Light-Duty Vehicle Emissions
A look at what lies ahead for the automobile sector: policy uncertainty, hybrid/electric vehicles, and autonomous transportation.
Staff and Contributors

A&WMA Headquarters
Stephanie M. Glyptis
Executive Director
Air & Waste Management Association
Koppers Building
436 Seventh Ave., Ste. 2100
Pittsburgh, PA 15219
1-412-232-3444; 412-232-3450 (fax)
em@awma.org
www.awma.org

Advertising
Jeff Schurman
1-412-904-6003
jschurman@awma.org

Editorial
Lisa Bucher
Managing Editor
1-412-904-6023
lbucher@awma.org

Editorial Advisory Committee
Teresa Raine, Chair
ERM
Term Ends: 2022

Bryan Comer, Vice Chair
International Council on Clean Transportation
Term Ends: 2020

Leiran Biton
U.S. Environmental Protection Agency
Term Ends: 2022

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SABIC Innovative Plastics
Term Ends: 2022

Prakash Doraiswamy, Ph.D.
RTI International
Term Ends: 2020

Ali Farnoud
Ramboll Environ
Term Ends: 2020

Steven P. Frysinger, Ph.D.
James Madison University
Term Ends: 2021

Keith Gaydosh
Affinity Consultants
Term Ends: 2021

Jennifer K. Kelley
General Electric
Term Ends: 2020

John D. Kinsman
Edison Electric Institute
Term Ends: 2022

Mingming Lu
University of Cincinnati
Term Ends: 2022

David H. Minott, QEP, CCM
Arc5 Environmental Consulting
Term Ends: 2020

Brooke A. Myer
Indiana Department of Environmental Management
Term Ends: 2022

Brian Noel, P.E.
Trinity Consultants
Term Ends: 2020

Golam Sarwar
U.S. Environmental Protection Agency
Term Ends: 2022

Melanie L. Sattler
University of Texas at Arlington
Term Ends: 2022

Anthony J. Schroeder, CCM, CM
Trinity Consultants
Term Ends: 2022

Justin Walters
Southern Company Services
Term Ends: 2022

Susan S.G. Wierman
Johns Hopkins University
Term Ends: 2021
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Light-Duty Motor Vehicle Emissions
by Justin Walters

Recent policy changes to mileage standards affecting light-duty vehicles in the United States have resulted in increased uncertainty for the automobile industry. At the same time, electric vehicles are growing in popularity and penetration is expected to substantially grow over the next decade. The focus for this month’s EM is the emissions trajectory of the light-duty vehicle sector.

Features

What’s Ahead for Light-Duty Motor Vehicle Emissions?
by H. Christopher Frey and Michael P. Walsh

Are Electric Vehicles a Panacea for Reducing Ozone Precursor Emissions?
by Gary A. Bishop

California’s Commitment to the Rapid Transition to Zero-Emission Vehicles is Undeterred
by Alberto Ayala

Columns

PM File: Backlog: An Eye to the Future
by David Elam
A look at backlog and why it is an important metric for environment, health, and safety (EH&S) consulting firms.

Departments

Message from the President: Challenges for Cleaner Transportation
by Kim Marcus

Back In Time: A&WMA’s Annual Critical Review Turns 50
This month, *EM* focuses on the dynamic between light-duty vehicles and issues around emission standards, and the increasing acceptance, quality, and place of electric vehicles. The surge of technology, infrastructure, and the public’s acceptance of electric vehicles signals the next quantum leap for transportation. We are moving from depending on the use of carbon-based resources to the direct use of the sun’s energy. Clearly, as with any major change, not everyone will embrace this shift, but enough people are moving in that direction that we can anticipate a meaningful reduction in future fossil fuel use. To learn more, read the feature articles in this issue that focus on the emissions trajectory of the light-duty vehicle sector.

Looking ahead to A&WMA’s Annual Conference & Exhibition (ACE; www.awma.org/ace2020) in San Francisco later this summer, one of the conference highlights includes a Keynote plenary session on “Environmental Challenges for Transportation” featuring leading industry executives who will share their perspective and solutions during an interactive panel discussion. Featured speakers include: Severin Borenstein of the Haas School of Business, whose current research projects include the economics of renewable energy, economic policies for reducing greenhouse gases, alternative models of retail electricity pricing, and competitive dynamics in the airline industry; Delphine Hou, who develops regulatory strategy for the California Independent System Operator (CAISO); and Laurie Shelby, who leads worldwide environment, health, and safety operations for Tesla, Inc.

It is not too late to start planning to attend ACE. Other conference highlights include the 50th Annual A&WMA Critical Review on “Wildfire and Prescribed Burning Impacts on Air Quality in the United States” by Dr. Daniel A. Jaffe; a mini symposium on “Embracing Innovation”; and over 300 platform, panel, and poster presentations. Add to that the many professional development and networking opportunities, as well as a truly beautiful venue, and you have all the makings for a great conference. Hope to see you there! *em*
Recent policy changes to mileage standards affecting light-duty vehicles in the United States have resulted in increased uncertainty for the automobile industry. At the same time, electric vehicles are growing in popularity and penetration is expected to substantially grow over the next decade. The focus for this month’s *EM* is the emissions trajectory of the light-duty vehicle sector.
Are you in the market for a new vehicle? A look around the local auto mall may have your head spinning with options. While many Americans are enamored with SUVs and pick-up trucks, the popularity of low- and zero-emitting vehicles has grown substantially over the past decade. According to the 2019 Electric Vehicle Outlook by Bloomberg New Energy Finance (https://about.bnef.com/electric-vehicle-outlook/), battery prices are expected to continue to fall dramatically over the next few years, which may help zero-emitting plug-in electric vehicles reach price parity with internal combustion engine vehicles by the mid-2020s.

While low-emitting technology options continue to expand, recent policy changes leave a great deal of regulatory uncertainty for the automobile industry. In 2012, aggressive light-duty vehicle (LDV) emissions and fuel economy targets were established for model-years 2017 through 2025. However, the U.S. Environmental Protection Agency (EPA) and the U.S. National Highway Traffic Safety Administration (NHTSA) recently proposed to freeze targets at 2020 levels through 2026 and withdrew California's waiver to set its own greenhouse gas emissions standards and zero-emitting vehicles mandates.

In this issue, we consider these and other drivers impacting the auto industry as we examine what's ahead for LDV emissions and regulations.

In the first article, Chris Frey and Michael Walsh discuss several factors that could impact emissions from LDVs, both domestically and internationally, particularly emissions of carbon dioxide. While LDVs continue to be more efficient, trends in vehicle preference toward SUVs and increasing vehicle miles traveled could overwhelm these efficiency gains. Domestic and international policy will be important for adoption of low-emission technologies and continued emission reductions from LDVs.

