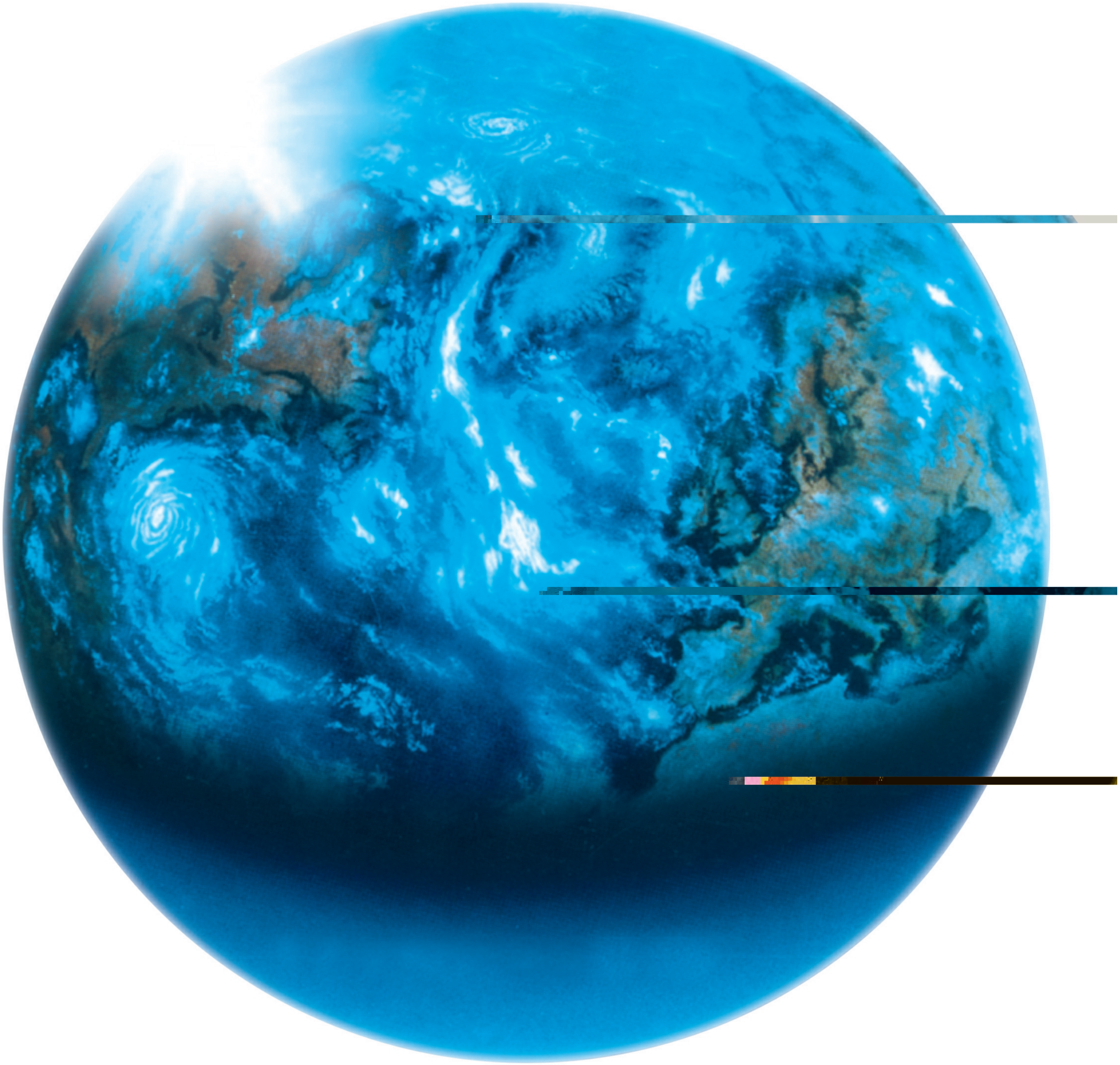

Diesel Emission Research for Informing Air Quality and Climate Policy in California

