
Ultrafine Particulate Matter and the Benefits of Reducing Particle Numbers in the United States

**A Report to the Manufacturers of
Emission Controls Association
(MECA)**



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Executive Summary

Over the past decade, regulators in the United States, California, and Europe have taken major steps to reduce the human health impacts from car, truck, bus, nonroad diesel engines, and other transportation-related pollution. In the United States, the Environmental Protection Agency (EPA) has implemented a series of rules that have dramatically reduced sulfur levels in gasoline and diesel fuel, opening the door to a new generation of catalysts, filters, and other emission control technologies and strategies that are making the black smoke of an old diesel bus or truck a thing of the past, and that have led to the cleanest cars, trucks, and buses in the world.

Taken together, the Heavy-Duty Engine rule for trucks and buses (adopted in 2001), the Nonroad Diesel Engine rule for agricultural, construction and other nonroad diesel engines (adopted in 2004), and the Locomotive and Marine Diesel Engine rule (adopted in 2008) will eliminate an estimated 21,400 premature deaths annually, and create more than \$152 billion in net health benefits annually in 2030, according to EPA.

EPA has also taken major strides to make our cars, light trucks and sport-utility vehicles even cleaner and more fuel-efficient than ever before. In March of this year, EPA proposed a new Tier 3 program of fuel and emission standards for these light-duty vehicles, which will lower the average sulfur content in gasoline from today's 30 parts-per-million (ppm) to 10 ppm and introduce new tailpipe emission standards for all new cars, light trucks, and sport-utility vehicles, starting in the 2017 model year.

The Tier 3 proposal comes on the heels of groundbreaking steps to reduce fuel consumption and greenhouse gases from these vehicles. In 2011, EPA and the National Highway Traffic Safety Administration (NHTSA) adopted new fuel economy and greenhouse gas emissions standards for light-duty vehicles that will ultimately lead to vehicles that average 54.5 miles per gallon (equivalent to 163 grams of carbon dioxide per mile) in the 2025 model year.

The Tier 3 proposal also follows the California Air Resources Board's (ARB's) latest regulatory program to reduce emissions from vehicles in its state. In January 2012, ARB adopted a suite of clean cars standards, including its LEV III emission standards for light-duty vehicles. LEV III includes the most stringent PM mass limit in the world—1 mg/mile, starting in 2025. EPA's Tier 3 proposal, for the most part, harmonizes with LEV III up to 2025 with a 3 mg/mile PM limit starting in 2017. In this paper, we explain why EPA should consider further harmonization with ARB, by adopting the same 1 mg/mile standard.

All of this great progress has occurred against the backdrop of an increasing understanding of the strong evidence linking particulate matter emissions from vehicles with a wide range of

adverse health impacts, including increased asthma emergencies, cancer, heart and lung diseases, and premature death.

As we look ahead, we see some clouds forming on the horizon that deserve attention.

First, there is a growing concern in the public health community about the contribution of the so-called ultrafine particulates (UFPs, i.e., particles that are finer than 0.1 microns in diameter) to the overall health impacts of PM. Given their small size, UFPs are not a major factor in measurements of overall PM mass, but they constitute the largest contributor to overall particle numbers. This is an especially important issue in urban areas and near busy highways and other major roads.

While the body of epidemiological and toxicological studies on UFPs is not as robust as the body of literature on the health impacts of overall PM mass, we see emerging trends in the research that suggest evidence of potential health impacts. In light of these trends, Europe has adopted first-ever limits on particle number (PN) as a way to ensure that diesel particulate filters (DPFs) are used and UFPs are reduced. In addition, Europe will soon begin implementation of a PN limit for gasoline-fueled cars that are equipped with direct injection, which will accelerate the introduction of PM reduction technologies such as gasoline particulate filters (GPFs), high pressure spray guided injectors and other combustion control technologies for PM in the European car market. This is a topic that deserves additional research and attention in the U.S.

Second, it is clear that using DPFs creates emission reductions beyond what is required by the emission standards—a bonus that translates directly into additional, quantifiable health benefits enjoyed by all Americans. Indeed, the DPFs that engine manufacturers and others are using to meet existing heavy duty and nonroad diesel emissions standards in the United States result in additional emission reductions that far exceed the applicable PM standards for highway and nonroad diesel engines—by an average of roughly 90 percent and more than 80 percent, respectively.

The environmental and health benefits of these additional emissions reductions are substantial. Over the life of today's vehicle and engine fleets, these reductions will yield an estimated \$19.1 - \$43.5 billion of additional environmental and health benefits from the highway diesel sector, as well as another \$5.6 - \$12.9 billion in environmental and health benefits from the nonroad diesel sector. These benefits include the elimination of 349 -780 premature deaths and almost 50,000 lost work days annually from the highway diesel sector and another 86-196 premature deaths and roughly 12,238 lost work days annually from the nonroad diesel sector.

Adding a PN limit in the light-duty sector would create additional, bonus emissions benefits of an additional \$35.1 - \$80.0 billion beyond the benefits of the proposed Tier 3 emissions

standards over the life of these vehicles (including another roughly 900 premature deaths and 56,000 lost work days annually).

Some manufacturers are starting to consider new strategies to meet EPA and CARB nonroad emission standards that do not include DPFs. Already, several engines have been certified to meet EPA's Tier 4 interim standards without DPFs. EPA certification data shows clearly that, while these engines meet the basic standards, almost all of the additional, bonus emission reductions are lost with this approach.

In addition, approaches that rely on engine-based strategies rather than DPFs are more likely to lead to increased emissions in actual use. These increased emissions are likely to result from a number of factors, including off-cycle operating conditions, poor maintenance, and excess idling. Thus, while this approach may comply with the certification requirements of EPA's standards, it would represent a lost opportunity from the perspective of clean air and human health, by leaving significant emissions and health benefits on the table if this approach becomes widespread.

Third, as the EPA/NHTSA greenhouse and fuel economy standards and the likely Tier 3 proposal are implemented, we expect to see an acceleration of the shift towards using direct injection (GDI) and turbocharging in gasoline-fueled light-duty vehicles. Already, more than half of the light-duty vehicles sold in the U.S. have a GDI option—and the number of GDI-equipped models is rapidly increasing. There is ample evidence that engines equipped with GDI emit UFPs and PM that is comparable to the emissions of diesel engines that do not use DPFs. As EPA finalizes its Tier 3 proposal, it will be important that the agency consider the PM and UFP impacts of a shift from port fuel injection (PFI) to GDI and turbocharging, and the opportunities to capture additional PM reductions afforded by emerging PM reduction technologies, such as gasoline particulate filter (GPF) technology.

In this report, we aim to assist EPA and CARB as they consider these clouds on the horizon.

First, we summarize the current understanding of the potential adverse health impacts of UFPs. Second, we outline the various control strategies and technologies that can be used to meet current and upcoming EPA standards. Third, we document the success story of using DPFs to meet and exceed U.S. and European emission standards (including Europe's particle number limit). Perhaps most significantly, we propose a correlation between PN and PM that can be used in conjunction with PM based health data to estimate the health benefits and surmise that a PN measurement may offer a more robust unit for determining compliance at very low PM levels. Last, we quantify the emissions and health benefits of the additional emission reductions that are enjoyed when DPFs or GPFs are used. We then outline the risk that will be created if

and when engine companies abandon their highly successful DPF approach or choose to not add GPFs to their future GDI-equipped light-duty vehicles.

We close with recommendations to help the EPA and CARB achieve the maximum environmental and health benefits of their current and upcoming standards, as follows:

EPA and CARB should add a PN limit to its regulatory structure for mobile sources.

Adding a PN limit to EPA's Tier 3, Highway Diesel, and Nonroad Diesel emissions standards would help ensure that diesel and gasoline particulate filters are used to reduce both the mass of PM and the number of UFPs and other particles. Adding a PN limit would complement the existing regulatory regime, and would lock into place the surplus emission reductions that are currently benefiting the health of millions of Americans. For the same reasons, the California Air Resources Board (CARB) should consider adding a PN limit to its LEV-III program in its upcoming midterm review, as well as to its highway and nonroad diesel regulatory programs.

Both EPA and CARB should consider a new set of heavy-duty diesel engine PM standards that would be equivalent in stringency to CARB's 1 mg/mile standard for light-duty vehicles.

Emissions testing has shown that, when equipped with a DPF, 1 mg/bhp-hr is a technologically feasible emissions threshold for new heavy-duty diesel engines. This level is seen in certification testing of diesel engines with DPFs, which regularly yields engines that exceed the current PM standard by more than 90 percent. According to our analysis, this over-compliance currently creates an estimated \$19.1 - \$43.5 billion of surplus environmental and health benefits and eliminates 349 - 780 premature deaths annually in the highway diesel sector—in addition to EPA's original estimated benefits from the Highway Diesel rule. Given that DPFs are widespread in the marketplace, there is no question that this technology is widely available and working. The Clean Air Act requires EPA to set emissions standards at the level that is technologically and economically feasible, taking certain other factors into account. It is time for EPA and CARB to consider a new round of PM standards that would lock the existing over-compliance in place.

EPA should increase its in-use compliance monitoring of nonroad diesel engines that are certified without DPFs.

There is ample evidence showing that engine-based strategies are prone to higher in-use emissions than DPF-equipped engines, due to cold starts, extra idling time, poor maintenance, and other factors. Given the complex nature of the nonroad diesel engine sector—involving dozens of engine families and a wide array of duty cycles—in-use field testing is especially important. EPA should allocate extra compliance and enforcement resources to following up with in-use emissions testing of any Tier 4 engines that are certified without DPFs.

Backsliding on DPFs in the nonroad sector could result in the loss of \$5.6 - \$12.9 billion in environmental and health benefits in just seven of the equipment groups in the nonroad diesel sector over the life of these engines (lost benefits that would include 86-196 premature deaths and roughly 12,238 lost work days annually). Nevertheless, some companies are moving forward with nonroad Tier 4 certification strategies that rely on engine controls, rather than DPFs. While these engines may meet the certification requirements in the controlled environment of a testing facility, these engines will not provide the >90 percent margin of surplus extra emission reductions that are common with DPF-equipped engines, and these surplus environmental and health benefits will be lost.

EPA and CARB should coordinate activities to develop a methodology for measuring UFP and particle numbers.

Concerns have been raised by both agencies about whether the European Particulate Measurement Programme (PMP) is suitable for setting a PN limit in the U.S. context. At the same time, the agencies have raised concerns about the ability of their existing framework to measure PM mass emissions at very low levels (e.g., <3 mg/mile). The two agencies should work together to develop a single methodology that could be used to support a PN limit or other UFP standard in the U.S. Because of the relative ease in measuring particle number versus particle mass at the 1 mg/mile level, the agencies should agree on a scientifically sound conversion factor between particle number and particle mass. This may provide a more robust measurement technique than a mass measurement, and may be used in conjunction with mass-based epidemiological data to estimate health impacts of ultrafine PM.

Both Federal and state governments should play a greater role in accelerating the retirement or retrofitting of older, dirtier diesel engines and the introduction of cleaner diesel replacements.

With so many older trucks still on American highways and roads, there is a great need for funding incentives to accelerate the retrofitting or retirement of these remaining dirty diesels.

The federal government has two programs that can help accelerate the clean-up of today's remaining dirty diesels. First, in 2010, Congress passed the Diesel Emissions Reduction Act (DERA), which authorized \$100 million/year to cleaning up the legacy fleet of older, dirtier diesel engines. Unfortunately, this program has never been fully funded. Over the past three years, DERA was funded at \$50 million in FY 2011 and \$30 million in FY 2012 and \$20 million in FY 2013. MECA understands the fiscal constraints facing the 114th Congress, yet strongly urges Congress to maintain the \$20 million appropriation in the coming year and to explore new, additional ways to encourage the accelerated clean-up of the nation's older, dirtier diesels. Second, the Department of Transportation's Congestion Mitigation and Air Quality (CMAQ) funding provides over \$300 million per year for states to maintain the highway infrastructure.

Some of this money should go towards retrofitting the diesel vehicles and equipment that are used on projects funded with CMAQ monies.

At the state level, existing retrofit funding programs in California and New Jersey add valuable focus and resources to the task of accelerating diesel clean-up. These programs should be fully funded and other states should consider following the model set by these two state leaders. Another state example is the Texas Emission Reduction Plan (TERP), which was established by the Texas Commission on Environmental Quality (TCEQ). TERP provides significant incentive funds for NO_x emission reductions from Dallas-Fort Worth, Houston-Galveston, and other east Texas ozone non-attainment areas. To date, TERP has not provided any significant funding for NO_x retrofit technology and no funding at all for PM technology. Clean construction mandates represent another effective means for states that are in PM non-attainment to clean-up construction equipment and other diesel vehicles that are used on state funded construction projects. A state may require a small portion of a grant to go towards retrofitting vehicles that are used on the project.

Environmental agencies around the world should tighten evaporative emission limits as a way to control secondary organic aerosols.

The California and U.S. LEV III/Tier 3 evaporative emissions programs provide the most comprehensive approach to minimizing evaporative and refueling emissions from gasoline vehicles, a significant source of secondary organic aerosol-based particulates. Other major world air quality agencies in major automobile markets should adopt U.S. style evaporative and refueling emission requirements.

Introduction

An estimated half a billion gasoline- and diesel-powered cars and trucks are in use in the United States and Europe today.¹ All of these vehicles emit some amount of particulate matter (PM) from their engine during combustion.

Engine PM is a complex mix of solid, semi-solid, gaseous and liquid hydrocarbons, metals, elemental carbon, sulfates, and nitrates that range in size from a few nanometers to several microns in aerodynamic diameter.

For most of the last forty years, transportation-related PM emission regulations have focused on reducing the mass of PM emitted. However, a growing body of evidence suggests that mass alone is not a sufficient measure of exposure to PM and its associated health risks.

In recent years, researchers have studied the impacts of ultrafine particles (UFPs), with aerodynamic diameters of less than 100 nanometers (nm). Although UFPs are not a major factor in mass-based PM measurements, they are the dominant contributor to the overall number of particles.² Although there are many sources of UFPs in the atmosphere, vehicle exhaust is the major contributor to UFP concentrations in urban areas, particularly in proximity to major roads.³ UFPs are also of special research importance because of concerns about their chemical composition and ability to bypass the human body's natural respiratory filtration systems.

Recent evidence suggests that regulators should consider adding new protections to reduce the number of UFPs as a complement to their existing framework of mass-based PM standards. Such protections would help lock in the use of the most advanced PM filter technologies, provide added environmental and human health benefits, and create a simpler, faster, and more effective way to measure the reduction of PM from vehicles. For these reasons, the E.U. has implemented the world's first particle number (PN) limits, which add limits of the number of particles emitted to the E.U.'s existing structure of standards that limit the mass of PM emitted by new vehicles.