Next, T.J. Wallington, et al. with Ford Motor Company provide an historical overview of vehicle emissions trends, discussing the significant reductions in emissions of pollutants such as nitrogen oxides and carbon monoxide that have so far been achieved. Further reductions in these pollutants from LDVs will likely be dependent upon addressing emissions from high emitters that are on the road. As zero-emission vehicles gain market share, the emissions footprint from these vehicles, including carbon dioxide, will be dependent upon upstream emissions from the electricity sector.

Gary Bishop discusses research conducted by the University of Denver, using data collected recently in Denver, Chicago, and Los Angeles, showing that a small number of vehicles are responsible for a large portion of emissions. His article highlights the importance of focusing on addressing high emitters to achieve further emission reductions from the transportation sector.

In the final article, Alberto Ayala with the Sacramento Metropolitan Air Quality Management District provides a critical perspective on how policy changes, such as the Safer, Affordable, Fuel-Efficient (SAFE) Vehicles Rule, present challenges for states like California that have areas that are struggling to meet U.S. National Ambient Air Quality Standards. California emissions standards have been a driver for zero-emission vehicle technology development and the state is expected to continue to seek ways to force technology solutions to reduce emissions from the transportation sector.

Justin Walters, Principal, Environmental Policy & Engagement, Southern Company. Walters is a member of the EM Editorial Advisory Committee.
What’s Ahead for Light-Duty Motor Vehicle Emissions?

An overview of the projected trajectory for light-duty motor vehicle emissions, trends, and standards.
The global stock of on-road light-duty vehicles (LDVs) grew by nearly 32% from 2010 to 2018, reaching over 1.3 billion (see Figure 1), with increases to over 2.4 billion vehicles projected by 2050. Much of this growth will occur in Asia. Although market shares of alternative vehicles—including plug-in hybrid electric vehicles (PHEVs), battery-powered electric vehicles (BEVs), natural gas-fueled vehicles, and hydrogen fuel-cell vehicles (FCEVs)—are expected to increase, in the absence of policies to the contrary, the vehicle fleet is expected to be dominated by internal combustion engine (ICE) fossil-fueled vehicles for the next few decades.¹

U.S. LDV greenhouse gas emissions increased by 13% from 1990 to 2018 to 1.09 billion metric tons of carbon dioxide (CO₂)-equivalent.²

**Improvements in Conventional Vehicle Technology**

Conventional LDVs are becoming more energy efficient through the use of improved technologies (e.g., direct injection, more efficient transmissions, hybridization).³ Although average vehicle weight is approximately the same, and although average engine horsepower is 70% greater, the U.S. LDV fleet today is approximately twice as fuel efficient as it was in 1970. While fuel economy improvements could lead to net reductions in energy consumption in developed countries, growth in vehicle stock and vehicle miles traveled (VMT) elsewhere is likely to increase global energy consumption (see Figure 2).¹,⁴

**Trends in Consumer Choices**

The rise of sport utility vehicles (SUVs) has been one of the major drivers of recent global CO₂ emissions growth, according to the International Energy Agency, putting increased pressure on advanced technologies for reducing CO₂ emissions from vehicles. The U.S. market share of light-duty trucks, including SUVs, has recently far outpaced that of sedans and wagons (see Figure 3). In 2018, the fuel economy of truck-based SUVs averaged only 22 miles per gallon (mpg), compared to 30 mpg for sedans.²

Social attitudes toward transport may be changing in ways that could increase energy consumption. For example, energy consumption for vehicles used in ridesourcing services (e.g., Uber, Lyft) may be substantially higher, by 40%–90%, compared to previous transport mode choices, because of miles accumulated to reach a service territory and during deadheading (driving without passengers) between rides.⁵ However, although some ridesharing is replacing walking and mass transit use, much of it replaces private car or taxi usage; thus, the overall effect on vehicle miles traveled and greenhouse gas emissions is small.⁶
equivalent ICE vehicles and, as coal gradually gets phased out, this CO₂ advantage will increase. The global share of power generation from renewables, such as wind and solar, is expected to increase, and the emissions intensity of power generation is expected to decrease.¹³

Emissions from battery manufacturing are roughly comparable to that for ICEs used in conventional vehicles, and will decrease as electric power is decarbonized.⁹ There are unlikely to be raw resource constraints (e.g., rare earth metals) on battery production capacity.¹⁰ EVs are also not likely to be constrained by power generation capacity, although there will be a growing need for home and public chargers. Public policies to promote new vehicle technologies tend to benefit disproportionately wealthy populations.¹¹ To address equity in BEV adoption, California has been piloting a Clean Vehicle Assistance Program aimed at low-income adopters.¹²

**Disruption from Autonomous Vehicles**

The emergence of autonomous vehicles (AVs) is likely to disrupt trends in LDV energy use and emissions. The effect of AVs will depend on many factors, such as levels of autonomy, vehicle connectivity, whether vehicles are shared, and the mix of AVs and traditional vehicles, as well as choices of fuels and powertrains. Broadly, AVs are likely to have two major impacts: at the individual vehicle level and at the macroscopic level.

At the individual vehicle level, AVs could be operated more efficiently by smoothing speed trajectories and coordinating with traffic and infrastructure. However, AV performance goals may differ by manufacturer and may not emphasize energy efficiency. Vehicles could be controlled, for example, to minimize travel time rather than energy use.

At the macroscopic level, such as for an urban region, AVs may dramatically change trip-taking activity. For example, children not old enough to drive a traditional vehicle may be allowed to use AVs. AVs could be used by elderly or disabled persons who are not easily able to drive a traditional vehicle. Furthermore, leisure time in an AV could lead to tolerance of longer commutes and increased sprawl in land-use patterns. Depending on these and other factors, AVs could substantially reduce or increase transport energy consumption, by roughly a factor of two.¹³ ¹⁴

**International Policy and Regulation**

Although light-duty diesel vehicles (LDDVs) are more fuel
efficient and lower CO₂-emitting than equivalent gasoline vehicles, their future is uncertain. Markets that have historically had high shares of LDDVs, particularly the European Union (EU) and India, have promulgated more stringent tailpipe nitrogen oxides and particulate matter emission standards, which require expensive emission controls. Many European cities are restricting diesel cars in light of the VW diesel emissions scandal. The prospect of such restrictions leads to loss of consumer confidence that, if they buy a diesel car, they will be able to drive it as they normally have.

Numerous countries are adopting passenger car CO₂ emission and fuel consumption regulations (see Figure 5). The EU is currently the most aggressive with stringent requirements going into effect in 2020, 2025, and 2030. Meeting these standards in the future will be difficult without BEVs. BEVs are inherently clean and do not require large and ongoing investment in strong emissions compliance programs. To address climate change, many countries and cities are calling for the elimination of ICE vehicles. For example, the sale of petrol and diesel cars would be banned in Ireland from 2030 under draft proposals for a new climate law. The Irish proposal sees the country join Denmark, Sweden, and the Netherlands in targeting a 2030 deadline. France and Spain have announced similar plans with a 2040 date, while the United Kingdom and Norway plan to ban sales of petrol and diesel cars from 2035 and 2025, respectively.