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Abstract

Motor vehicles are vital to the fabric of modern society for personal mobility, services, and the movement of goods. But transportation is energy-intensive, and vehicles are prominent sources of emissions that adversely impact air quality, health, and the local, regional, and global environment. These factors underlie our increasing need for the environmental reconciliation between our growing reliance on fossil fuels for transportation and reductions in air and climate-active pollutants. In California, transportation is the single largest contributor to anthropogenic greenhouse gas emissions and efforts are underway to achieve significant reductions by 2020 and beyond. Emissions from mobile sources are also a major burden on the environment, taxing our air with more CO and NO_X than any other sector. The diesel engine, used principally in the heavy-duty sector, is recognized for its superior efficiency, performance, and durability, but is a major source of PM and NO_X emissions. Fortunately, advances in cleaner vehicles and engines, low-carbon fuels, engine design, particle filtration and NO_X reduction aftertreatment are yielding ultra-low emissions and enabling compliance with the most stringent emission standards. The resulting PM mass emissions are in some cases at or near background levels, but they can exhibit a different physicochemical and toxicological character. Beyond air quality, control of the fraction of PM emitted as black carbon is emerging as a topic of high interest as a means to counteract some climate change in the short term. These issues have led to active and important research efforts, driven by the overarching policy need for science-based rule making and standard setting. Research outcomes are successfully filling knowledge gaps and guiding the implementation of "no-regret" policies that often have co-benefits for air quality and climate protection.

1. Outlook on policy outcome

In spite of the arguably modest progress achieved in Copenhagen, the concern over climate change will continue to be firmly rooted in U.S. public policy and the scientific mainstream. In particular, the lack of a binding international agreement for greenhouse gas (GHG) emission reductions does not change the course of many existing and important sub-national actions for climate and environmental protection that are well underway, such as those in several U.S. states including California. But irrespective of policies and politics, the pressure for achieving the environmental reconciliation between our growing reliance on fossil fuels - for transportation and other uses - and reductions in air and climate active pollutants will not cease.

In 2006, California enacted the Global Warming Solutions Act [1], which mandates a return of the state's GHG emissions to 1990 levels by the year 2020, an approximately 30% reduction. This Act encompasses all sources of GHG emissions and calls for a mix of approaches for achieving reductions including command-and-control rules, fees, voluntary actions, incentives, and market-based mechanisms. To date, approved measures for major sectors of the economy that contribute to GHG emissions will yield about half of the needed reductions. Other policies now under development such as a cap-and-trade regulation, a new Low Emission Vehicle program (LEVIII), and a renewable electricity standard, will deliver the remaining reduction commitments. These policies look beyond mitigation by 2020 to achieve a vision of an 80% reduction by 2050, and include measures for carbon capture and sequestration, water efficiency, recycling and waste management, and a strategy to develop "green collar" jobs, as well as a climate adaptation strategy [2].

This tendency towards continued vigorous effort on climate and environmental protection may be found in recent federal action. In one example, the U.S. Environmental Protection Agency rendered an endangerment finding for man-made GHGs in the atmosphere, paving the way for command-and-control of GHG emissions under the existing authority granted by the U.S. Clean Air Act. In general, recent actions reinforce the notion that the quest for sustainable policies that achieve concurrent abatement of GHGs and air pollutants will continue to guide future environmental management priorities at the national, sub-national, and local levels.

2. Transportation – a key source of air and climate pollution and opportunities for reductions

Motor vehicles are vital to the fabric of modern society for personal mobility, services, and the movement of goods. But transportation is energy-intensive, and vehicles are prominent sources of emissions that adversely impact air quality, health, and the local, regional, and global environment. Motor vehicle pollution control started in California a half-century ago, and has now spread all over the world. The internal combustion engine will continue to face demand for more efficient use of fossil fuel and increasingly strict emissions limits, especially given the recognition of the associations between adverse health outcomes and exposure to traffic-related air pollution as recently reported by the Health Effects Institute [3].