In the U.S., stringent emissions standards for PM mass emissions went into effect for new heavy duty diesel engines in 2007, dramatically reducing PM emissions through the use of diesel particulate filters (DPFs). While DPFs were designed primarily to reduce PM mass emissions,

¹ Federal Highway Administration estimates 245 million cars and trucks in the U.S. and the E.U. estimates 273 million cars and trucks operate in the E.U. Sources: National Transportation Energy Data Book and EU Transport in Figures.

² Health Effects Institute, Understanding the Health Effects of Ambient Ultrafine Particles, January 2013, executive summary, at 3.

³ Id. at 5.

tests show that they also significantly reduce the number of UFPs emitted. However, in the U.S., diesel PN and UFP emissions are only controlled indirectly through the use of DPFs to meet EPA and California Air Resources Board (CARB) mass-based PM standards currently.

Engine manufacturers are increasingly using selective catalytic reduction (SCR) technology to reduce nitrogen oxides (NO_x) emissions. SCR is a proven, cost-effective technology to reduce NO_x emissions. Its use enables manufacturers to adopt strategies to reduce PM during combustion, rather than through the use of DPFs. (During combustion, NO_x and PM emissions are inversely related. With SCR, manufacturers tune their engines to produce very low levels of PM and higher levels of NO_x, and then use the SCR system to reduce the NO_x before it leaves the vehicle's tailpipe). As a result, some nonroad diesel engines are now being certified without DPFs. If this trend continues, it will eliminate the primary form of diesel PM and UFP control in the U.S.

New gasoline technologies like GDI are likely to expand the diesel-focus of PM control to a broader focus on both gasoline and diesel engines. There is a growing awareness that cars equipped with GDI can produce UFP and PN rates similar to diesel engines without a particulate filter. For that reason, the Euro 6 PN limits for light-duty vehicles⁴ apply to GDI engines, as well as to diesel engines. Many experts believe that the Euro 6 PN limits will compel many engine manufacturers to consider a variety of particle emissions control strategies including gasoline particulate filters (GPFs) and combustion-based approaches to control PN and meet the new standards. As gasoline direct injection (GDI) and turbocharging become the norm in U.S. and European light-duty vehicles, it is time for the U.S. to consider adopting PN limits.

The sections that follow will make the case that North American environmental regulators should consider taking action on PN limits, as a complement to their already world-best PM mass standards.

⁴ In the European system, Euro 1-6 standards refer to light-duty vehicles. Roman numbers (e.g., Euro IV, V, and VI) are used to refer to the emissions standards for heavy-duty engines.

Section 1 – The Health Impacts of Ultrafine Particulates

In recent years, particulate matter (PM) has received a great deal of attention from regulators and others who are concerned about the health impacts of pollution. In dozens of studies, PM has been linked with a wide range of health impacts, including increased asthma emergencies, bronchitis, cancer, heart disease, low birth weights, and premature deaths. In 2012, the Health Effects Institute reported that ambient (or outdoor) PM pollution was responsible for 3.2 million premature deaths annually, based on World Health Organization data – on HEI’s list of the top causes of premature mortality in 2010, PM pollution ranked 8th.⁵

PM is a general technical term that describes the mixture of solid, semi-solid, liquid and gaseous particles that are a natural byproduct of combustion. Particulate formation is complex and generally produces a broad range of particles, both in terms of size and chemical composition. Most particulates are formed from incomplete combustion of fuel. Other particulates form when metal compounds and other noncombustible components are introduced into the combustion chamber of an engine.

Existing PM regulations in the U.S. are mass-based standards that differ only in the size of the particles they target. PM₁₀ standards target particulates no larger than 10 microns in diameter, and PM_{2.5} standards limit the emissions of particulates no larger than 2.5 microns in diameter. As Figure 1 shows, a human hair tends to be in the 50-70 micron range.

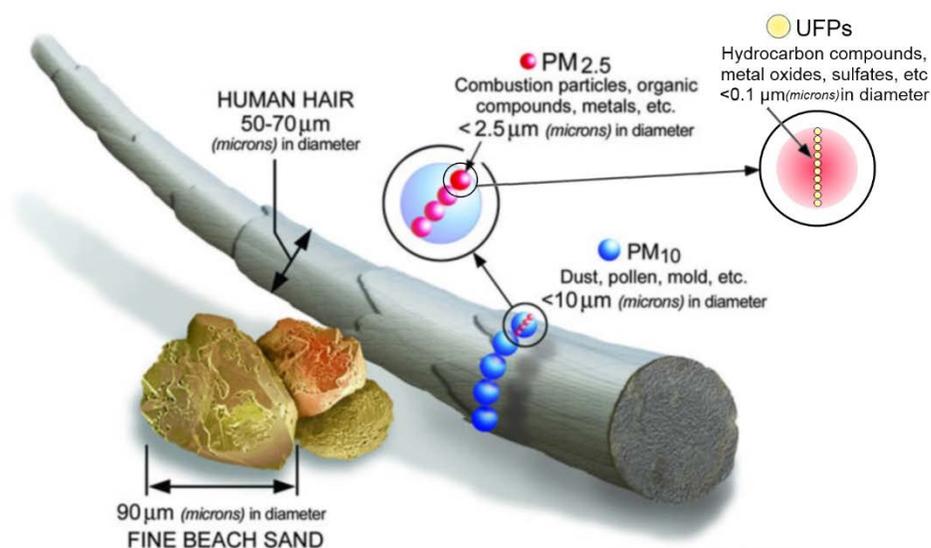


Figure 1. Size comparison of various classes of PM (adapted from U.S. EPA)

⁵ Health Effects Institute, “Outdoor air pollution among top global health risks in 2010”, Press Release dated December 13, 2012. Accessed online at <http://www.healtheffects.org/International/GBD-Press-Release.pdf>.

Defining ultrafine particulate matter

In recent years, researchers have spent a great deal of time studying a class of particulates called “ultrafine particulates” (UFPs). UFPs have an aerodynamic diameter of 0.1 microns in diameter or less, i.e., 1% of the size of a PM10 particle. It is interesting to note that ultrafine particles are not found in nature from the combustion of biomass—PM from combustion sources tend to be much smaller than naturally occurring combustion particles.

Once released into the atmosphere, UFPs remain suspended for periods of time ranging from minutes to days, and may continue to grow in size and react with other atmospheric constituents. Eventually, UFPs settle to the ground, wash out during rain, impact and adhere to objects, or are inhaled by people. Once inhaled, UFPs are small enough to evade our respiratory defense mechanisms and lodge in the deepest recesses of our lungs. There, they are small enough to cross cellular walls and enter our bloodstream. Indeed, it is well known that inhaled UFPs differ from larger particles in their lung deposition patterns, in their clearance mechanisms, and in their potential to be transmitted from lungs to other tissues in the body.⁶

In addition to their health impacts, UFPs are also important because they represent the largest category of particulates from engine combustion. As shown in Figure 2, the greatest number of particles and the greatest amount of lung deposition occurs in the ultrafine particle size range.

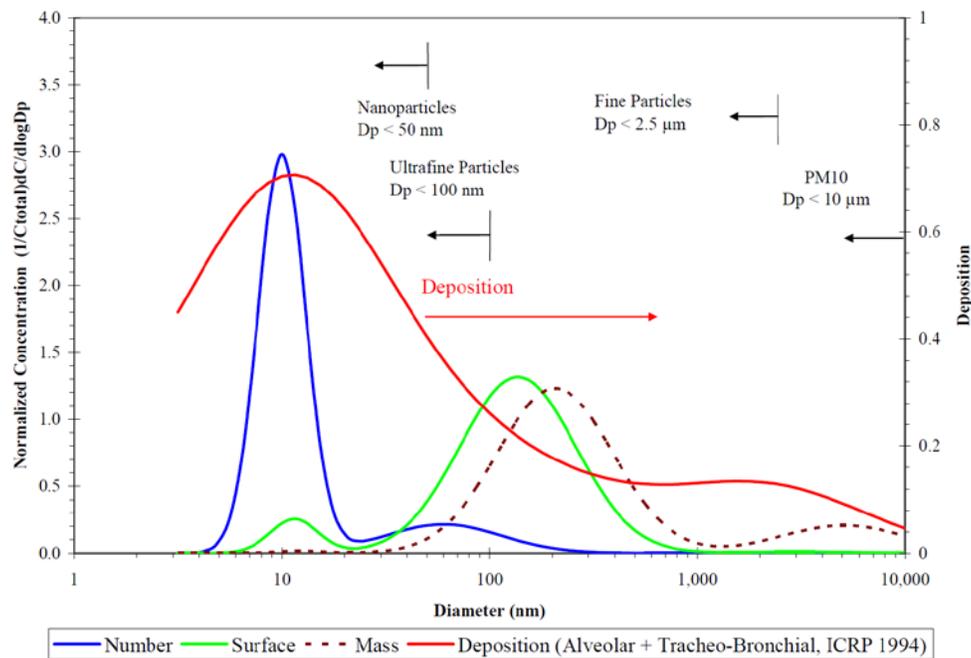
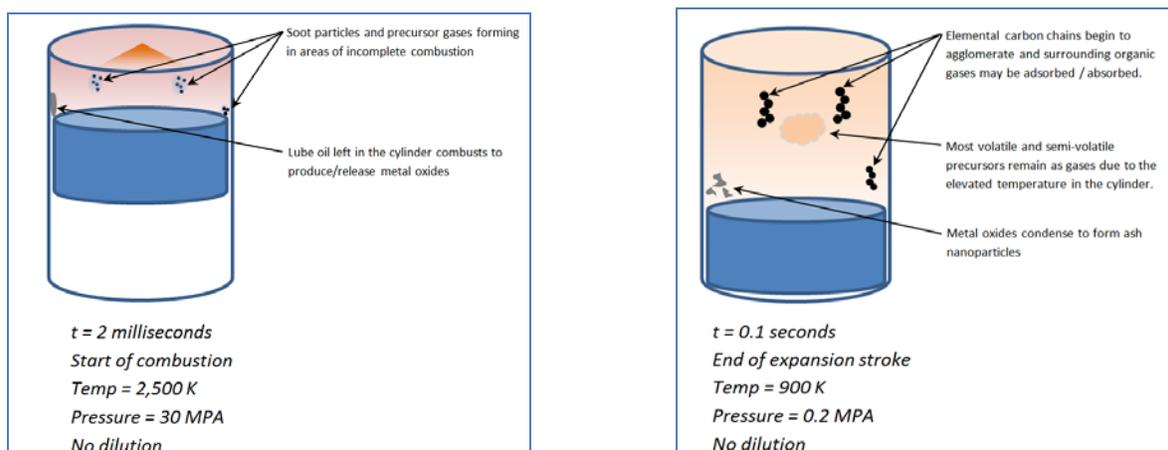


Figure 2. Particle size distributions of typical engine exhaust PM (Kittelson, 2006)

⁶ Health Effects Institute, “Understanding the Health Effects of Ambient Ultrafine Particles.” HEI Perspectives 3. Health Effects Institute, Boston, MA. 2013, at 3.

How UFPs are formed

In typical gasoline and diesel engine combustion and exhaust, UFPs formation begins in the engine cylinders where combustion takes place. In real-world conditions, combustion is never perfect or complete. Soot particles (elemental carbon) and precursor gases (organic carbon) form in areas of the cylinder that prevent complete combustion of the fuel ((L) Figure 3). Incomplete combustion yields a range of partially oxidized hydrocarbons and soot particles ((R) Figure 4).⁷ As the combustion gases are exhausted from the engine and emitted from the tailpipe, the chemical composition and structure of the soot, precursor gases, and metal ash change (Figure 5). Evaporation from fuel systems, particularly gasoline systems, can also release vapor-phase hydrocarbons into the air. Whether from engine exhaust or evaporative emissions, these complex hydrocarbons react with ground level ozone and oxides of nitrogen to form a wide variety of acids, nitrated organic compounds, and other chemicals that contribute to the health impacts of ambient aerosols (Figure 6).⁸



(L) Figure 3. Initial formation of PM precursors in the combustion chamber,

(R) Figure 4. Agglomeration of soot particles and metal ash particles.

⁷ There are several reasons incomplete combustion occurs, but the primary mechanisms in an engine cylinder are (1) imperfect mixing of the air and fuel and (2) quenching of the combustion reaction at walls and crevices.

⁸ Hallquist, M. et al., "The formation, properties and impact of secondary organic aerosol: Current and emerging issues" *Atmos. Chem. Phys.*, 9, 5155–5236, 2009.

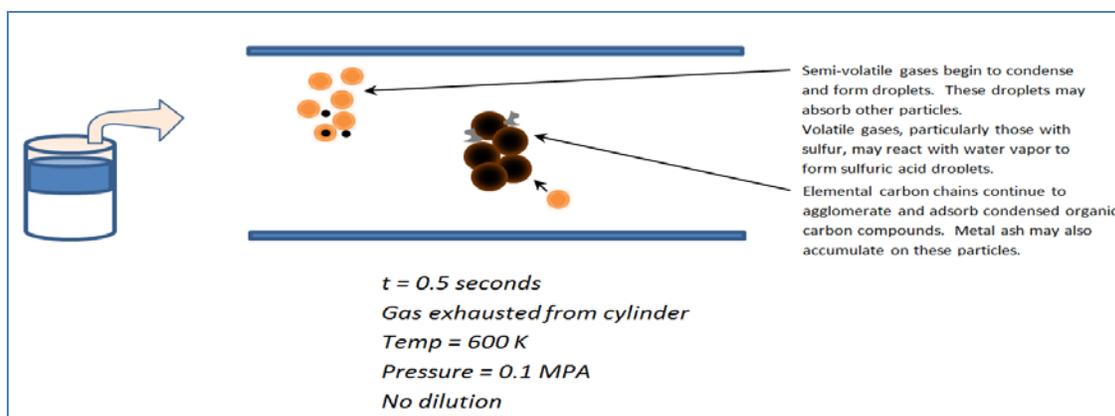


Figure 5. Particle condensation, nucleation, and adsorption in the exhaust

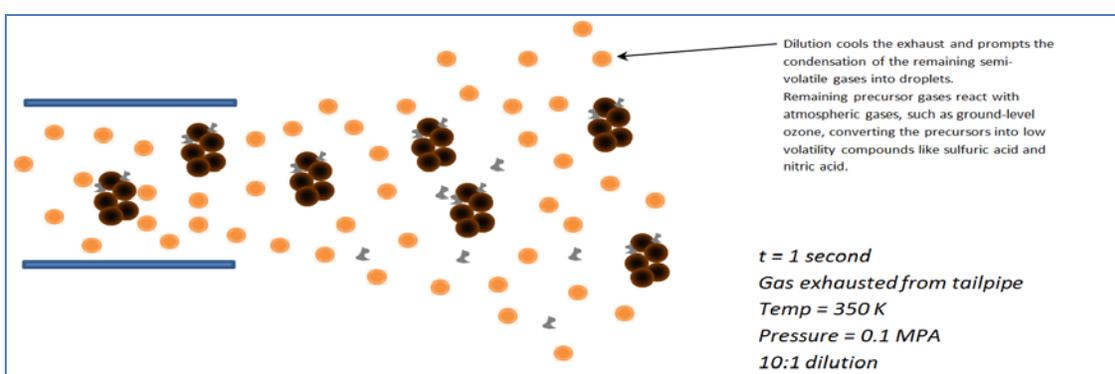


Figure 6. Exhaust of complex mixtures of UFPs and secondary aerosol precursors

UFPs are only one component of the diverse pollutant mix that is found in typical engine exhaust, which includes the following categories of emissions:

Soot: Soot is formed when elemental carbon particles agglomerate and adsorb or absorb other particles and gases. This leads to long carbon particle chains with a mix of organic chemicals and metal ash adsorbed⁹ onto the surface of the carbon particles. When these soot chains impact each other, they can stick together and form larger particles. Particles that grow large enough will be less mobile and tend to accumulate in a given space. Hence, these larger particles (>50 nm) are referred to as accumulation mode particles.