Numerous manufacturers have announced investment of hundreds of billions of dollars for the production of BEVs and batteries, assuring an increasing variety of models and vehicle types and thereby increasing consumer options. As sales volumes climb, the cost of so-called zero-emissions vehicles (ZEVs), including BEVs, is approaching that of ICE vehicles, with cost parity expected within five to seven years. Increased affordability could enable more widespread adoption of BEVs.

California’s Unique Leadership Role

Because of historically uniquely severe air quality problems, California has the right under the U.S. Clean Air Act to request a waiver from the U.S. Environmental Protection Agency (EPA) to set its own state-level motor vehicle emission standards. For example, the California Air Resources Board (CARB) adopted the first ZEV mandate in 1990, primarily to address the serious ozone air pollution problem in the Los Angeles basin. As concerns regarding climate change increased, CARB viewed growth of ZEVs as critical to addressing that problem as well. Based on Section 177 of the Clean Air Act, other U.S. states can adopt either the federal or California standard. Thirteen states follow California’s Low Emission Vehicle (LEV) standards of which nine also follow the ZEV mandate.

To place California’s role in historical context, the state’s technology-forcing regulations led to the introduction of three-way catalysts (TWC) to reduce carbon monoxide, hydrocarbon, and nitrogen oxides emissions from gasoline cars; advanced electronic controls and fuel-injection systems to assure proper air fuel mixture controls to optimize the performance of TWCs; onboard diagnostics to monitor emissions performance; and BEVs. These technologies have been adopted globally and have profoundly changed the global motor vehicle industry and its emissions footprint. For example, following California’s technology and policy lead, China, which is the world’s largest new car market, is now also the largest ZEV market.
Reversal of U.S. Policy on Vehicle GHG Emissions

The recent U.S. trajectory toward more energy-efficient vehicles is being tempered by climate change regulatory efforts of the current administration. In 2012, in an effort to assure a single national program, EPA, the U.S. National Highway Traffic Safety Administration (NHTSA), and CARB agreed to tighten greenhouse gas (GHG) and fuel economy standards through model-year 2025. To monitor progress, they provided for a mid-course review. In January 2017, EPA carried out an extensive review and concluded that the standards through model-year 2025 were feasible and more cost-effective than originally estimated. However, in April 2017, then-EPA Administrator Scott Pruitt reversed EPAs decision with the intent to freeze standards at 2020 or 2021 model-year levels.

In 2018, EPA and NHTSA issued a proposed regulation that would reverse California’s waiver, at least with regard to GHG emissions and the ZEV mandate. The EPA/NHTSA proposal received strong criticism from the environmental and scientific communities, including EPA’s own Science Advisory Board. In particular, the modeling assumption that lowering the purchase price of new cars would result in overall VMT reductions was considered by many to be illogical. As of the time of writing, a final rule has not been promulgated, but is expected to require much more modest efficiency and CO2 improvements annually from 2021 to 2025 than the 2012 rule. All parties expect the legal issues relating to California’s authority to set standards for vehicle GHG emissions and to mandate ZEV sales to go to the U.S. Supreme Court for final resolution over the next year or so.

Looking to the future, if California is prevented from continuing its leadership role in reducing climate-related pollutants from vehicles, the likelihood of achieving the transportation emissions targets necessary to adequately address the climate crisis will be greatly diminished.

Summary

Light-duty vehicle energy use and emissions are affected by a variety of trends, such as the current rollback of vehicle GHG emission standards in the United States, policies in other countries to promote cleaner vehicles, and manufacturer commitments to various technology options. Changing user needs for mobility and changing preferences for how mobility needs can be met will affect energy use and emissions, depending on how technology adoption and deployment is managed. There is a growing need for research, demonstration, and implementation related to innovative technologies and policies to help manage these large changes. Technology-forcing regulation is an essential component of policies that can effectively reduce vehicle GHG emissions.

H. Christopher Frey, Ph.D., is the Glenn E. and Phyllis J. Futrell Distinguished University Professor at North Carolina State University. He chaired the U.S. Environmental Protection Agency’s Clean Air Scientific Advisory Committee from 2012 to 2015 and authored A&WMA’s 2018 Critical Review (https://www.tandfonline.com/doi/full/10.1080/01962247.2018.1454357) on vehicle emissions. Michael P. Walsh is the founding chair of the Board of Directors of the International Council on Clean Transportation (https://thecict.org/). He has directed motor vehicle emission control programs and received a MacArthur Fellowship in 2005 for his innovative vehicle emissions work.

References


The authors provide a condensed and updated version of their 2018 published perspective of what’s ahead for light-duty vehicle emissions.
Most light-duty vehicles (LDVs) are powered by internal combustion engines using gasoline or diesel fuel. Tailpipe emissions include carbon dioxide (CO₂), non-methane hydrocarbons (NMHC), carbon monoxide (CO), nitrogen oxides (NOₓ), and particulate matter of size less than 2.5 microns (PM₂.₅). Emissions of CO, NMHC, NOₓ, and PM₂.₅ can adversely impact local air quality and have been regulated since the 1970s. In the United States, federal Tier 3 and California Low Emission Vehicle (LEV) III LDV standards are phasing in from 2015 to 2025. California LDVs will need to meet the Super Ultra Low Emitting Vehicle (SULEV) standard of combined emissions of NOₓ and NMHC of 0.030 g/mile (SULEV30) in 2025. In the European Union, the Euro 6 LDV standard went into effect in 2015 and real driving emissions (RDE) standards started in 2017. Increases in stringency in emission limits (i.e., Tier IV and Euro 7) are under discussion and are likely to be implemented post 2025.

**Historical Success**

**Vehicle Emissions**

To meet regulations, advanced vehicle emission after-treatment systems such as three-way catalytic converters, lean NOₓ traps, selective catalytic reduction (SCR), and diesel particulate filters (DPFs) have been developed and fuel sulfur concentration reduced. The combined after-treatment and fuel approach has enabled highly effective emission control systems. Starting in the early 1990s, the successive LDV emission standards have lowered the regulated emission intensity (g/mile or g/km) of NMHC+NOₓ emissions by 98% in the United States (Tier 1 to Tier 3) and by 80–85% in the European Union (Euro 1 to Euro 6). Heavy-duty vehicle (HDV) emissions standards for NMHC+NOₓ have decreased by 95% or more since 1988 in the United States.

The New European Drive Cycle (NEDC) and test procedure did not fully reflect on-road emissions, and the decrease in NOₓ emissions from on-road diesel vehicles in the European Union was less than expected based on laboratory emission measurements. Nonetheless, gasoline vehicle on-road NOₓ emission rates decreased by approximately a factor of 10 since pre-Euro 1 emissions controls. In the current Euro 6 regulations, the NEDC has been replaced by the Worldwide Harmonized Light Vehicle Test Procedure (WLTP) and a real driving emission (RDE) component has been added to bring on-road emissions close to the standards as measured in laboratory emissions testing.