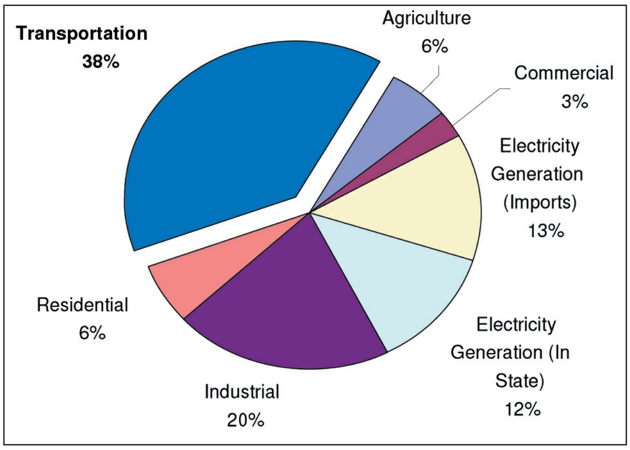

Figure 1:
Source contributions to greenhouse gas emissions in California, 2004. Total average emissions are approximately 487 $MMTCO_2E$ according to the CARB GHG emissions inventory [4]. Emissions include CO_2, CH_4, N_2O, PFCs, SF6, and HFCs.

California has a "car culture." With more than 25 million gasoline vehicles on the road and more than 1.2 million diesel engines in use, the transportation sector is the single largest contributor to anthropogenic GHG emissions in California (Fig. 1). Within this sector, personal cars and other light-duty vehicles account for nearly three quarters of all emissions. The heavy-duty vehicle fleet is responsible for another 20% of these emissions. Thus, efforts are underway to achieve significant reductions by 2020 and beyond.

Emission reductions will come from cleaner vehicles and engines, low carbon fuels, efficiency improvements and reductions in vehicle use and vehicle miles traveled.

Emissions from mobile sources are also a major burden on the environment, taxing our air with more CO and NO_X than any other sector. The diesel engine, which offers fuel economy, performance, and durability that are superior to the gasoline engine, is used principally in the heavy-duty sector and is a major source of PM and NO_X emissions, with NO_X contributing to the formation of both ambient ozone and PM2.5. Recent assessments by CARB, U.S. EPA, and others suggest that diesel PM emissions represent a major cause of premature mortality and morbidity. In California, exposure to diesel exhaust from conventional, older technology (not equipped with diesel particle filters, or DPFs) accounts for the majority of the estimated cancer risk by inhalation attributable to air pollution (Figure 2). Since public health is the most important control policy consideration, an aggressive plan is in place to abate emissions and reduce exposure. California's Diesel Risk Reduction Plan [5], adopted in 2000, is a collection of measures including stringent emission standards for new engines, cleaner fuels, and modernization and retrofit requirements for existing fleets – public and private. To support this diesel control plan, significant diesel emission research activities have been advancing the understanding of technology options for reducing NO_X and PM emissions, with a heavy focus on retrofit devices.

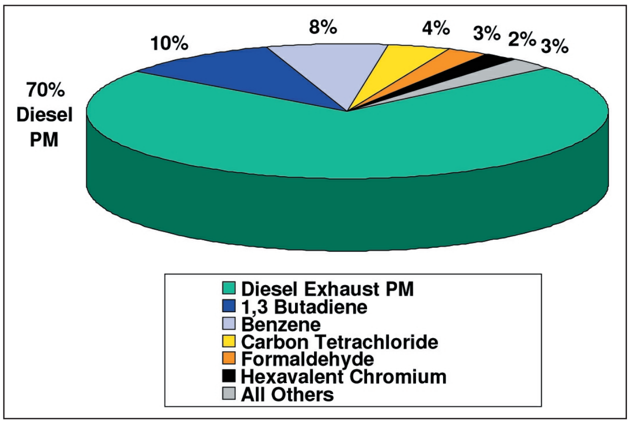

Figure 2:
Total cancer risk by inhalation of known air toxics in California [6].

Finally, there is now broad agreement that significant synergies and co-benefits are possible through a concerted consideration of air quality and climate change policies (e.g., Williams (2006) [7]). Specifically, surface transportation in North America offers the greatest potential for substantial, simultaneous benefits for air quality and global warming, according to the U.S. Climate Change Science Program [8]. In this context, abatement of black carbon (BC) pollution is emerging as a central topic in policy discussions. BC aerosols are second (behind only CO_2) in their contribution to global warming [9]. In California, transportation accounts for more than 40% of BC emissions as illustrated in Figure 3 [10]. Thus, work is now underway for the identification of defensible policy options that maximize the air quality and climate co-benefits from reductions of BC from California sources.