Precursor gases: Technically, precursor gases are gases that participate in chemical reactions that produce another chemical compound. Often, it is the resulting compound that is of environmental concern. One of the most commonly-known examples of this in the vehicle sector concerns nitrogen oxides and non-methane hydrocarbons, which combine in sunlight to

⁹ Adsorption is the adhering of molecules or ions to the surface of a particle. This is different from absorption, where a molecule or ion enters the particle.

form ozone. This category of emissions includes a wide range of gases that can be relatively simple molecules or complex hydrocarbon chains. If the fuel contains sulfur, some of the gases will be composed of sulfur compounds. As the exhaust cools, some of the gases condense to form droplets or adhere to soot and ash particles. Complex hydrocarbon gases may condense into unresolved complex mixtures that have been evocatively described as “little tarry balls” by Professor David Kittelson, a leader in the field.¹⁰

Some of these precursor gases are too volatile to condense and will pass out of the tailpipe unless they react with other chemicals to convert into less volatile compounds. For example, when a sulfur-containing gas reacts with water, sulfuric acid is typically formed. Because sulfuric acid readily condenses to a liquid below 200 °C, droplets are formed in the exhaust through a process known as nucleation. These droplets may then become the site for more gases and droplets to accumulate. UFPs formed through nucleation are referred to as nucleation mode particles or Aitkin mode particles. It is possible for these particles to grow large enough to become accumulation mode particles.

Metal ash: Lube oil is the primary source of metal ash particles. Due to imperfect oil control in engines, lube oil can enter the cylinder. In such instances, it is burned along with the fuel. Worn engines tend to allow more oil into the cylinder, which increases the amount of lube oil that is burned. This lube oil contains metallic compounds (added to improve the performance of the oil), which form inorganic metal ash upon combustion which remain in the exhaust after the oil burns. Metal ash particles tend to be small, electrically charged, and highly mobile. In the exhaust stream, the metal ash particles may combine with other particles or be exhausted directly into the atmosphere.

Secondary Aerosols: Gases that leave the tailpipe or are emitted directly into the atmosphere from fuel evaporation can react to form additional particulates known as secondary aerosols. Common inorganic gases that are emitted by vehicles include sulfur dioxide, nitrogen dioxide, and ammonia. When they leave the vehicle, these inorganic gases react with atmospheric constituents such as sunlight, ground level ozone, NO₃, or hydroxyl radicals to form sulfate, nitrate, and ammonium particles. Complex organic gases that are emitted from engines and/or evaporated from the fuel can also react with the same atmospheric constituents, but produce complex organic oxidants that may condense into droplets or become water soluble. Because of the complexity of the organic gases and the degradation chemistry involved, there are tens of thousands of oxidants in the atmosphere, with varying propensities to form secondary aerosols.

¹⁰ Kittleson, D., “Ultrafine Particle Formation Mechanisms” South Coast Air Quality Management District Conference on Ultrafine Particles: The Science, Technology, and Policy Issues, 2006.

Secondary organic aerosols are a mix of complex organic compounds derived from polycyclic aromatic hydrocarbons (PAHs), organic acids, and other volatile or semi-volatile compounds formed from partially oxidized fuel, lube oil, and evaporative emissions. Because of their semi-volatile nature, they may form nucleation mode particles in engine exhaust or ambient air. While there are tens of thousands of potential organic aerosols that may be present in engine exhaust or formed through oxidative degradation of other organic compounds in the atmosphere, some of the known organic compounds include benzene, toluene, and xylene. All three of these compounds are known carcinogens.¹¹

While the previous discussion of UFP formation applies broadly to all internal combustion engines, the observed emissions of UFPs from individual engines are highly dependent on the type of engine, fuel, and technologies employed, as will be discussed below.

Summarizing the health impacts from UFPs

PM from engine exhaust has long been linked to numerous short and long term negative health effects, including cancer, cardiovascular disease, and reduced lung function.^{12,13} However, attribution of various health end points to specific components of engine PM has been difficult due to the complex chemical and physical composition of PM, as well as the complexity of assessing human exposure-response to the various constituents of PM.

Although precise apportionment of the health impacts of UFPs relative to total PM mass is not yet possible, a growing body of literature suggests that UFPs may be more toxic on a mass-equivalent basis than the elemental carbon that makes up much of engine PM mass emissions. For example, Sager and Castranova found that ultrafine black carbon particles were 65 times more inflammatory and cytotoxic, on a mass basis, than PM_{2.5}-sized black carbon in the alveolar epithelial cells of rats.¹⁴ They also found that ultrafine titanium oxide particles produced inflammatory responses that were more persistent than responses from ultrafine black carbon, indicating that both particle size and composition affect dose response.

Researchers in Germany evaluated the toxicity of diesel exhaust with and without the application of a diesel oxidation catalyst (DOC).¹⁵ They observed that particle emissions were

¹¹ Krzyzanowski M., Kuna-Dibbert B., and Schneider J.: Health effects of transport-related air pollution: World Health Organization 2005.

¹² U.S. EPA, "Health assessment document for diesel engine exhaust", 2002.

¹³ World Health Organization, "Health effects of transportation-related air pollution", 2005.

¹⁴ Sager T, Castranova V. Surface area of particle administered versus mass in determining the pulmonary toxicity of ultrafine and fine carbon black: comparison to ultrafine titanium dioxide. *Particle and Fibre Toxicology* 2009, 6:15

¹⁵ Westphal, Goetz A., et al., "Mutagenicity of Diesel Engine Exhaust is Eliminated in the Gas Phase by an Oxidation Catalyst but Only Slightly Reduced in the Particle Phase", *Environmental Science & Technology* at: pubs.acs.org/doi/abs/10.1021/es300399e.

reduced with the DOC, due mostly to the oxidation of the soluble organic fraction of particles. Furthermore, the DOC was found effective at reducing ultrafine and volatile particles but made only a small impact on reducing the mutagenicity of the solid particle phase. They concluded that the DOC is not effective at eliminating the toxic hydrocarbon species that are bound tightly to solid diesel particles, such as PAHs and nitro-PAHs, although they are effective in reducing PAHs in the gaseous phase.

UFPs can produce inflammation of the airway that is generally attributed to the generation of reactive oxygen species (ROS) from organic and metallic components.^{16,17,18} While ROS are produced naturally in the body as a byproduct of metabolism, acute exposures can aggravate allergies and asthma. Plus, oxidative damage caused by ROS to cells and DNA is implicated in a number of chronic conditions, including diabetes, neurodegenerative disorders, and cancer.¹⁹ The importance of the role of metals in ROS activity is supported in a study by CARB, finding that the removal of metals from diesel PM via metal chelation treatment reduced ROS activity by an average of 77%. Iron, the most abundant metal species in the exhaust, was found to have the largest effect on ROS activity while other metals (chromium, cobalt, cadmium, magnesium, lead, and zinc) also correlated well with ROS activity.²⁰ Similarly, Li et al. found that UFPs with metallic components produced increased ROS activity and linked differing compositions of metals and organic compounds to different levels of ROS activity and inflammation.²¹

¹⁶ Carter JD, Ghio AJ, Samet JM, Devlin RB: Cytokine production by human airway epithelial cells after exposure to an air pollution particle is metal dependent. *Toxicology and Applied Pharmacology* 1997, 146:180-188.

¹⁷ Nel AE, Diaz-Sanchez D, Ng D, Hiura T, Saxon A: Enhancement of allergic inflammation by the interaction between diesel exhaust particles and the immune system. *J Allergy Clin Immunol* 1998, 102:539-554.

¹⁸ Saldiva PHN, Clarke RW, Coull BA, Stearns RC, Lawrence J, Murthy GGK, Diaz E, Koutrakis P, Suh H, Tsuda A, Godleski JJ: Lung inflammation induced by concentrated ambient air particles is related to particle composition. *American Journal of Respiratory and Critical Care Medicine* 2002, 165:1610-1617.

¹⁹ Waris G, Ahsan H. Reactive oxygen species: Role in the development of cancer and various chronic conditions. *J Carcinog* 2006; 5:14.

²⁰ Sioutas Sc. D, Constantinos Physiochemical and toxicological assessment of the semi-volatile and non-volatile fractions of PM from heavy-duty vehicles operating with and without emissions control technologies, California Air Resources Board 2011.

²¹ Li et al., Ultrafine particles from diesel vehicle emissions at different driving cycles induce differential vascular pro-inflammatory responses: Implication of chemical components and NF-κB signaling. *Particle and Fibre Toxicology* 2010, 7:6.

In vitro vs. in vivo testing

An important characteristic of health studies is whether they are performed “in vitro” or “in vivo.” In vitro, meaning “in glass”, refers to testing conducted outside of a living organism. For example, many health impact studies related to UFPs are conducted by exposing living cells in a petri dish to a water-based solution containing UFPs. In contrast, in vivo (“within the living”) testing involves living organisms. Commonly, these organisms are mice, rats, or dogs, which are used as human surrogates. The benefit of in vivo testing is that it can capture the influence of the many complex mechanisms that occur in a living organism that do not exist when considering a small group of cells outside the body. On the other hand, in vitro testing allows researchers to target specific mechanisms and pathways with greater control than would be possible with in vivo testing. Ideally, in vitro experiments provide the preliminary understanding of the mechanism of action at a cellular level, which would be validated by in vivo experiments. Many experts believe that in vitro experiments are strong indicators of the results of in vivo experiments.

Other researchers have explored the correlation of nickel metal concentrations in ambient air with cardiovascular effects. Lippman et al. found that atherosclerotic mice exposed to increased levels of nickel experienced decreased heart rates and increased heart rate variability, suggesting that similar effects might be present in humans with atherosclerosis. A second element of the study found that daily mortality rates in 60 U.S. cities correlated well with nickel concentrations, supporting the conclusion that nickel in ambient air is influential in producing cardiovascular responses in humans.²²

The oxidative potential of exhaust particulate matter has also been attributed to certain complex organic compounds, including PAHs²³ and water soluble organic compounds (WSOC)²⁴. Because the compounds are typically semi-volatile, they represent a significant portion of the nucleation mode particles (less than 50 nm) and precursor gases present in engine exhaust. Sioutas et al. showed a significant correlation between particle number, but not particle mass, and the oxidative potential of diesel exhaust; again indicating that particulate size and composition strongly influence particle toxicity.

With respect to secondary aerosols, they can generally be segregated into inorganic and organic aerosols. Inorganic aerosols are primarily composed of sulfate, nitrate, and ammonium

²² Lippmann M., Ito K., Hwang J., Maciejczyk P., Chen L.: Environ Health Perspectives 2006, 114:1662–1669.

²³ Geller MD, Ntziachristos L, Mamakos A, Samaras Z, Schmitz DA, Froines JR, Sioutas C: Physicochemical and redox characteristics of particulate matter (PM) emitted from gasoline and diesel passenger cars. Atmospheric Environment 2006, 40:6988-7004.

²⁴ Sioutas Sc. D, Constantinos Physicochemical and toxicological assessment of the semi-volatile and non-volatile fractions of PM from heavy-duty vehicles operating with and without emissions control technologies, California Air Resources Board 2011.

particles that form when sulfur dioxide, nitrogen dioxide, and ammonia react with ground level ozone. Numerous “time-series” studies have compared mortality to ambient sulfate or SO₂ levels, showing that increased mortality is associated with increased ambient sulfate levels. For example, a mandated reduction in sulfur emissions corresponded with a reduction in mortality and morbidity when it was implemented in Hong Kong.²⁵ However, other studies have suggested the mass concentrations of ambient sulfate and nitrate aerosols are not correlated with mortality, but rather that these compounds may enhance the toxicity of metals and organic aerosols, which in turn have health impacts.²⁶

Engine-specific UFP Issues

The composition and quantity of UFPs produced vary, in part, based on the type of engine and the manner in which the engine is operated. Historically, normally aspirated port-fueled gasoline engines have produced the least PM per mile or per brake horsepower hour, both by particle mass and particle number. As a result, environmental regulations did not even bother to regulate PM from gasoline engines until recently. However, newer gasoline technologies like today’s GDI engines emit significantly higher levels of PM emissions than DPF-equipped diesel engines in terms of particulate number, as shown in Figure 7. In fact, PN emissions from GDI engines are intermediate, in both mass and particle number, to the emissions from gasoline PFI and older diesel engines that are not equipped with DPFs. While not shown in Figure 7, gasoline engines using turbocharging also show increased PM number emissions.²⁷ In contrast, newer diesel engines have lowered UFP tailpipe emissions through the use of diesel particulate filters, achieving PM mass and particle number emissions similar to normally aspirated, port-fueled gasoline engines and compressed natural gas (CNG) engines.

²⁵ Brunekreef, B.: Health relevance of particulate matter from various sources. World Health Organization 2007.

²⁶ Reiss R, Anderson EL, Cross CE, Hidy G, Hoel D, McClellan R, Moolgavkar S.: Evidence of health impacts of sulfate- and nitrate-containing particles in ambient air. *Inhal Toxicol.* 2007 May;19(5):419-49.

²⁷ Hyundai, IQPC Conference “Advanced Emission Control Concepts for Gasoline Engines”, Sindelfingen, Germany. May 2012.