In the United States, the vehicle miles traveled tripled between 1970 and 2017. In the European Union, the number of registered passenger cars grew about 45% from 1995 to 2017 and passenger car travel (passenger km) increased 25%. Despite increased vehicle mileage, U.S. and EU total highway vehicle (LDV, HDV, commercial vehicle and motorcycle) NOₓ and volatile organic compound (VOC) emissions have decreased 60–80% since 1990, as shown in Figure 1.

**Air Quality**

Air quality has improved reflecting the decreases in emissions from vehicle and stationary sources. As shown in Figure 2, ambient concentrations of ozone (O₃), CO, NOₓ, and PM₂.₅ are declining in U.S. cities. O₃ (annual 4th highest 8-hr average), CO (2nd maximum 8-hr average), and NO₂ (annual 98th percentile of daily maximum 1-hr average) concentrations decreased 31%, 83%, and 61%, respectively, from 1980 to 2018. PM₂.₅ (seasonally weighted annual average) levels decreased by 39% from 2000 to 2018. The O₃ concentrations in Los Angeles have decreased by approximately a factor of 5 since the 1950s when peak 1-hr oxidant levels were approximately 600 parts per billion (ppb)!}

While country-wide average air quality today is much improved in the United States and Europe, local concentrations can still exceed the ambient air quality standards. In many U.S. urban areas, especially California, O₃ concentrations continue to exceed the air quality standard (70 ppb). Many EU monitoring stations exceed the O₃ standard.
The EU annual air quality standard for NO\(_2\) is still widely exceeded at roadside sites, although with the progressing fleet renewal toward Euro 6 and electric vehicles this exceedance is declining and will continue to decline in the future.

**What's Ahead?**

**Zero-Emission Vehicles**

Limits or bans on internal combustion engine (ICE) vehicles in several major city centers are being implemented or considered to further control emissions, with the Netherlands, Norway, France, and the United Kingdom considering bans on the sale of new gasoline and diesel cars by 2025–2040. The EU Parliament is in favor of registering zero-emission vehicles (ZEVs) only, starting 2040, as a contribution to the planned EU target of net carbon neutrality by 2050 (EU Green Deal). ZEV mandates are in place in California, 10 other U.S. states, and China.

ZEVs—including battery-powered electric vehicles (BEVs) and hydrogen fuel-cell vehicles (FCVs)—have zero tailpipe emissions, but are not zero-emission. Upstream electricity generation emissions for a BEV can be comparable to ICE vehicle tailpipe emissions. A typical U.S. 2020 BEV has a label electricity consumption of approximately 25 kWh/100 miles. The U.S. electric grid, on average, produces 0.33 g NO\(_x\)/kWh of generated electricity. Assuming 5% grid loss, the BEV produces upstream NO\(_x\) emissions of 0.086 g/mile (0.053 g/km), the same as the vehicle standard of 0.086 g NO\(_x\) + N\(_x\)HC/mile (53 mg/km in Table 1). The best-in-class ICE vehicle, a hybrid electric vehicle (HEV) for example, emits 0.004 g NO\(_x\) + H\(_x\)C/mile, 21 times less than the BEV, but ICE emissions occur closer to residential areas.

Table 1 compares the emissions of criteria pollutants for the U.S. BEV, best-in-class ICE, and average on-road fleet, a typical Euro 6 gasoline direct-injection (DI) ICE, and the applicable EU and U.S. vehicle standards. Ranking by total NO\(_x\) emissions per km, ICE emissions are less than BEV emissions, and both are below the new vehicle standards. As seen in Table 1, California has a grid that is cleaner than the U.S. average. Electricity generation must transition to renewables (e.g., wind, solar) for ZEVs to match ICE vehicle lifecycle NO\(_x\) emissions. The share of renewable electricity generation emissions for a BEV can be comparable to ICE vehicle tailpipe emissions. A typical U.S. 2020 BEV has a label electricity consumption of approximately 25 kWh/100 miles. The U.S. electric grid, on average, produces 0.33 g NO\(_x\)/kWh of generated electricity. Assuming 5% grid loss, the BEV produces upstream NO\(_x\) emissions of 0.086 g/mile (0.053 g/km), the same as the vehicle standard of 0.086 g NO\(_x\) + N\(_x\)HC/mile (53 mg/km in Table 1). The best-in-class ICE vehicle, a hybrid electric vehicle (HEV) for example, emits 0.004 g NO\(_x\) + H\(_x\)C/mile, 21 times less than the BEV, but ICE emissions occur closer to residential areas.

Table 1. U.S. and EU standards and emissions from selected light-duty gasoline ICE vehicles and BEVs and non-exhaust brake and tire wear emissions from Winkler et al.

<table>
<thead>
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<th>Standards and Emission</th>
<th>mg/km</th>
<th>NO(_x)+HC</th>
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<th>SO(_2)</th>
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<td>2</td>
<td>0.3</td>
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<td>17–100</td>
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<td><strong>Typical 2020 BEV electricity emissions</strong></td>
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*Notes: BEV emissions and 2018 fleet average were updated. The 2018 California electric grid was added.*

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needs to further increase in all regions to fully leverage the advantages of electric vehicles.

Non-exhaust emissions have become relatively more important as the tailpipe emissions have decreased. Tire and brake wear PM emissions are of the same magnitude or perhaps higher than tailpipe emissions. Tire wear is a function of many factors: heavier BEVs are expected to give more tire wear PM emissions while brake wear PM emissions can be lower on electrified vehicles, which use regenerative braking. Windshield washer fluid is a source of VOC emissions that is regulated in some locations.

**Future Air Quality**

Air quality models can be used to estimate the benefits of future vehicle emission regulations and programs. In 2030, when U.S. Tier 3 standards are fully reflected in the on-road fleet, it has been projected that O₃ will be reduced in most areas, but there may be some exceedances of the standard.⁴ There are diminishing returns of successive vehicle emission regulations. For example, peak O₃ declined by 1–13% from 2008 to 2018 (Tier 1 to Tier 2) but is projected to only decrease by 1–4% from 2018 to 2030 (Tier 2 to Tier 3). Substantial air quality improvements are projected in Europe. Fleet turnover with Euro 6 RDE-compliant vehicles will lead to a significant reduction in NO₂ concentrations and it is estimated that less than 1% of roadside air monitors in Germany in 2030 will exceed the NO₂ standard compared with 59% in 2016.⁵

With large reductions in LDV emissions the relative importance of emissions from other sectors have increased. Aviation is now the largest transportation source of lead emissions in the United States.⁶ Air quality modeling indicates that electrification of off-road equipment (e.g., garden equipment, construction equipment) would provide greater air quality improvement than on-road electrification. Consumer products (e.g., adhesives, personal care products, etc.) are becoming the single largest source of petrochemical VOC emissions in industrialized cities.⁸

**Zero-Impact Emission Vehicles**

With tailpipe emissions from modern ICE vehicles decreasing to very low levels, a new concept of “zero-impact emissions” is being discussed.⁹ Zero-impact refers to a level of emissions so low that it has a negligible impact on air quality. As a simple example, Figures 1 and 2 show the large decrease in CO emissions since 1970 and the current situation with all monitoring sites having CO levels well below the U.S. National Ambient Air Quality Standard (NAAQS).
From the viewpoint of CO emissions, modern vehicles are zero-impact emission vehicles.