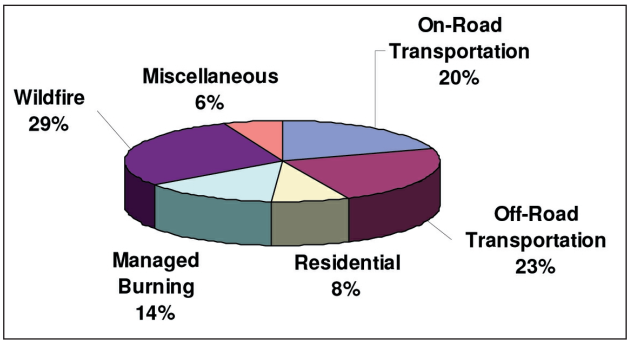

Figure 3:
Black carbon emissions in California, based on 2006 PM2.5 inventory and source profiles from Chow et al., 2008 [11].

3. Research generating the science underpinning diesel policy

Science-based rule making and standard setting are overarching policy goals. In the diesel control program, these goals are the key drivers for an active and expanding research portfolio on transportation emissions. The research portfolio covers a wide range of topics, including general studies on engine, lubricant, and fuel effects, to specific studies focused on inventory improvement, characterization of regulated and un-regulated emissions, comparison of measurement instruments and metrics, sampling methodologies, on-board measurements and aftertreatment technologies for retrofit application.

Large emission reductions have been achieved through advances in fuel reformulation, engine design, and exhaust aftertreatment. In the latter category, the wall-flow type, highly-efficient DPF has truly been a game-changing advance for PM emission reductions in both new and in-use engines. Extensive data confirms that order-of-magnitude reductions in PM mass and elemental carbon (EC) emissions are possible from a DPF-equipped diesel engine (BC and EC are commonly used interchangeably, but they have different operational definitions and are not necessarily identical). Figure 4 compares the magnitude and make-up of PM from a diesel without a trap, and the same vehicle retrofitted with a DPF and selective catalytic reduction (SCR). Reductions in PM and EC are significant, while the composition of the reduced emissions, often at or near background levels, becomes dominated by ions that exhibit a different physicochemical and toxicological character. We have high expectations for significant reductions of NO_X emissions from mobile sources with the imminent widespread use of urea-based SCR for the heavy-duty diesel

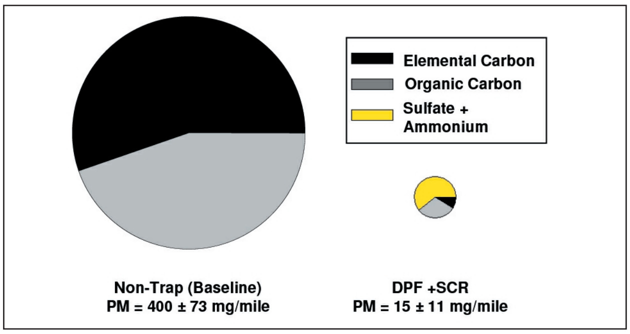

Figure 4:
Magnitude and composition of PM mass emissions for a baseline diesel vehicle and for the same vehicle when equipped with a DPF+SCR retrofit.

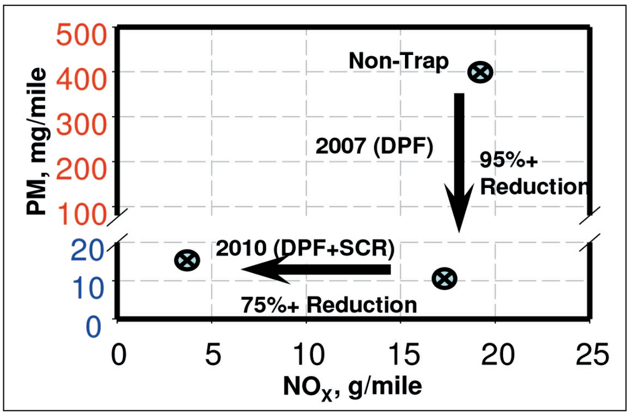

Figure 5:
PM and NOX emission reductions from application of DPF and DPF+SCR retrofits to an existing 1998 model year diesel engine, extracted from results by Herner et al., 2009 [12].