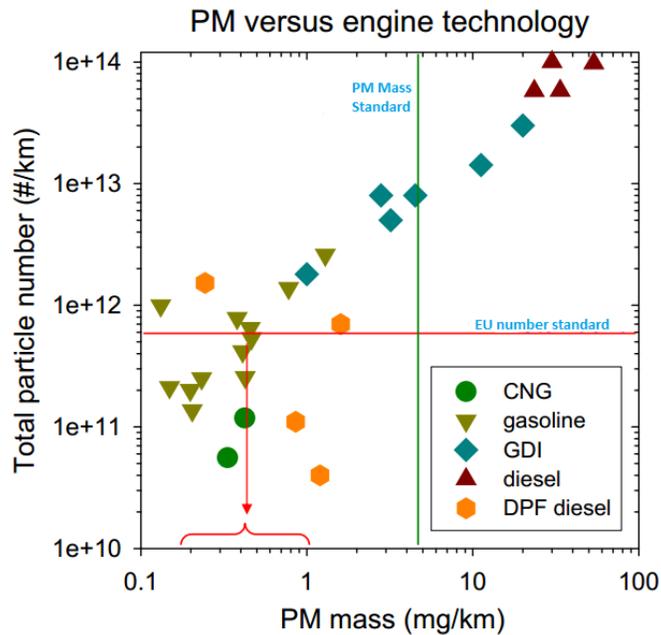


Figure 7. Particle Number vs. Particle Mass for various LDV engine technologies²⁸

It is possible to see the difference in PM levels visually, by examining particles collected over the course of the FTP-75 vehicle test cycle. In reviewing Figure 8, it can be seen that the LEV II vehicle equipped with a GDI engine emits a level of PM during the Phase 1 cold start portion of the test cycle that is visually comparable to a conventional diesel engine that does not have a DPF. During stabilized or hot start portions of the cycle (i.e., Phases 2 and 3), the GDI engine still emits more PM than a PFI gasoline-fueled LEV II vehicle or the DPF-equipped diesel vehicle.

²⁸ Maricq M., How are emissions of nuclei mode particles affected by new PM control technologies and fuels?, Ford Motor Company, Health Effects Institute Annual Conference, 2009.

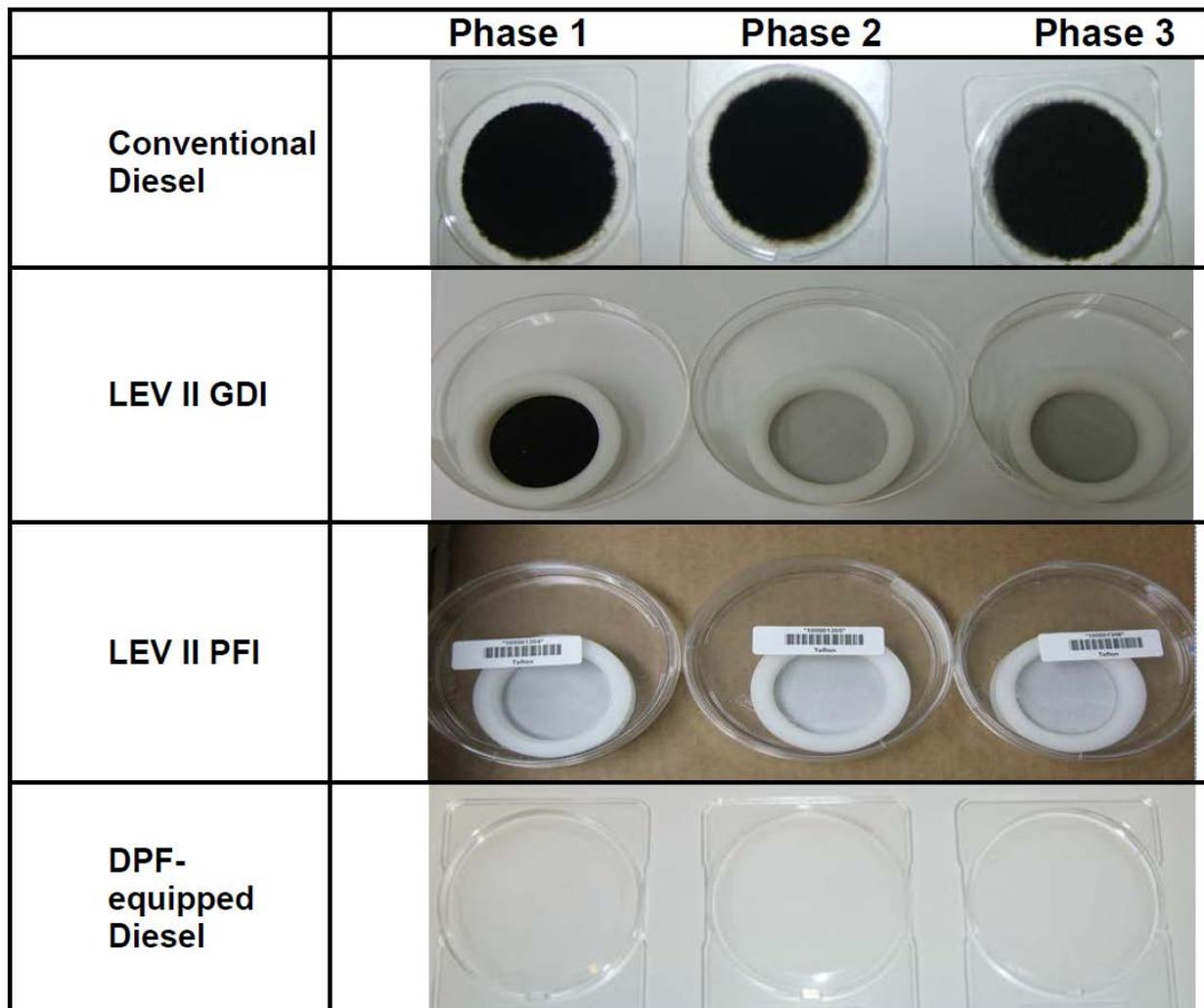


Figure 8. Visual comparison of PM deposits from various LDV technologies over FTP-75 test cycle²⁹

UFPs from Diesel Engines

Conventional diesel engines (those without diesel particulate filters) produce UFPs from incomplete combustion that are dominated by accumulation mode particles (>50 nm). These particles consist of a carbonaceous core with semi-volatile chemicals adsorbed onto the particle surface. To reduce incomplete combustion and improve overall engine performance, engine manufacturers have introduced higher fuel injection pressures, fuel injection “shaping”, and other advanced combustion chamber strategies. While all of these technologies have improved fuel/air mixing and can reduce PM emissions, no engine manufacturer has yet commercially demonstrated the ability to meet 2010 EPA or Euro VI heavy-duty engine PM emission

²⁹ California Air Resources Board, LEV III PM Technical Support Document, Appendix P, 2011.

standards without the use of a DPF. Several European manufacturers have indicated that it is possible to meet the Euro VI PM mass limit without a particulate filter.

UFPs from Gasoline Engines

Today's gasoline engines employ a wide range of technologies, both on the engine and in the tailpipe, which are designed to improve fuel economy and power while meeting emissions requirements. Two areas of engine technology – fuel injection and air induction – are having significant effects on the production of PM from gasoline engines.

Until recently, the dominant gasoline engine in new American and European light-duty vehicles was naturally aspirated and used port fuel injection that, in combination with a three-way catalyst and evaporative controls, would meet U.S. and Euro emissions standards. However, as fuel prices rise and the U.S. and E.U. implement new, more stringent standards for fuel economy and greenhouse gas emissions, turbocharging and GDI are quickly gaining market share. While both of these technologies can improve fuel economy, Figure 9 shows that both technologies can increase PN emissions from engines.

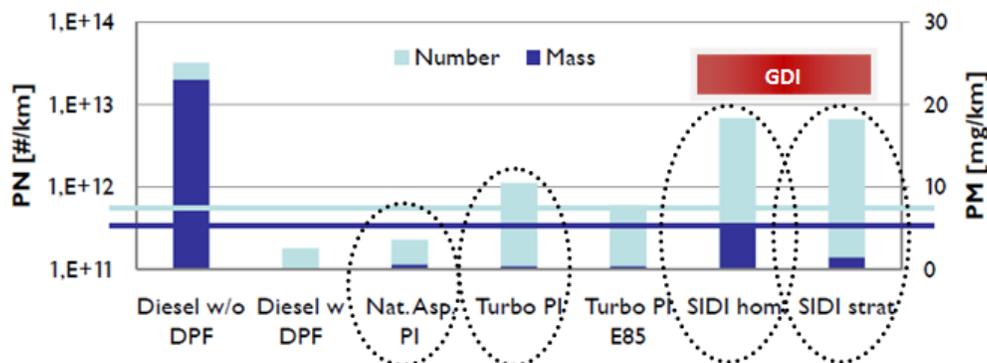


Figure 9. Comparison of PM and PN emissions from different fuels and engine technologies³⁰

Gasoline Direct Injection

GDI improves engine fuel economy and power by directly injecting fuel into the cylinder rather than upstream of the intake valve. This allows the engine to operate in a diesel-like lean combustion mode at light engine loads or in a stoichiometric combustion mode similar to PFI engines in other situations. The lean combustion mode is possible because fuel is injected at a position very close to the spark plug, creating a local, stratified, fuel-air mixture that is capable of combusting, even though the overall fuel-air ratio is much too lean for combustion. While operating in the lean combustion mode, the engine does not have to throttle the incoming air

³⁰ Ericsson, P., Particulate Number Emissions from Spark-Ignition Engines, 2010.

as a PFI engine would. Eliminating this throttling can increase fuel economy by 10-20%. However, this mode of operation also reduces the amount of time the fuel has to mix with the air, which can increase PM and UFP formation due to the incomplete combustion caused by heterogeneous mixing. Lean GDI combustion also has high NO_x emissions that require the use of sulfur sensitive NO_x control strategies such as lean NO_x traps. This technology has seen limited application on a few vehicles in Europe but is being considered for future U.S. deployment by several manufacturers as a possible approach to help comply with future fuel economy standards.

PN and PM mass emissions from a GDI engine operating in the stoichiometric mode are strongly dependent on the injection strategy and hardware configuration used in the engine. Many GDI engines use “wall-guided” fuel injection. In this configuration, the fuel injector is placed off center from the cylinder and injected fuel impinges on the cylinder wall and piston head. (Figure 10 compares a wall-guided GDI fuel injector with a PFI injector.) Fuel in contact with the cylinder wall during combustion is more likely to form soot or other semi-volatile compounds because the wall quenches the flame and prevents the complete combustion of the fuel. The alternative to wall-guided injection is “spray-guided” injection. In this configuration, the injector is centered over the cylinder (where the spark plug would be on a wall-guided or PFI engine). The fuel injector confines the fuel spray such that it does not contact the cylinder walls, improving mixing and reducing soot formation. While the wall-guided injector configuration is not optimal, it is commonly used because it is cheaper to implement than spray-guided designs. More stringent emissions standards such as the Euro 6c GDI particle number limits and California LEVIII 1 mg/mi PM standard are likely to compel engine manufactures to move to spray-guided designs with advanced piezoelectric injectors or add gasoline particulate filters to meet lower PM mass and PM number emissions limits.

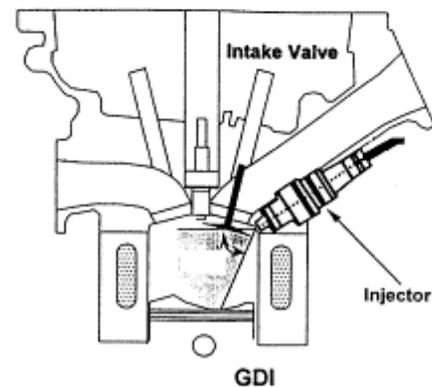
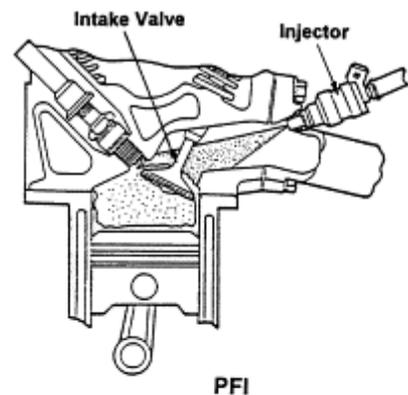


Figure 10. Comparison of GDI and PFI fuel injection location

Port vs. Direct Fuel Injection

Regardless of the fuel injector placement, GDI engines generally achieve poorer mixing of the air and fuel than PFI engines. This is because PFI engines inject the fuel further upstream, allowing for greater mixing times, vaporization of the fuel as it contacts the hot intake valves, and large scale mixing as the air enters the cylinder. By contrast, a stoichiometric GDI engine using a homogeneous injection strategy will inject all of the fuel into the cylinder during the compression stroke, significantly reducing the mixing time available.

To improve mixing and reduce rich PM formation, some stoichiometric and all lean GDI engines operate in a multi-injection mode. This mode of operation injects the fuel over several pulses that can span both the intake and compression stroke. GDI engines using stratified injection can show reduced PM mass emissions but similar PN emissions to homogeneous injection modes (Figure 9). PFI engines generally produce UFPs that are primarily composed of nucleation mode particles and metal ash less than 50 nm in size. Homogeneous injection, wall-guided GDI engines of the type common today, show elevated levels of soot formation relative to PFI engines, particularly during cold-start operations due to the increased quenching of the cold cylinder walls. This effect of increased PM (soot) production is represented visually in Figure 8. Because the soot is comprised of long carbon chains that can accumulate semi-volatile compounds, GDI engines produce UFPs with larger accumulation mode particle diameters as shown in Figure 11.

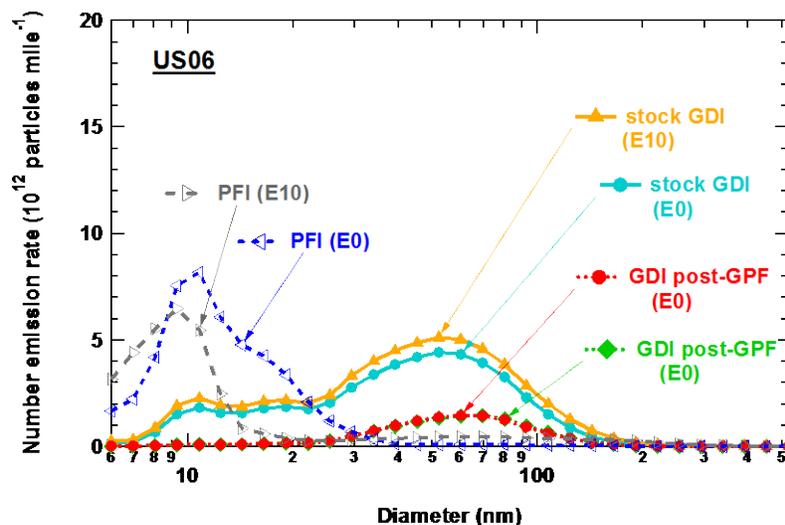


Figure 11. PN size distributions for various gasoline engine configurations over the US06 test cycle.³¹

³¹ Chan, T. et al. "Effectiveness of a Gasoline Particulate Filter in Controlling Emissions from a Gasoline Direct Injection Vehicle" SAE Technical Paper 2012-01-1727 and "Impact of Ambient Temperature on Gaseous and Particle Emissions from a Direct Injection Gasoline Vehicle and its Implications on Particle Filtration" SAE Technical Paper 2013-01-0527.