Automotive research suggests additional tailpipe emission reductions are possible. By adjusting engine operation and the aftertreatment system in a research vehicle, exhaust NMHC+NO\textsubscript{x} emissions in the laboratory have been reduced by a factor of 10 below the future SULEV30 standard.\textsuperscript{10}

Electrofuels
Climate change is a pressing societal issue and there is a need for large reductions in fossil CO\textsubscript{2} emissions from vehicles and other sources. Electrofuels (E-fuels) are chemical fuels synthesized from electricity and water.\textsuperscript{11} E-fuels produced using CO\textsubscript{2} captured from the air and renewable (e.g., wind, solar, or hydro) or nuclear electricity offer net-zero carbon emissions for transport, and would probably see first use in aviation and heavy-duty vehicles where other...
options are more limited. Use of fossil fuels combined with capturing and sequestering CO₂ from the air offers an additional net-zero carbon option. Figure 3 shows the diversity of options based on renewable electricity to power BEVs, hydrogen FCVs, and E-fueled ICE vehicles. It is too early to pick winners. A technology neutral framework is needed to develop a portfolio of options from which customers can pick according to their needs.

Future Opportunities
As the on-road fleet turns over and as increasing stringent emissions standards come into force, the trend of decreased emissions shown in Figure 1 will continue. ICE vehicle criteria pollutant emissions have reached very low levels. Air quality and human and ecosystem health research is needed to define zero-impact levels for criteria emissions. Electric vehicles eliminate local emissions and when powered using clean grids (e.g., California) have major CO₂ and criteria pollutant benefits. Future vehicle emissions reduction efforts might be targeted on reducing the effect of gross emitters, which represent 2–5% of the fleet, but can produce up to half the emissions. A lower emissions future lies ahead, enabled by ultra-clean internal combustion engine vehicles, electric vehicles, and hydrogen fuel-cell vehicles.

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Are Electric Vehicles a Panacea for Reducing Ozone Precursor Emissions?

As electric vehicles begin to enter the market in increasing numbers, the author asks what vehicles are they most likely to displace in evaluating their ability to have a meaningful impact in reducing ozone precursor emissions across the United States?
During the past three decades emissions from on-road vehicles have been reduced dramatically.1,2 With the introduction of new vehicles that have met increasingly stringent emissions standards, reductions of 80%–90% in carbon monoxide (CO) and hydrocarbon (HC) emissions have been achieved, while oxides of nitrogen (NOx) emissions have been cut by more than half. These reductions have enabled all areas of the country to meet the U.S. National Ambient Air Quality Standards (NAAQS) for CO and nitrogen dioxide. However, ozone, which is a secondary product formed in the atmosphere from the reaction of HC and NOx emissions, still exceeds the standard in many areas of the country.3

The continuing difficulty in meeting the NAAQS for ozone, combined with the large reductions in vehicle emissions that has already occurred, has led some state authorities to look at electrification of the vehicle fleet as a way to further reduce vehicle tailpipe emissions. For example, the Denver metro area was recently reclassified from a moderate to a serious ozone non-attainment area and the Governor of Colorado has publicly touted electric cars as one way the state plans to meet the ozone NAAQS by 2021.4 This is an easy sell to the public because the idea of replacing an internal combustion engine with a “zero-emitting” vehicle seems a simple slam dunk for quickly reducing all tailpipe emissions, not just carbon dioxide (CO2) emissions. However, careful analysis of current fleet emission distributions leads to predictions of significantly lower reductions from this strategy in the near term.

Fuel Efficiency Automobile Tests
The University of Denver has been remotely collecting fuel-specific emission measurements from passing vehicles at locations across the United States since the late 1980s. Using absorption spectroscopy our Fuel Efficiency Automobile Test (http://www.feat.biochem.du.edu) units measure tailpipe emitted pollutants as molar ratios to CO2, which can be easily converted into grams of pollutant/kilogram of fuel consumed knowing the carbon fraction of the fuel.5 One of the most significant results of this work has been to highlight the importance of the vehicle fleet’s emission distribution to total emissions.

Vehicle emissions are not normally distributed—where the median vehicle in the fleet is close to also representing the mean emission vehicle—but are highly skewed, where a small number of vehicles are responsible for a disproportionate share of the total. In today’s on-road fleets, it is common to find that the highest emitting 1% of the fleet is responsible for more than a third of the CO and HC emissions, and a quarter of the NOx emissions. In these distributions one finds that the most common vehicle (the median) has emissions that are factors of 2 to 10 lower than the mean. This results from the fact that the majority of vehicles in the current U.S. fleet (60% or more, depending on the pollutant) today have near-zero tailpipe emissions.

Emissions Percent Contributions
Figure 1 contains three graphs that detail the emissions percent contributions by fuel and vehicle type versus model-year for CO (top), HC (middle), and NOx (bottom) emissions using data all collected in 2018 in Denver (January), Chicago (September), and Los Angeles (May). For these graphs, gasoline trucks, as classified for emission purposes...
Electric Vehicles by Gary A. Bishop

by the U.S. Environmental Protection Agency (EPA), include vans, sport utility vehicles (SUVs), and light- and medium-duty trucks (weight classes 1-6). The fuel-specific percent contribution (left axis) of the fleet total is the product of each model-year’s mean emissions and its fleet percent representation (right axis) divided by the total. The median model-year for each data set is plotted as an open circle. The percent of the total of each fleet 2009 and newer model-year vehicles is given and its contribution to the total emissions.

Beginning with the 2009 model-year, all new vehicles sold in the U.S. met the Federal Tier II or California Low Emission Vehicle (LEV) II standards for tailpipe emissions. These vehicles have proven to have consistently low emissions for CO, HC, and NOx and the ability to maintain those low emissions for many years. This is reflected in the annotations for each city that details the fraction of the fleet represented by these 2009 and newer vehicles and their contribution to the total emissions. For CO and NOx, the overwhelming majority of the emissions are contributed by a minority of the fleet that is older than these 2009 and newer model-year vehicles. HC is the one exception; however, keep in mind that these graphs are the percent of the total emissions generated by the observed fleet. Successful reductions in HC emissions have extended to vehicles significantly older than the 2009 model-year vehicles and we now generally find that HC emissions do not increase with age until after the first 20 model years that have the same near-zero emissions. This results in the emissions contribution trend closely following the fleet percentage trend as seen in the middle graph.

