodologically, more work is needed to better quantify and communicate uncertainties in emission inventories.

Mean emission rates based on sampling of a large number of cycles need to be incorporated into emission factor models. Comparisons of real-world driving cycles illustrate that some driving patterns can lead to lower emission rates. The concept of eco-driving has been tested mainly with respect to fuel consumption and should be further evaluated with regard to emissions. Lessons learned from comparative analysis of driving cycles need to be considered in designing advice for human drivers and algorithms for automated driving.

Non-exhaust emissions from evaporation and wear (e.g., brake pads, tires) are an important contributor to the environment from motor vehicle operation. Given their complexity in terms of gaseous and particle species, these emissions need to be better characterized. There will be an ongoing need to characterize and manage non-exhaust emissions, as illustrated by venting processes for compressed natural gas (CNG) vehicles, challenges in dealing with fuel tank venting for HEVs, and the effect of increased vehicle weight on wear emissions for battery electric vehicles.

Lower cost micro-portable emissions monitors, low-cost air quality sensors, and new open path measurement methods may make it easier for governments, communities, businesses, or individuals to monitor local emissions and air quality. Deployment of sensors on roving vehicles, such as Google Street View or mass transit vehicles, can enable extensive spatial and temporal data collection that can be used to develop, calibrate, and validate high-resolution transportation air pollutant exposure models.

More work is needed to characterize spatial and temporal variability in traffic-related air pollution exposures, especially in the onroad and near-road environments. Vehicle activity, energy use, emissions, exposure, and health effects are highly heterogeneous, which implies the need to develop effective sampling strategies to account for the myriad of factors that contribute to variability and to have large enough sample sizes to obtain robust findings. This implies a need for adequate commitment of resources for measurements, data collection, data analysis, model development, and data interpretation.

About the Author/Presenter

Dr. H. Christopher Frey is the Glenn E. Futrell Distinguished University Professor of Environmental Engineering in the Department of Civil, Construction, and Environmental Engineering at North Carolina State University. Dr. Frey is an internationally recognized expert in transportation energy use and emissions.

Dr. Frey has served as a member and chair of the U.S. Environmental Protection Agency (EPA) Clean Air Scientific Advisory Committee (CASAC). He has reviewed National Ambient Air Quality Standards for all criteria pollutants. He was lead author of the uncertainties chapter on in the 2006 International Panel on Climate Change (IPCC) Guidelines on National Greenhouse Gas Emission Inventories, and in 2016 was an invited expert regarding the updates to those guidelines. He was also a technical contributor to the U.S. Department of Transportation 2010 Report to Congress regarding transportation’s role in reducing U.S. GHG emissions. He is a Fellow of the Association, serving on the A&WMA Board of Directors. He is a past president of the Society of Risk Analysis. He has a bachelor’s of science degree in mechanical engineering from the University of Virginia, a master’s of engineering in mechanical engineering from Carnegie Mellon University, and Ph.D. in engineering and public policy from Carnegie Mellon.

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