Turbocharging

Once principally the domain of diesel engines and high performance gasoline engines; turbocharging has become a common strategy for extracting improved fuel economy and power from smaller engines common in many passenger cars and light trucks. Turbocharged engines utilize a small turbine to compress the air entering the engine using energy in the exhaust stream or by a linked second turbine. This results in higher cylinder pressures that support a higher thermodynamic efficiency of the engine. In addition, overall vehicle efficiency can be improved through weight reductions because the engine can be downsized while still producing the same amount of power by utilizing smaller combustion cylinders and more intense combustion. Because of these significant benefits, turbocharging is commonly applied to both GDI and PFI engines. However, as shown in Figure 12, normally aspirated GDI and turbocharged engines have PN emission rates up to 100 times as high as normally aspirated PFI engines. There is also evidence that turbocharging a port fuel injected engine increases particle number emissions.

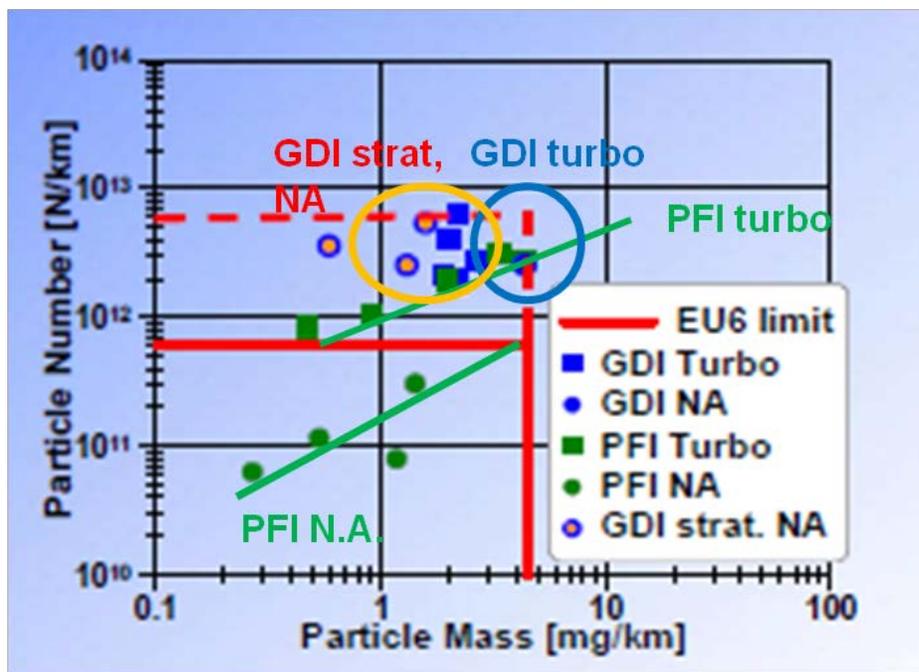


Figure 12. PN emissions from turbocharged and normally aspirated engines³²

³² Hyundai, IQPC Conference “Advanced Emission Control Concepts for Gasoline Engines”, Sindelfingen, Germany. May 2012.

Popularity of GDI and Turbocharged Gasoline Engines

The prevalence of GDI and turbocharging technologies in new light duty vehicles has risen dramatically in recent years, both in the U.S. and Europe. As Figure 13 shows, sales of engines with GDI technology in the EU have risen from approximately 5% of new gasoline engine sales in 2007 to nearly 15% of sales in 2010.³³ In the U.S., approximately half of all light-duty vehicle certifications for the 2012 model year included GDI engines, and one third of all certifications included turbocharged engines.³⁴ As seen in Figure 14, projections of future sales in the U.S. show continued growth from 2012 levels, and could exceed 90 percent by 2025.

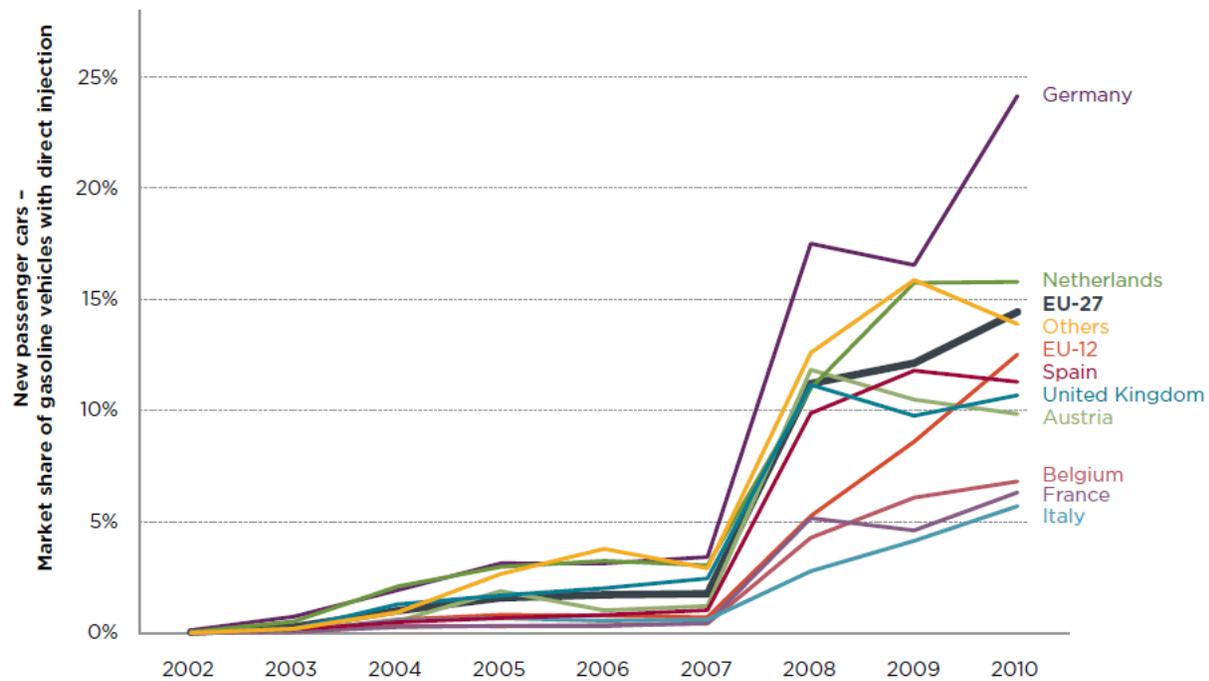


Figure 13. Historical market share of GDI engines in the EU³⁵

³³ Campestrini M., Mock P., European Vehicle Market Statistics, International Council on Clean Transportation, 2011.

³⁴ Based on data from the U.S. EPA's 2012 Fuel Economy Guide for light duty vehicles.

³⁵ Campestrini, M., 2011.

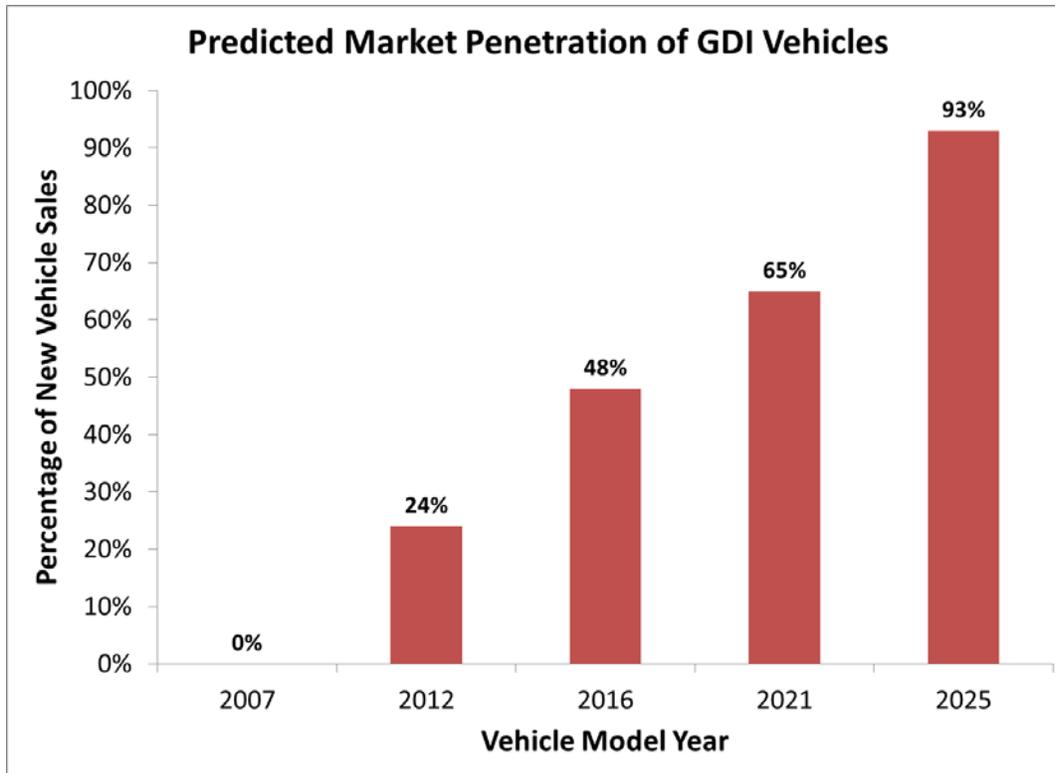


Figure 14. Historical and projected market share of GDI engines in the US³⁶

³⁶2007 and 2012 data from US EPA, "Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2012", 2013. 2016 to 2025 data based on figures presented by Ed Nam, 2013 SAE Emission Control for Light-Duty Automotive Vehicles Symposium, Ann Arbor, MI. January 16, 2013.

Section 2 – Control Strategies for UFPs and Particle Numbers

Over the past decade, a number of effective strategies to reduce the mass of particulate matter emitted from diesel engines have emerged in the diesel marketplace. As regulators, environmental organizations, and companies increasingly turn their attention to the emerging issues of UFPs and black carbon, it is clear that several of these mass-based strategies are similarly effective at reducing UFPs and black carbon emissions³⁷ from diesel and gasoline engines—while continuing to reduce PM mass.

PM control strategies fall into three general categories. These categories include fuel-based strategies (e.g., reducing sulfur levels and changing other fuel properties); engine-based strategies (e.g., altering combustion to reduce emissions); and strategies based on reducing emissions after combustion has taken place but before they leave the tailpipe (known as exhaust emission control strategies, and including technologies like particulate filters). Each of these strategies has its own advantages and tradeoffs, as summarized in the following paragraphs.

Fuel Sulfur Reduction

Generally speaking, when people think of the role of fuel sulfur reductions in reducing PM emissions, they think of the role that reducing sulfur plays in enabling the use of sulfur-sensitive emission control technologies. However, reducing sulfur in diesel or gasoline fuel actually results in reduced PM emissions in all engines (i.e., existing vehicles as well as new vehicles), although not enough to meet EPA, CARB or European vehicle emission standards on their own.

In the fall of 2006, when EPA implemented its ultra-low sulfur diesel fuel (ULSD) regulation, allowable sulfur levels in U.S. highway diesel fuel were reduced from 500 ppm to 15 ppm.³⁸ This change expanded the application of precious metal catalysts to diesel emission control systems and paved the way for diesel particulate filters (DPFs), selective catalytic reduction (SCR) and lean NO_x adsorber technologies to become standard equipment on new diesel trucks, buses, and cars the following year and ever since. Indeed, these remain the primary technologies used to meet 2007 and 2010 heavy-duty and Tier 2 light-duty EPA PM and NO_x emissions limits for highway diesel engines.

In addition to enabling these emission control technologies, the introduction of ULSD also directly reduced the sulfate portion of PM emissions from all diesel engines. That is because, as

³⁷ Diesel PM typically contains a high percentage of black carbon, which has been identified as an important short-lived climate-forcing pollutant. See, e.g., http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_report.pdf.

³⁸ 66 Federal Register 5001 et seq. (January 18, 2001).

Figure 15 shows, sulfate-based PM will be reduced in direct proportion to any reduction in the sulfur level of the fuel. (As the figure also shows, overall PM will be reduced dramatically by the introduction of PM emission control technologies (ECT) at particular sulfur levels, generally considered to be roughly 500 ppm, 50 ppm, and 10-15 ppm.)

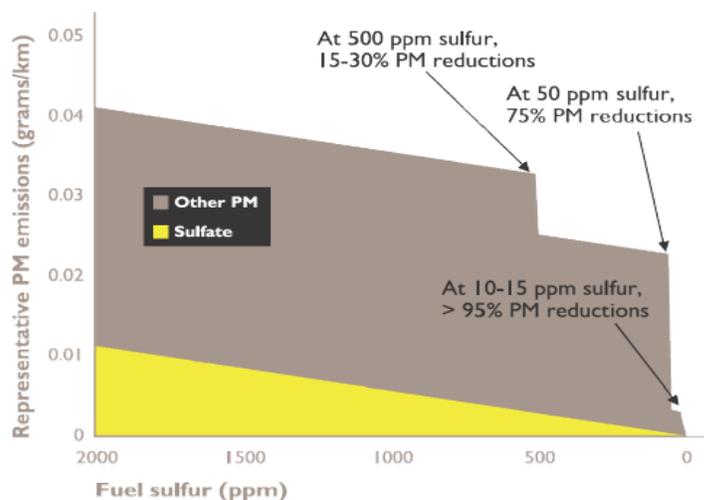


Figure 15. Reducing fuel sulfur levels reduces sulfate and total PM by enabling ECT³⁹

Sulfur levels in gasoline have a similar impact on PM emissions. Reducing the sulfur content in gasoline reduces the sulfate portion of any gasoline PM in direct proportion to the sulfur reduction, and opens the door to more advanced catalysts at various cutpoints. Like any reduction in diesel sulfur levels, this would yield relatively small per-vehicle PM reduction that would be multiplied across the entire vehicle fleet.