Chicago has the youngest fleet (7.5 years old), likely due to wintertime road salt, and the lowest diesel fraction (1.6%). Denver has the oldest fleet (9.2 years old) and the largest truck (69%) and diesel fractions (3.4%), while the Los Angeles site has the highest percentage of vehicles classified as passenger (59%) and hybrids (7%). While these differences are influenced by factors specific to that region of the country, the emissions behavior of the vehicles result in an emissions distribution that are all similar.

As emissions have decreased, dramatic changes in the fleet makeup have occurred as well. U.S. vehicle fleets have historically been dominated by passenger vehicles with trucks being largely composed of pickups. With the popularity of vans and all sizes of sport utility vehicles the in-use truck fleet, as classified by EPA emissions certification standards, has steadily grown to where today trucks are typically the dominant type found. This is often also reflected in the emission contributions breakdown, as shown in Figure 1, where trucks (gas and diesel) account for 59% of the total CO in Denver, 47% of the HC in Chicago, and 58% of the total NOx in West Los Angeles.
The Future for Electric Vehicles?

As electric vehicles begin to enter the fleets in increasing number, one needs to ask what vehicles are they most likely to displace in evaluating their ability to have a meaningful impact in reducing ozone precursor emissions across the United States? Vehicle replacement left on its own will generally follow the fleet's age distribution, meaning the most likely vehicle replaced is the most common one in the fleet or a near-zero emissions median-aged vehicle. However, the median vehicle in many markets is a truck or SUV and there are currently few all-electric choices for these types of vehicles, though many more are promised in the future.

Economic considerations involved in the purchase of electric vehicles likely works against even a median-aged vehicle being replaced as older higher emitting vehicles will be disproportionately owned by individuals where the purchase price of an electric vehicle will be a significant hurdle. This presents a major problem for reducing ozone precursor emissions from the current fleet as the vehicles most likely to be replaced are already a near-zero emissions vehicle.

Of course, Tier II/LEV II vehicles will continue to move down the replacement chain and provided they can continue to maintain their low emissions breakage rate, emissions will continue to slowly decrease. Without a concerted effort to target the replacement of older vehicles with an all-electric vehicle, it will likely require replacement of a majority of the current fleet before realizing any significant emissions reduction. It is unfortunate, but unlikely, that municipalities can expect significant reduction in ozone precursor emissions from electric vehicle adoption to help with their ozone problems in the near future.

Gary A. Bishop is with the University of Denver, Department of Chemistry and Biochemistry, Denver, CO.

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Held at the Doubletree Hilton Atlanta Airport
California’s Commitment to the Rapid Transition to Zero-Emission Vehicles is Undeterred

Federal rollback stunts, but does not derail, policy actions for cleaner cars, air quality, climate change, or renewable transportation energy.
Although the subject is evolving, at the time of this writing, 54.5 miles per gallon (mpg) is no longer the vehicle fleet average carbon efficiency target for model-year 2025 expected under the Obama-era clean car rules promulgated by the U.S. Environmental Protection Agency (EPA) and the California Air Resources Board (CARB) in 2012, and broadly supported by the auto industry at that time. Instead, the current federal administration intends to stall progress on efficiency improvements at the model-year 2020 level of about 37 mpg, according to the Safer, Affordable, Fuel-Efficient (SAFE) Vehicle Rule issued by the Trump EPA and the U.S. Department of Transportation (DOT) in September 2018. If the SAFE Rule survives mounting legal challenges or more automakers siding with California, and actually were to get implemented, then it would have, among other impacts, a direct and detrimental effect on air quality. These impacts would be felt across the United States, resulting in excess, unplanned vehicle emissions.

The transportation sector is the largest source of air and climate pollution in California and in many other states and light-duty vehicles (LDVs) are the most numerous vehicle category in the emissions inventory. Thus, any action that results in more emissions from future vehicles is also a direct contradiction to progress toward clean air and attainment of the U.S. National Ambient Air Quality Standards (NAAQS). Ironically, the SAFE Rule appears on the heels of the EPA Administrator stating in a letter to California regulators “foremost concern” for “ensuring clean air for all Americans.”

This federal action also comes at a time when California and many urban areas in other states in the United States are still suffering from too much ambient air pollution. According to the American Lung Association, in 2019, five California cities, including Sacramento, topped the list for the worst ground-level ozone pollution in the United States and three California cities are in the top five for the worst particle pollution.

The excess pollution the SAFE Rule represents will be significant because the recently released Part One Rule specifically revokes the ability for California to set its own greenhouse gas (GHG) standards, including the Zero Emission Vehicle (ZEV) Mandate. Arguably, the ZEV Mandate, dating back to 1990, is the most consequential regulatory requirement for car electrification ever adopted (California’s definition of a ZEV includes plug-in hybrid electric, battery electric, and fuel-cell electric vehicles). Single-handedly, it has led to today’s flourishing world electric vehicle (EV) market, introduced electricity and hydrogen as viable transportation fuels, and gave wings to disruptors like Tesla. The ZEV Mandate is in effect in California and a dozen other states that have adopted the California requirements.

In a recent analysis shown in Figure 1, CARB estimates that the SAFE Part One Rule alone can result in approximately a 12% cumulative increase in vehicle criteria pollution emissions in California by mid-century. The actual pollution effect is likely worse because this analysis does not include excess upstream emissions associated with more gasoline

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**ATMOSPHERIC OPTICS: AEROSOLS, VISIBILITY, AND THE RADIATIVE BALANCE**

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combustion cars on the road. The decade between 2025 to 2035 is critical for many California regions to come into NAAQS attainment. Figure 1 also shows that even in those early years, the SAFE Rule will still result in a significant 2–6% cumulative increase in vehicle emissions on top of the more than 45% increase in carbon emissions right off the bat in 2025. If nothing else changes, affected businesses responsible for stationary and area-wide sources of emissions will need to be subject to additional regulatory requirements in order to offset the increase from mobile sources.

**One National Program**

The celebrated “one national program” of coordinated vehicle emission standards in the United States was the result of years of cooperation and extensive work by federal agencies, the states, industry, and non-government organizations (NGOs). These standards changed a historically bad trend of stagnant vehicle fuel economy and a lack of focus on mitigation of GHG emissions in the United States. The Obama-era standards were far reaching. They targeted vehicle performance improvements for model-years 2017–2025. A technical assessment conducted by agencies in 2016 in support of a midterm evaluation of the augural model-year 2022–2025 standards showed that car makers have ample opportunity to innovate on lower-emitting, higher-efficiency gasoline combustion engines to comply with the adopted emission limits. The assessment also suggested that automakers could meet the standards at similar or lower costs than what was originally anticipated.