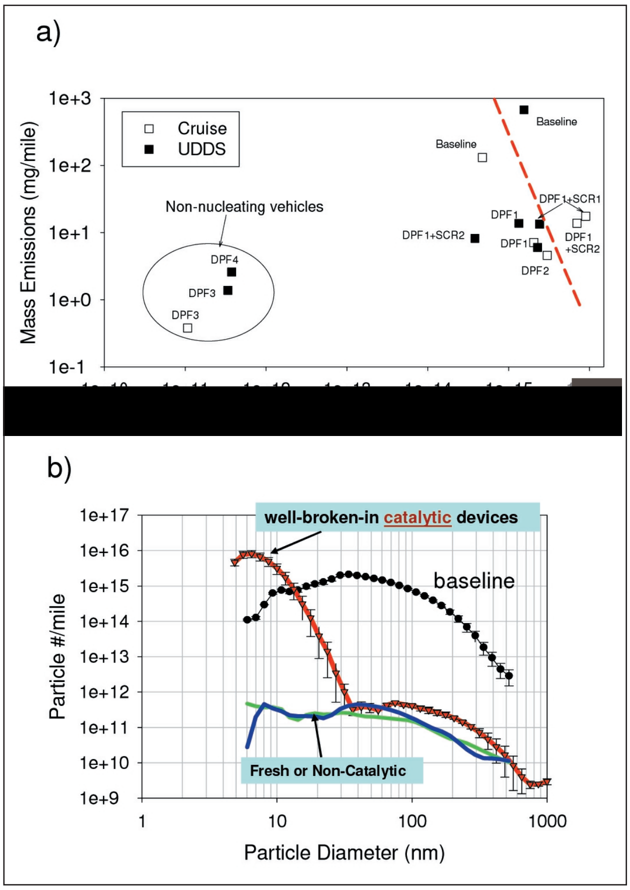

Figure 6:
a) PM mass and total particle number emissions reported for various types of DPF-equipped diesel vehicles for two different driving cycles (DPF1=DOC+DPF; DPF2=Catalyzed DPF; DPF3=Non-catalyzed DPF; DPF4=DOC+Catalyzed DPF SCR1=Vanadium-based SCR; SCR2=zeolite-based SCR) and b) nominal particle size distributions Biswas et al. (2008) [13].

sector. Thus, the aftertreatment technology roadmap, enabling the heavy-duty diesel engine to meet (and exceed some of) the US 2010 standards is clear (Figure 5) [12]. Also, it is now well established that in some cases, reductions in PM mass have led to an increase in the total number of particles as illustrated in Figure 6a and discussed by Biswas et al. (2008) [13]. However, we note that "not all particles are created equal." The increase in total number is due primarily to volatile particles formed by nucleation in the sub-20 nm size range under some conditions and whose composition, as noted above, is dominated by relatively non-toxic ions like sulfate. Correspondingly, a retrofit also leads to a different toxic potency for the particles. The increase in particles depends on a number of factors including duty cycle and type and age of the retrofit, as shown in Figure 6b. Fortunately, recent studies are advancing our understanding of the nature of these emissions, their precursors, the influence of fuels, lubricants, and aftertreatment, and the potential implications for exposure and, ultimately, health.

4. Conclusions

Diesel emissions are relevant for air quality and climate change. Fortunately, current designs and aftertreatment technology for filtration and emissions reduction, applicable as original equipment or retrofit, can yield ultra-low emissions without a significant penalty on fuel economy. The nature of criteria pollutant emissions from diesel exhaust is relatively well understood, based on a global and extensive research effort. Also, great strides are being made for resolving diesel exhaust aerosol according to metrics such as size, morphology, chemistry, toxicity, which will help to promote the cleanest options. With respect to GHG emissions, the CO_2 benefits of the diesel engine are well understood and further efficiency improvements are underway. But consideration of other climate-active pollutants such as BC and nitrous oxide (N_2O) is also recognized to be important. The dynamic operation of motor vehicles, coupled with introduction of new biofuels and advanced engine and aftertreatment designs, results in highly variable emissions that are influenced by a number of factors. This creates an ever-increasing need for improved emission monitoring and characterization, aided by sophisticated and fast instrumentation and a robust research effort to keep pace with the rapidly changing nature of the emissions and the technology packages chosen to control them. The proven performance of the DPF, enabled by clean fuel, resulting in the near-elimination of PM, and its BC fraction, is emerging as an important topic for additional policy action in the U.S. and abroad. Research progress is continuing to generate the science that must underpin these new innovative policies all over the world.

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Disclaimer

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