This reduction in PM mass also reduces UFPs in two possible ways. First, as discussed in Section 1 above, sulfur compounds (e.g., SO_3) can nucleate and mix with water as the exhaust cools, forming sulfuric acid droplets as directly emitted particles. Second, SO_2 will also oxidize to SO_3 in the atmosphere and form secondary aerosols in reactions with ground level ozone.⁴⁰

Recently, the U.S. EPA proposed its new Tier 3 fuel and emission standards for light-duty vehicles (which are discussed below). If this proposal is finalized and implemented as currently proposed, sulfur levels in U.S. gasoline will be cut from today's average of 30 ppm and a refinery cap of 80 ppm to an average of 10 ppm and a refinery cap in the range of 20 ppm to 80 ppm in 2017.⁴¹ When Tier 3 is implemented, U.S. gasoline will match the average sulfur levels

³⁹ Slide provided by the International Council on Clean Transportation (ICCT), 2012.

⁴⁰ It is worth noting that these sulfur compounds degrade the performance of three-way catalysts (TWC) currently used to control NO_x , CO, and hydrocarbon emissions from most gasoline engines in the U.S. They would similarly degrade the performance of new control systems that use catalysts under a future Tier 3.

⁴¹ <http://www.epa.gov/otaq/documents/tier3/420f13016a.pdf>.

in Europe, Japan and Korea, which, as Figure 16 shows, are the lowest sulfur levels in the world. China has committed to a 10 ppm gasoline sulfur limit no later than the end of 2017. As Figure 17 shows, the U.S. and Europe already have the world’s lowest diesel fuel sulfur levels.

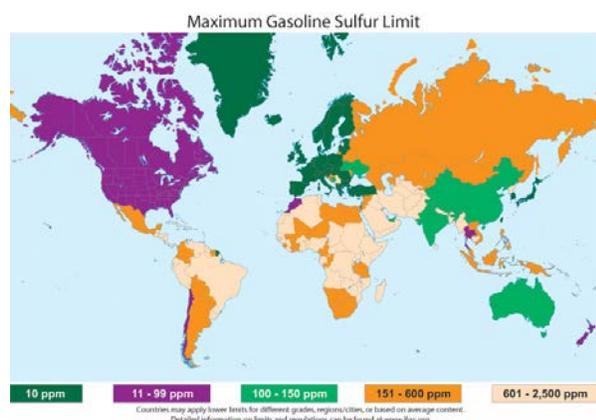


Figure 16. World gasoline fuel sulfur requirements⁴²

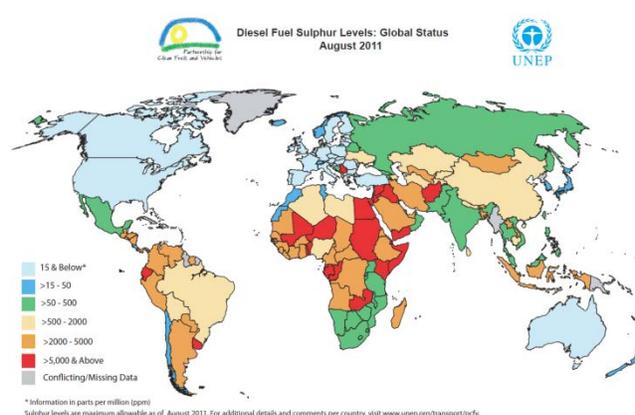


Figure 17. World diesel fuel sulfur levels⁴³

Implementing Tier 3 will reduce the sulfate component of total PM emissions—as well as UFPs—from all gasoline vehicles. This would yield a relatively small per-vehicle PM reduction that would be multiplied across the entire light duty vehicle fleet.

To put it all together, a reduction in gasoline sulfur levels can offer a direct, but limited, means of UFP control in addition to its well-known benefit of improving or enabling the performance of current and future emission control systems.

Strategy: Reduced Fuel Sulfur Content
(Applies to: New and existing U.S. gasoline vehicles)

Benefits

- Reduced SO₂ emissions
- Reduced secondary aerosol formation (sulfates)
- Reduced degradation of TWCs and related NO_x, HC, and CO emissions

Challenges

- Minor increase in fuel price (approx. \$0.01/gallon)
- Limited PM benefits compared to other strategies

⁴² International Fuel Quality Center, April 2012.

⁴³ United Nations Environmental Program/Partnership for Clean Vehicles and Fuels, August 2011.

Recently, other fuel properties have been found to significantly impact the tailpipe PM emissions.⁴⁴ Researchers have reported that PM emissions were a strong function of the number of carbon double bonds or rings present in the molecule and the vapor pressure of the fuel. The highest volatility fuels showed the lowest PM emissions. Fuel formulations containing higher fractions of low vapor pressure hydrocarbons (such as C10 to C12 and more double bonds) resulted in higher PM number emissions.⁴⁵

Diesel Particulate Filters

The high-efficiency wall-flow diesel particulate filter (or more commonly referred to as a DPF) is the primary technology used by engine manufacturers to meet the world's most stringent PM emissions standards. Since 2007, nearly all of the approximately 2.6 million medium and heavy-duty diesel trucks sold in the U.S. have been equipped with a DPF, which enables them to meet EPA's PM standards for heavy-duty engines. In Europe, DPFs are expected to become standard equipment on heavy-duty diesel trucks this year, as engine makers implement steps to comply with the new Euro VI particle number (PN) limits. In addition to their use by engine OEMs, DPFs are also available in many retrofit systems for existing diesel engines (both vehicles and stationary applications). To date, more than 250,000 on-road vehicles and 50,000 off-road pieces of equipment have been retrofitted with DPFs around the world.⁴⁶

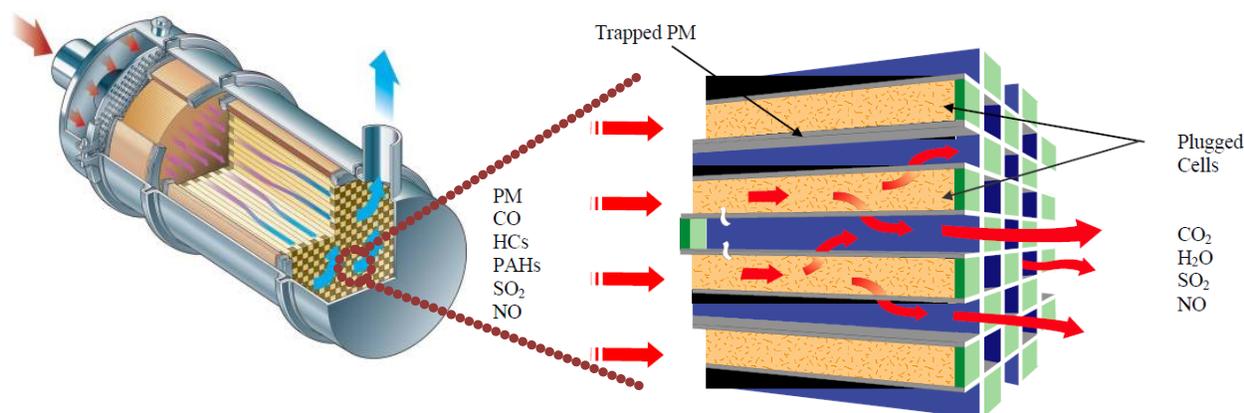


Figure 18. Overview of a DPF

⁴⁴ Khalek, I. et al., "Particle Emissions from a 2009 Gasoline Direct Injection Engine Using Different Commercially Available Fuels", *SAE Int. J. Fuels Lubr.* 3(2): 623-637, 2010, doi:10.4271/2010-01-2117.

⁴⁵ Aikawa, K. et al., "Development of a predictive Model for Gasoline Vehicle Particulate Matter Emissions", *SAE Int. J. Fuels Lubr.* 3(2): 610-622, 2010, doi:10.4271/2010-01-2115.

⁴⁶ Manufacturers of Emission Controls Association, "Written Statement on the proposal to revise the National Ambient Air Quality Standards for Particulate Matter, Docket ID NO. EPA-HQ-OAR-2007-0492, 2012.

DPFs have been successful in the marketplace because they combine an ability to reduce PM emissions by more than 90 percent with a reasonable price and widespread applicability. DPFs are the only diesel technology currently able to consistently demonstrate high levels of reduction for all types of diesel PM that concern environmental regulators—PM mass, ultrafine and nano-sized particles, overall particle numbers, and black carbon.

The technology in a nutshell

As the name implies, a DPF “filters” PM from the engine exhaust stream. A DPF consists of longitudinal, alternately plugged channels consisting of porous ceramic walls (see Figure 16). As exhaust gases enter the channels, the ceramic plugs at the end force the exhaust to pass through the porous ceramic channel walls making up the DPF. The solid particles contact the substrate, and get trapped in the inner wall of the channel and begin to build up a thin filtration layer of soot particles within the filter until the exhaust temperature gets high enough to burn off the combustible particles in a process known as regeneration.⁴⁷ The filters employing this type of filtration mechanism are also known as wall-flow filters. The soot layer is made up of loosely packed soot particles and acts as a very efficient filtration membrane. The incombustible component of the soot is made up of inorganic metal compounds such as oxides, hydroxides, sulfates among others that remain in the filter after regeneration as metal ash particles. The metals most often come from lubricating oil additives. Over time, the filter accumulates enough metal ash that it must be cleaned. However, with the use of the proper low-ash lube oil, this cleaning interval can exceed 250,000 miles in many new vehicles. There are also examples of particulate filters that utilize metal fiber mats or metal mesh structures.

DPFs can be coated with a catalyst or remain as a bare substrate. The filtration efficiency of both types is approximately the same, but the presence of a catalyst impacts the regeneration of the soot. The catalyzed filters regenerate the soot through oxidation facilitated by NO₂ produced by an upstream DOC or by the catalyst present on the filter. Uncatalyzed filters, or actively regenerated DPFs, rely on higher exhaust temperatures that are created through an active combustion process either within the engine cylinder or by injecting fuel over the DOC. By far, the majority of commercial DPFs include a catalyst on the filter substrate.

⁴⁷ Regeneration can happen naturally based on the operation of the engine, or may be assisted by heating the filter using fuel or electricity.

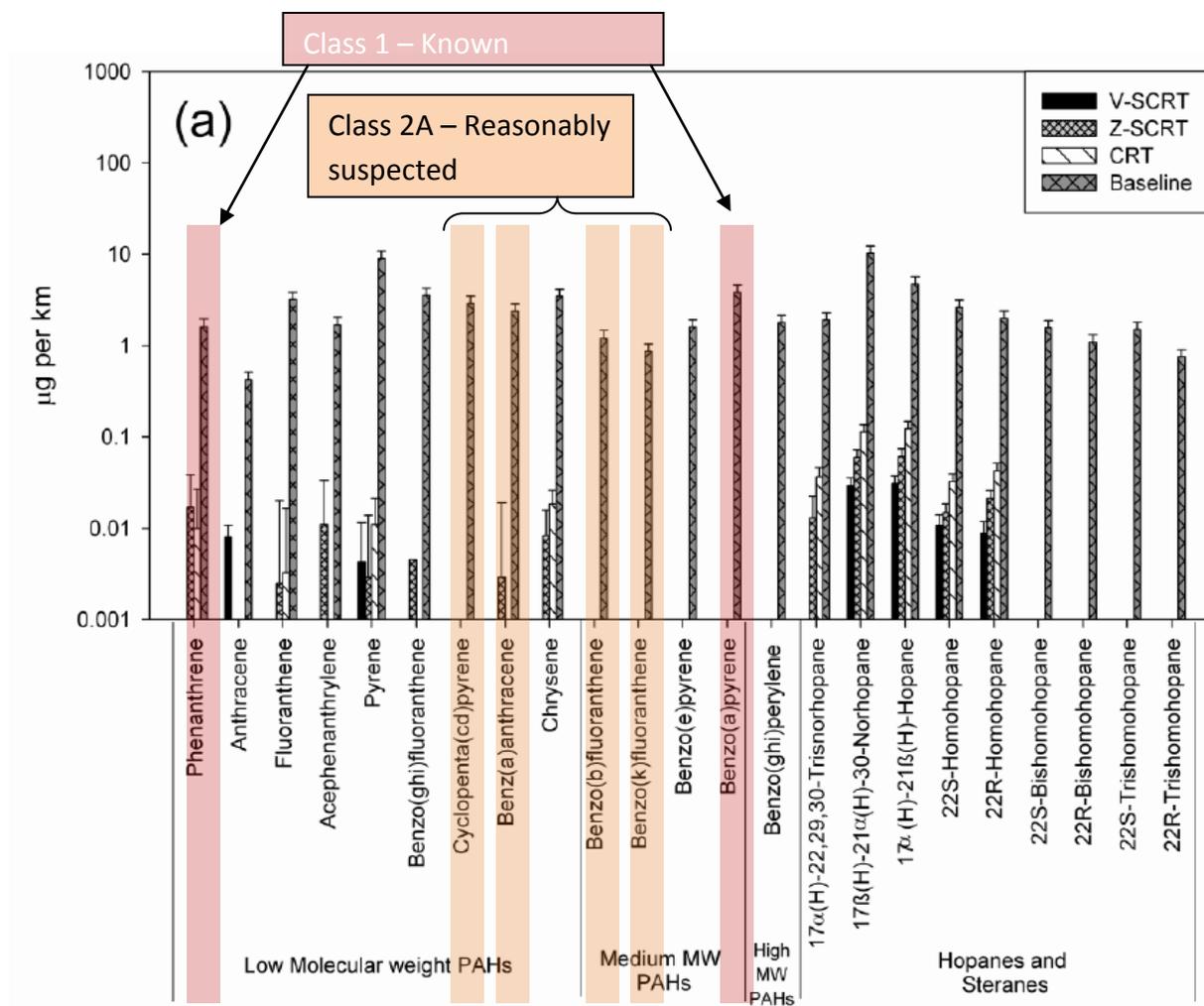


Figure 19. Reductions in PAH emissions from DPFs⁴⁸

By pairing a DPF with a diesel oxidation catalyst (DOC), DPF systems can also control the emission of semi-volatile gases that condense or oxidize to form secondary aerosols. It is worth noting that the DOC may also oxidize trace SO₂ gases to SO₃. The SO₃ can readily form sulfates with water vapor or metal oxides in the exhaust. The solid or liquid sulfate particles can be captured in the DPF substrate as part of the soluble fraction of the soot. Some gaseous sulfate particles may pass through the filter and condense as nucleation mode aerosol particles downstream of the DPF. The control of sulfate emissions is best affected by the reduction of fuel sulfur levels.

⁴⁸ See Footnote 20.