The standards foresaw a massive shift toward smaller, highly boosted gasoline direct injection engines and a long list of other complimentary innovations for future vehicles to make them safer, cheaper to operate, and simply better in every respect. Upfront costs would go up, but the payback period was short and in the end the consumer would have a lower-polluting and much better car that was cheaper to operate. Thus, these standards were a win-win-win for the auto industry, the consumer, and the planet. Now the federal government is reversing all that technology innovation potential and freezing progress on vehicle criteria and GHG emissions performance, which will result in vehicle drivers paying more for fuel at the pump.

In the grand scheme of things for California, the Obama “one national program” of new GHG standards was a compromise and a modest attempt, at best, to reduce future vehicle pollution because it did not significantly push for significantly cleaner combustion engines or, most importantly, the lowest-carbon solutions such as hybridization or electrification. Instead, the auto industry could comply fully and simply with more efficient gasoline engines.

This is the reason I said in a statement for the press in 2016 that “it is up to the combined efforts of California, our ZEV-state partners, and other supporters to advance on ZEV’s precisely because of the very low level of reliance on electrification needed to meet the national standards.” (As an aside, in retrospect and with these strong sentiments for vehicle electrification in mind, which also reflect broadly the state’s interests, it should be no wonder to the reader why the Volkswagen (VW) “diegate” settlement agreement that California forged to resolve the VW illegal actions is so heavily ZEV-centric and why so much of the settlement money is...
aimed at growing the ZEV market throughout the United States.)

Most importantly, California’s trailblazing spirit, economic prowess, and fervent desire to lead the world on climate action and in the electrification of transportation, starting with LDVs, are all still very much important forcing functions for state and local regulatory policies, investments, and broad bridge-building with other leading jurisdictions around the world such as China and Europe. California has invested hundreds of millions of dollars from its carbon cap-and-trade revenues to remove the barriers to electrification of transportation. Of the more than US$9 billion that the program has generated, nearly US$2 billion have gone for low carbon transportation, which includes more than 350,000 rebates for eligible ZEV buyers at a tune of more than US$820 million.

The sentiments for building bridges are captured well, for example, in two efforts started by California to accelerate the transition to a sustainable transportation energy sector. These are the International ZEV Alliance (http://www.zevalliance.org/) and the Under2Coalition (https://www.under2coalition.org/) of state and regions for climate action. Y. Wang argues very convincingly about a ZEV ecosystem created by California where cutting-edge vehicle innovation is flourishing. He also talks about how China is now running with the California ZEV Mandate idea and improving upon it to fast track China’s own global leadership on EVs.

However, it is clear the SAFE Rule and doing away with the long-standing California “waiver” authority to regulate vehicle emissions and other mobile sources, and if it stands, is an existential threat that would fundamentally re-shape transportation policymaking in the state that seven decades ago gave rise to the very concept of vehicle pollution control in the United States. As M. Kah recently reported, federal action is also having a chilling effect on EV progress in the United States. Kah’s work on forecast trends for the EV market suggests lower numbers of EVs than previously expected will be sold and greater divergence in the expected EV market share in the future. She cites the “U.S. federal government policy becoming more negative toward EVs and automotive fuel efficiency improvements” as one of two reasons for the slowing trends. The American consumer preference for larger, but less efficient vehicles, is also often cited as a reason for slower EV uptake. This factor is true and can affect the vehicle market as seen in the work of M. Sivak and colleagues who have been monitoring fuel economy trends of the U.S. fleet (see Figure 2). This work suggests that we may be back again in a period of stagnant fuel economy. At least until new EV pickups from Rivian, Bollinger Motors, Tesla, and other EV models entering the market now begin to generate consumer interest.

Figure 2. The “window sticker” average fuel economy of the U.S. vehicle fleet.
**Figure 3.** Timeline for CARB regulations focusing on the freight sector.

**Moving Forward**

California is already doubling down on its efforts. The state is driving for complete electrification of passenger cars, all shared mobility, and trucks. The state's strategy for the LDV sector relies on a true and proven “carrots and sticks” approach. This starts with defending to the maximum extent possible the regulatory authority for the ZEV Mandate and other requirements, while also continuing to heavily invest...
cap-and-trade proceeds in EV buyer rebates, charging and hydrogen fueling infrastructure, and other EV market-building actions. And in a “no stone left unturned” approach, the state is also expanding efforts to electrify larger vehicle categories in the freight sector using incentives and regulatory instruments for heavy-duty and off-road EVs. This will be a huge lift—an expansive and expensive effort designed to tackle both conventional pollution and zero-emission requirements for some of the most challenging vocations to electrify, as illustrated in Figure 3. The plan is far reaching, encompassing prominent heavy-duty applications like transit buses, freight trucks, and airport shuttles.

The state has already taken some important initial steps, having adopted regulatory requirements for 100% new zero-emission transit bus purchases by 2029, 100% zero-emission airport shuttles by 2035, and a ZEV Mandate for heavy-duty trucks from Class 2B vehicles all the way up to Class 8 tractors starting in 2024. Next, will be a more stringent nitrogen oxides emissions limit for new heavy-duty engines under the Heavy-Duty Omnibus Rule. All these policy developments clearly signal that while California may be stunted by recent federal actions, it is not, by any means, knocked out of the fight. The commitment for getting to a sustainable transportation energy future is unwavering and the fight for clean air and the climate has not let up. The stage is set for this commitment to play out in the courts of public opinion and of the legal system as the “waiver” authority, the LDV GHG emission standards, the ZEV Mandate, and other state policies are challenged aggressively by the federal government and defended ardently by The Golden State and its supporters.

Alberto Ayala, Ph.D., M.S.E., is Air Pollution Control Officer and Executive Director with the Sacramento Metropolitan Air Quality Management District, and Adjunct Professor of Mechanical and Aerospace Engineering at West Virginia University. Dr. Ayala is the Former Deputy Executive Officer of the California Air Resources Board. E-mail: AAyala@airquality.org.

Disclaimer: This article represents the author’s analysis, perspective, and opinions related to the evolving policy landscape for vehicle emission standards, the market uptake of electronic vehicles, and the broader topic of sustainable transportation in the United States. These views are not official positions for any of the listed affiliations.

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In Next Month’s Issue…

What Are PFAS?

Per- and polyfluoroalkyl substances (PFAS) and emerging contaminants are dominating headlines across all forms of media. This issue of EM will look at this confusing alphabet soup and help put into context for environmental managers what is the emerging threat to our natural water and land resources.
Backlog
An Eye to the Future

by David Elam

In recent columns we have examined key environment, health, and safety (EH&S) consulting firm metrics, including utilization, labor multiplier, billing rate, and revenue factor. In this column, we’ll examine backlog and why it is an important metric for EH&S consulting firms. While the aforementioned metrics are lagging business indicators, backlog is a leading metric and is predictive of future performance. In short, backlog is work that is yet to be completed.