A modern DPF system routinely achieves PM mass reductions of 90-99% or more over a broad range of particle sizes and engine duty cycles, as shown previously in Figure 18. In addition to reducing particle mass, DPFs are highly efficient at controlling UFPs and catalyzed DPFs also destroy polycyclic aromatic hydrocarbons (see Figure 19) – several of which are known or reasonably suspected carcinogens.⁴⁹ For example, CARB found that several DPF retrofit devices achieved reductions in PAHs and nitro-PAHs of over 99%. More recently, the Health Effects Institute's (HEI's) Advanced Collaborative Emissions Study (ACES) Phase II study has found that DPFs used on 2007-compliant and 2010-compliant heavy-duty engines reduced diesel PM emissions by 99 percent relative to 2004-type technology without either a DOC or a DPF.⁵⁰ Most significant, as Figure 20 shows, the ACES study reported that using DPFs resulted in PM emissions that were 84-97 percent lower than the EPA 2010 standard on average (as well as lower emissions of NO_x, CO, and NMHC⁵¹) through the use of an emissions system that included a DOC, catalyzed DPF, and SCR catalysts. These unrecognized emission benefits translate directly into health benefits in excess of what EPA originally predicted, as will be discussed in Section 4 below. The ACES study also found that PAHs, dioxins and other toxics were reduced by over 90% from engine-out levels through the use of 2007-compliant emission control system that included a DOC+DPF.

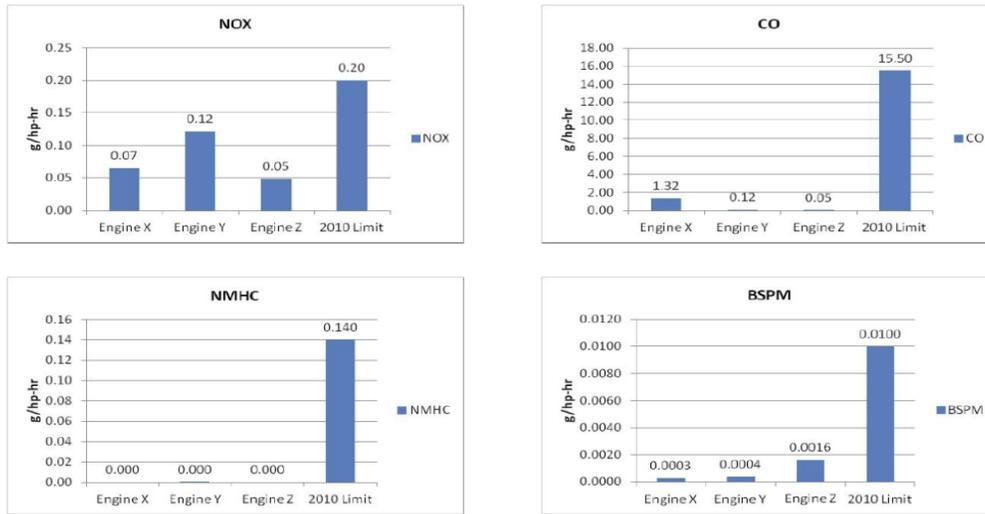
On a particle number basis, DPF systems can capture over 99.9% of UFPs, as shown in Figure 21 and easily meet the Euro VI heavy-duty diesel engine PN limit, as shown in Figure 22. Because the filter effectively removes particles regardless of size or composition, black carbon emissions are also nearly eliminated. As engine emissions increase over time due to component wear or failure, DPF systems continue to capture particulates at very high efficiencies and significantly mitigate these incremental emissions from aging vehicles.

⁴⁹ World Health Organization, Agents Classified by the IARC Monographs, Volumes 1–106, accessed January, 2013.

⁵⁰ Imad A. Khalek, Southwest Research Institute, "Update on Phase II" presentation to CRC MSAT Workshop, February 2013 and CRC Report: ACES Phase 1 (<http://www.crcao.com/reports/recentstudies2009/ACES%20Phase%201/ACES%20Phase1%20Final%20Report%2015JUN2009.pdf>)

⁵¹ Ibid.

Regulated Emissions (Composite Cold/Hot Start FTP)



Emissions from all three engines were substantially lower than the 2010 standard

Figure 20. Regulated emissions (Composite Cold/Hot Start FTP) from 2010 HD Engines⁵⁰

- ETC tailpipe emissions $\sim 4 \times 10^{11}$ /kWh
- DPF Efficiency > 99.9%
- WHTC tailpipe emissions $< 5 \times 10^{11}$ /kWh
- DPF Efficiency > 99.8%

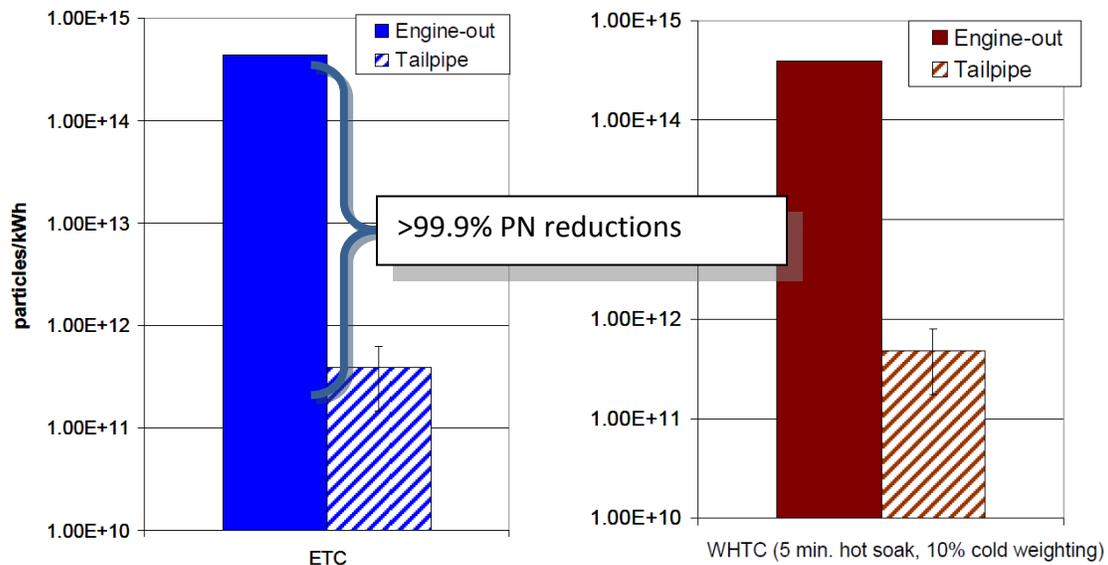


Figure 21. PN filtration efficiencies from DPFs⁵²

⁵² J. Anderson, "Particle Results from the AECC Programme and their Relationship to PMP" AECC, Euro VI Heavy-Duty Symposium, 2007, (http://www.aecc.eu/content/HD%20Seminar/10_UK%20Ricardo_Andersson.pdf)

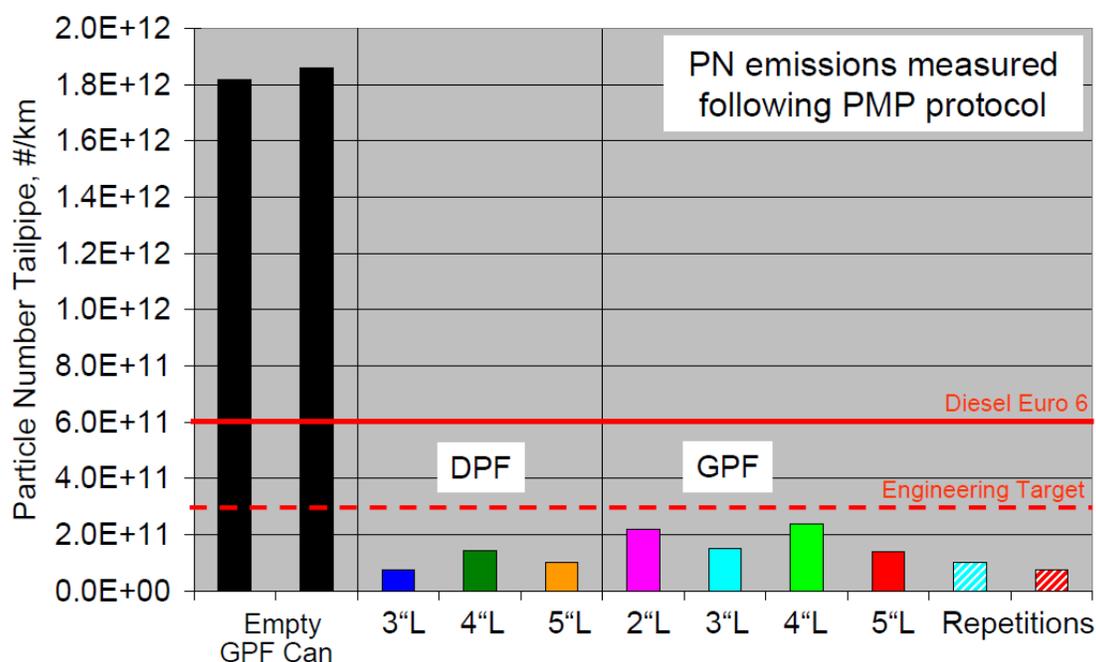


Figure 22. PN reductions of DPF and GPF systems on Passenger Cars⁵³

Emissions rates of UFPs from engines with and without DPFs

An important characteristic of “wall flow” particulate filters is that they retain very high filtration efficiency across a wide range of particle sizes and operating modes. As shown in Figure 23 and noted above, the average filtration efficiency can be well over 90% by mass for both UFPs and total PM. In practice, nucleation mode particle number reductions from a DPF may be limited due to the elimination of accumulation mode particles that serve to trap semi-volatile gases. In the absence of these larger particles, semi-volatile gases can condense into nucleation mode particles after the filter, contributing to UFP emissions. However, DPFs that are paired with diesel oxidation catalysts – as is common on many EPA 2007 and 2010-compliant trucks – can significantly reduce semi-volatile HC-based nucleation mode particles, thereby providing excellent PM mass, UFP and PN reductions.

Additional information about emissions rates comes from researchers in Europe, who characterized the PM emissions from a Stage IIIb nonroad engine that was equipped with a DOC and SCR but no DPF, and operated over multiple transient cold test cycles. The testing characterized the particle number concentration, size distribution and carbon characteristics of the particles. The DOC+SCR reduced the PN concentration by approximately 50% from the engine-out level. The researchers observed that the DOC and SCR impacted primarily the volatile organic portion of the PM, but it had little to no impact on the soot or non-volatile

⁵³ Koelman H., Dow AERIFY Particulate Filters for state-of-the-art direct-injection gasoline passenger cars, Emission Control Concepts Conference, November 2010.

organic particles that comprised approximately 34% of the total engine-out PM in the exhaust.⁵⁴ Another European study demonstrated that heavy-duty diesel engines certified to Euro V emissions and equipped with DOC+SCR exhaust controls would emit lower PN emissions than Euro III certified engines without a filter; however, a Euro III engine retrofitted with a DPF reduced PN by 2-3 orders of magnitude below the Euro V engine without a DPF.⁵⁵

It is also worth noting that current EPA and EU diesel emissions regulations require that crankcases no longer vent to the atmosphere. This has contributed to significant decreases in total vehicle emissions. If left open, the crankcase from a pre-2007 diesel engine can contribute

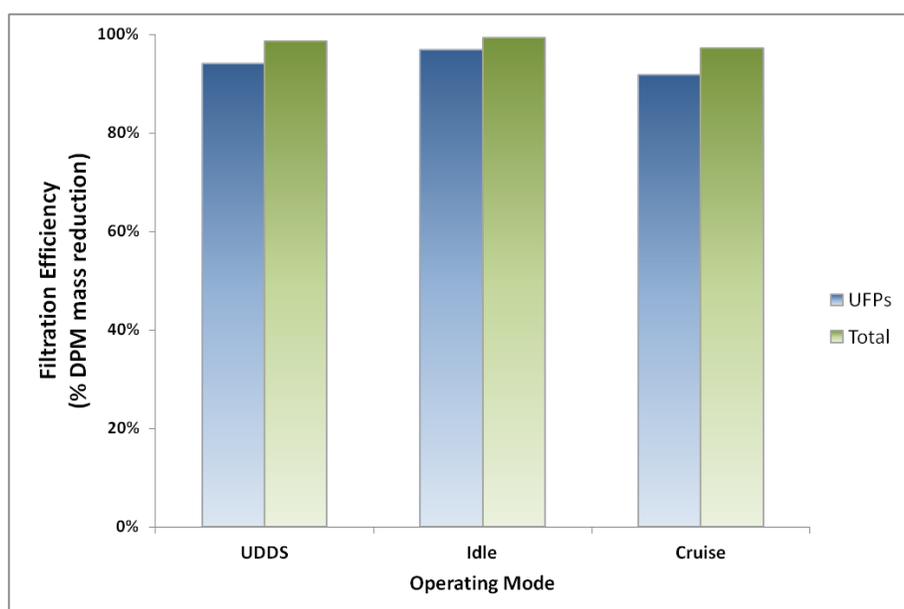


Figure 23. Average filtration efficiency of selected DPFs over particle size ranges and operating modes⁵⁶

25 percent of the total VOC and PM emissions from the vehicle. While crankcase emissions are not typically a significant source of direct UFPs, they can contribute to the formation of secondary aerosols when oxidized in the atmosphere. Therefore, diesel UFP control strategies should consider both the tailpipe emissions and crankcase emissions from pre-2007 U.S. engines and pre-Euro V engines in the E.U.

⁵⁴ Karjalainen, P., et al., "Reduction of Heavy-Duty Diesel Exhaust Particle Number and Mass at Low Exhaust Temperature Driving by the DOC and the SCR", *SAE Int. J. Fuels Lubr.* 5(3):2012, doi: 10.4271/2012-01-1664.

⁵⁵ Mayer, A. et al., "Nanoparticle Emissions of Euro IV and Euro V HDV Compared to Euro III with and without a DPF" SAE Technical Paper 2007-01-1112, 2007, doi:10.4271/2007-01-1112.

⁵⁶ Sioutas Sc., 2011. Based on mass emissions data for six DPF retrofits and a model year 1998 heavy duty diesel truck.

Estimated population of engines without DPFs

Approximately 2.6 million of the roughly 10.8 million heavy duty on-road highway diesel engines in the U.S. were built since 2007, when EPA’s most recent PM standards went into effect. These trucks typically employ DPFs to comply with strict PM emissions standards—and provide an added benefit of dramatic UFP reductions (see Section 4 below).