In manufacturing and industrial organizations, products are made to satisfy just-in-time delivery models or to build an inventory that is consistent with buyer demand. Accordingly, backlog can be viewed with concern because it represents orders that are unfilled, suggesting that production cannot keep pace with demand. Unless the customer is purchasing a custom-made product with the expectation of delayed delivery, they can shop elsewhere for the product and buy it if the delivery schedule and price are consistent with their expectations.

In contrast, backlog is viewed positively in the EH&S consulting business. Firms want to build a healthy backlog because it provides management an indication of work that is available for staff in the future. When accurate, backlog is a critical metric for financial projection and forecasting. For EH&S consulting firms, total backlog consists of two components:

1. **Hard / Contract Backlog**: This is work that is contractually authorized and is either in process or expected to be completed. Clients have formally approved a scope of work and the EH&S firm has planned to do the work. For example, if the firm has signed a contract for a $100,000-project, the hard or contract backlog is $100,000.

2. **Soft / Factored Backlog**: This is work that has been proposed or expected, but not yet awarded. Many firms will factor soft backlog to reflect the probability that the client will (a) perform the work and (b) award the work to the firm. For example, if the firm submits a $100,000-proposal and the firm believes there is an 80% probability that the client will proceed with the project and an 80% probability that the firm will be awarded the project, then the calculated soft or factored backlog is $64,000 ($100,000 × 0.8 × 0.8). Other systems factor backlog based on historic win rates or by proposal stage.
A firm would calculate its total backlog by adding together all contract backlog and all factored backlog. Thus, based on the above two examples, the total backlog for the firm would be $164,000.

To explore how backlog works, it is important to understand “burn rate,” or how quickly the firm will consume backlog. Let’s consider an EH&S consulting firm that operates profitably with gross revenue of $1,200,000 per year. This firm requires an average gross revenue of $100,000 per month at its target multiplier to continue to operate profitably. Thus, the burn rate for the firm is $100,000 per month.

If this firm has $400,000 in total backlog, it potentially has approximately four months of work that has to be completed; however, the actual analysis of backlog adequacy is more complex than simply dividing the total backlog by the burn rate. It is important to understand the project life cycle and the distribution of backlog between hard and soft components. To further explore this example, let's assume that the $400,000 in total backlog represents $200,000 in hard backlog and $200,000 in soft backlog:

- If the contract backlog is comprised of project work that can be performed in 45–60 days, the firm is probably in good shape if it is (a) able to convert $100,000 in soft backlog to contract backlog each month and (b) replace the converted soft backlog with new, high probability soft backlog each month.
- If the contract backlog is comprised of project work that requires 90–180 days to complete, the firm will likely find staff falling below utilization targets unless there is both (a) highly successful and immediate conversion of soft backlog to hard backlog and (b) timely replacement of converted soft backlog with new, high probability soft backlog.
- If the contract backlog is comprised of project work that must be completed in less than 45 days, the firm will likely find itself short-staffed and falling behind on both project deliverables and new proposal development unless it is able to add staff or subcontract work.

For these examples, we have focused on total contract value. Contract values will reflect varying direct labor costs, subcontract expenses, and other project expenses. If a typical contract for the EH&S consulting firm is 80% direct labor and 20% subcontract and project expenses, contract backlog available to support the burn rate will be reduced for a contract that is 50% direct labor and 50% subcontract and project expenses. Thus, it is important to understand the distribution of contract revenue between direct labor and project expenses when evaluating both hard and soft backlog. Often, firms will use net labor backlog and labor burn rate, versus total backlog and gross revenue burn rate, as it is more predictive for staff utilization.

Additionally, we have not considered the performance period in these examples. In most cases, firms issue proposals that are consistent with their project delivery cycle. Consider the firm that typically issues proposals for 15 days of work that is anticipated to start 120 days from the proposal date with contract award anticipated 60 days from the proposal date. If the firm is diligent about updating its proposal log with respect to lost work, total contract backlog will align with the burn rate. But in some instances, the firm will issue a proposal for more substantial effort in the near term or for project work at some distant future date. Similarly, large projects under contract may have a nonlinear or unusually slow spend rate that should be considered. In these cases, the backlog can be skewed. For this reason, using a specific performance period when calculating both hard and soft backlog will produce the most accurate forecast of available backlog.

Backlog is an important metric for EH&S consulting firms that allows management to make effective decisions regarding workload balancing, staff adjustments, and business development. Hard backlog is easier to understand and manage than soft backlog. Soft backlog represents potential work that determines the direction of the firm. For this reason, soft backlog requires proper initial attention to accurately estimate both the probability of the performance and award and ongoing attention to ensure that proposals included in the soft backlog are indeed active.
This year, we celebrate 50 years of A&WMA's Annual Critical Review. For half a century, A&WMA has solicited and published in the *Journal of the Air & Waste Management Association (JA&WMA)* an Annual Critical Review on a topic of critical importance to the air and waste management fields. Each year, the review author presents the Annual Critical Review at a special session held during A&WMA’s Annual Conference & Exhibition. Each month in this space, we will take a moment to look back at a singular review of critical significance from the past 50 years.

**1971 Annual Critical Review:**
National Air Quality Standards for Automotive Pollutants

by J.M. Heuss, G.J. Nebel, and J.M. Colucci

This month, we head all the way back to the very first Annual Critical Review. The 1971 review dealt with the then-recently promulgated U.S. National Air Quality Standards for carbon monoxide, nitrogen dioxide, hydrocarbons, and photochemical oxidants. The review, which was presented at the 64th Annual Meeting of the Air Pollution Control Association—a forerunner to A&WMA—in Atlantic City in June 1971, concluded that the newly promulgated standards were more restrictive than could be supported by available data at that time.

The authors, who were affiliated with General Motors Research Laboratories, stated that the carbon monoxide standard was based on a blood carboxyhemoglobin level below that associated with any physical or mental impairment; the nitrogen dioxide standard was based upon a questionable epidemiological study that needed further verification; the hydrocarbon standard was orders of magnitude below the levels associated with any health effects and thus unnecessary; and the photochemical oxidant standard was based on a questionable extrapolation of the results of a single study. Based on the available data, the authors concluded, less restrictive standards would adequately protect the public health and welfare.

In a discussion paper that accompanied the published review, authors Delbert S. Barth, J. Cyril Romanovsky, John H. Knelson, Aubrey P. Altshuller, and Robert J. M. Horton, with the Office of Research and Monitoring for the U.S. Environmental Protection Agency in Research Triangle Park, NC, asserted that the criteria that provided the basis for the National Ambient Air Quality Standards were developed through a series of difficult and involved projects, and that the material was subjected to rigorous review by responsible authorities both inside and outside of government. *em*

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**Past Critical Reviews**