Unfortunately roughly 8.2 million trucks remain in the "legacy fleet," and few of these have DPFs. In fact, approximately 7.2 million of these trucks are equipped with diesel engines that emit PM at rates roughly 10-20 times those equipped with DPFs.⁵⁷ In addition, the U.S. fleet includes an estimated 4.1 million light-duty diesel vehicles – of which 3.1 million do not meet EPA current Tier 2 emissions, and millions more off-road diesel engines.⁵⁸

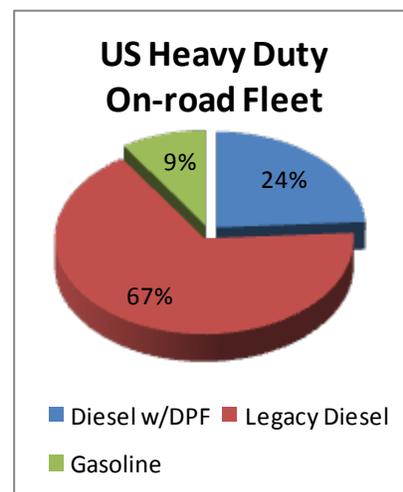


Figure 24. Composition of U.S. on-road heavy duty fleet by fuel type

Strategy: Diesel Particulate Filters (DPF)	
Applies to: New and existing diesel vehicles and stationary sources	
Benefits	Challenges
<ul style="list-style-type: none"> • 99%+ reductions in particle number • 90%+ reductions in particle mass • Comparable reductions in black carbon • Consistent performance over a wide range of operating conditions • Positive emission control, limit the impact of engine wear on PM emissions as engines age • Effective, proven technology 	<ul style="list-style-type: none"> • Not well-suited to older or poorly-functioning engines that have very high PM emissions and low average exhaust temperatures. • No ROI/cost savings for equipment owners

Gasoline Particulate Filters

Similar in construction and function to diesel particulate filters, gasoline particulate filters (GPF) can provide the same high efficiency filtration as DPFs. To date, the need for GPFs has been limited due to the generally low level of PM emissions from port fuel injected gasoline engines.

⁵⁷ Oak Ridge National Laboratory, National Transportation Energy Data Book, 31st ed., 2012. Figures based on calculations using data from Tables 5.1-5.3 and A.6.

⁵⁸ Oak Ridge National Laboratory, National Transportation Energy Data Book, 31st ed., 2012. Figures based on calculations using data from Tables 4.1-4.6, identifying non-DPF equipped vehicles as those sold between 1995 and 2008.

However, shifts in the gasoline engine market over the last several years toward turbocharging and GDI engine technology – primarily to improve fuel economy – have resulted in increased PM mass and particle number emissions. Future Euro 6 PN emissions requirements for direct-injected engines will require advanced PM reduction strategies such as advanced spray-guided injectors or GPFs on future GDI vehicles in Europe. The choice of PM reduction strategy will be governed by a number of factors including cost, durability and potential co-benefits such as improved engine efficiency or CO₂ reductions.

The technology in a nutshell

The design of the emerging GPF technology parallels the design of diesel particulate filters. These parallels are clear when comparing images of a typical GPF, as shown in Figure 25, and DPFs (Figure 18). Similarly, the emissions performance is comparable to DPFs, capable of providing up to 99.9% reductions in PM mass and number emissions.

There are some differences between the PM emitted from gasoline engines and the PM emitted from diesel vehicles. First, gasoline PM tends to be smaller in size and more volatile than diesel PM. Second, ash typically comprises a smaller portion of gasoline PM than diesel PM. Hence, the largest portion of gasoline PM is organic carbon, which includes the numerous PAH compounds present in the exhaust and are associated with carcinogenic risk.

GPFs can be coated with a three-way catalyst, effectively combining PM, NO_x, CO, and hydrocarbon control strategies into one device. Alternatively, GPFs can be separated from the three-way catalyst (TWC), affording some additional flexibility in the placement of the GPF and allowing a GPF to be an add-on control strategy. Integrated GPF+TWC devices are estimated to have some cost advantages over stand-alone GPFs, with integrated systems costing an estimated \$114 - \$156 for a typical 2 liter engine versus the separate costs of \$106 for a standalone GPF and \$56 for a TWC (net saving of up to \$48 per vehicle).⁵⁹

⁵⁹ Minjares, R., Sanchez, F., “Estimated Cost of Gasoline Particulate Filters”, ICCT Working Paper 2011-8, 2011.

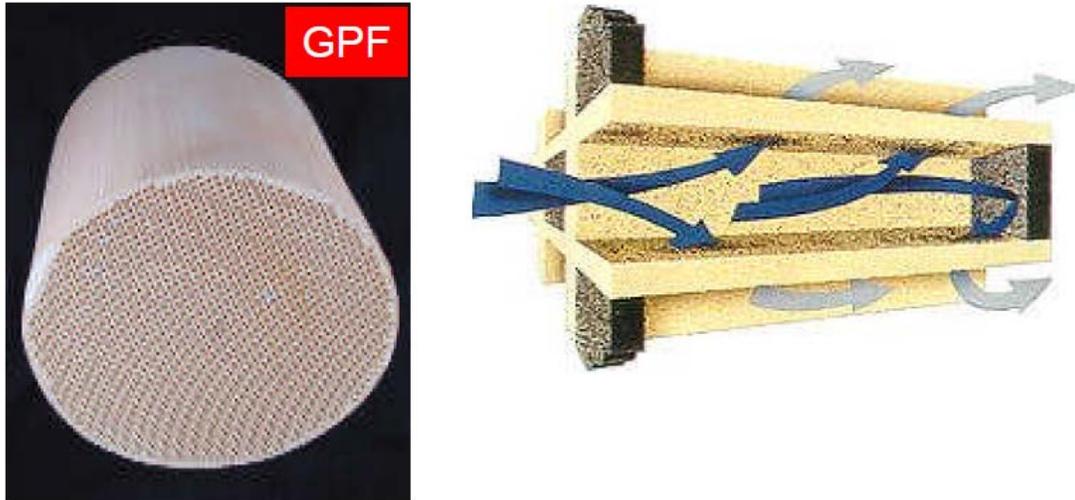


Figure 25. GPF construction

Section 3 – Regulatory Contexts and Market Opportunities

The U.S. and Europe have consistently used technology-forcing emissions standards for new vehicles and engines to reduce vehicle emissions over time. Figure 26 shows the evolution of U.S. and European emission standards for light-duty vehicles since the mid-1990s. Figure 27 shows the more recent standards in greater relief, and includes California’s upcoming LEV III standards (As will be discussed below, EPA’s Tier 3 standards would largely harmonize with the LEV III standards if they are finalized as proposed). Figure 28 summarizes the most recent emissions standards for heavy-duty vehicles.

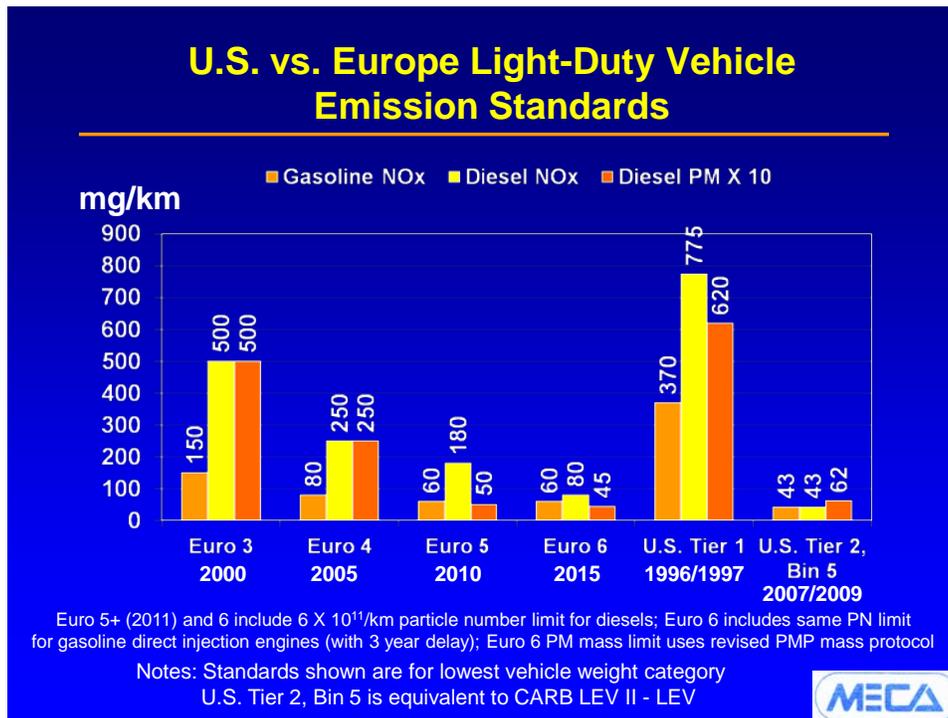


Figure 26. European emission standards for light-duty vehicles⁶⁰

⁶⁰ Manufacturers of Emissions Control Association (MECA), April 2013.

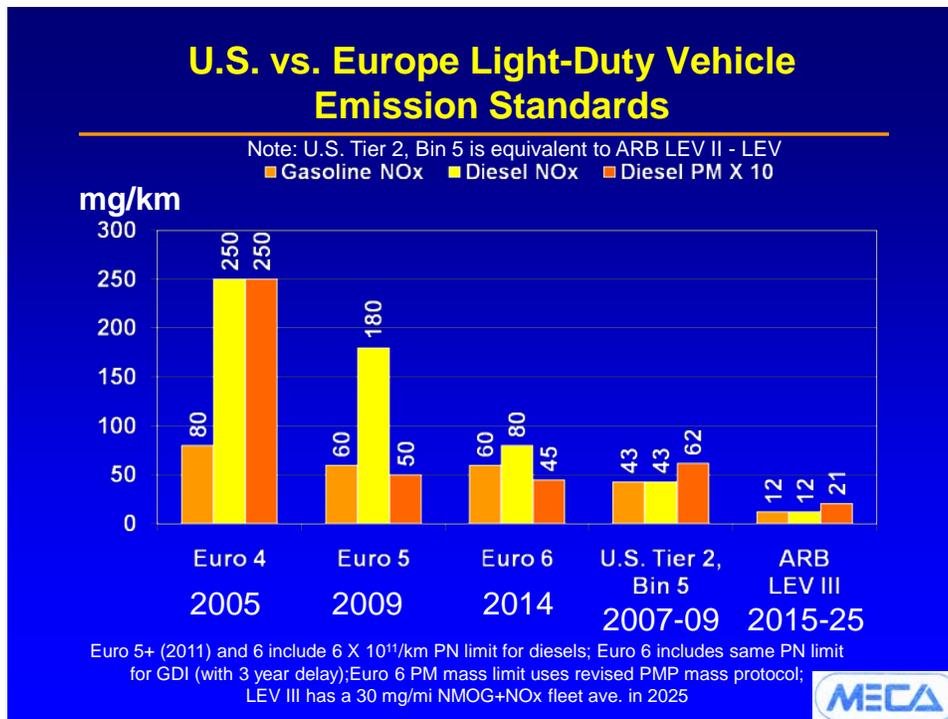


Figure 27. Comparison of European, US, and California light-duty emission standards since 2005.⁶¹

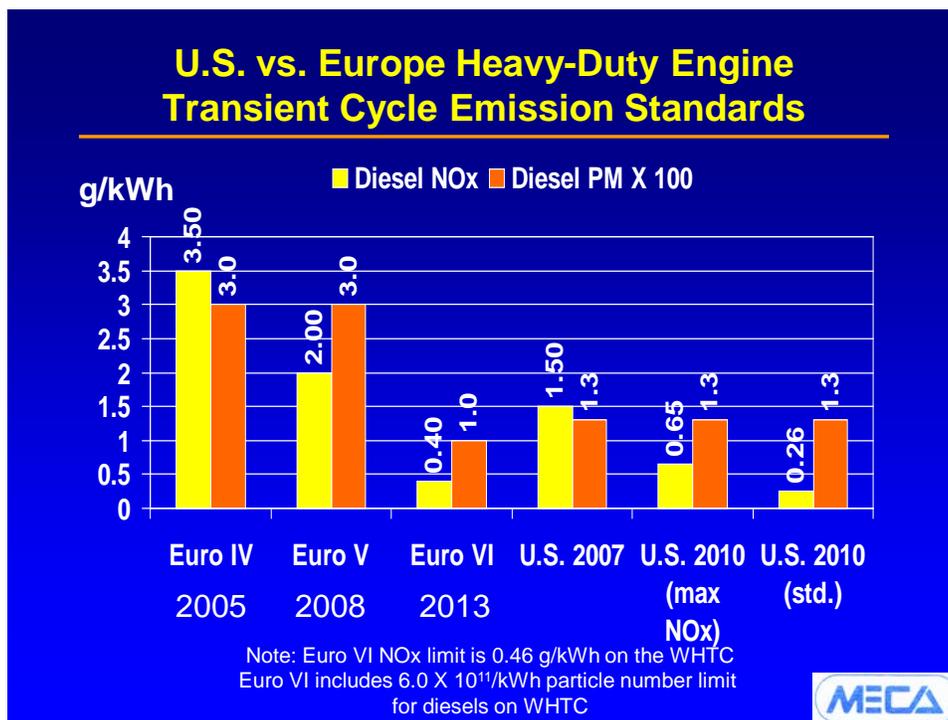


Figure 28. Comparison of European, US, and California heavy-duty emissions standards.⁶²

⁶¹ Manufacturers of Emissions Control Association (MECA), April 2013.

⁶² Ibid.

Europe's move towards implementing a PN limit

Regulators in Europe have taken the world's first steps towards directly controlling UFPs from vehicles. Their approach includes two key components: (1) establishing a protocol for measuring UFPs; and (2) adopting a Particle Number (PN) limit to control UFPs.

The Particle Measurement Program (PMP)

In 2001, addressing a growing concern about the impact of smaller particles on human health, Europe launched an extensive, multi-nation research initiative under the auspices of the United Nation's Economic Commission for Europe - Group of Experts on Pollution and Energy (ECE-GRPE or UN-GRPE) and under the direction of the Joint Research Center (JRC) of European Commission's Directorate General in Ispra, Italy.

Called the Particulate Measurement Programme (PMP), the PMP's objective was to develop and demonstrate new methods of measuring particle emissions, and with improved sensitivity at low particle emissions levels. These methods were to be suitable for use in a regulatory structure that would supplement or replace the then-existing particulate mass measurement protocols.⁶³

By 2006, the PMP had developed the world's first robust instrumentation and methodologies for counting of solid particles in vehicle exhaust emissions, and the JRC concluded that the particle number measurement procedure was "suitable for regulatory use."⁶⁴ More to the point, the PMP Working Group concluded:

"The PMP validation exercise has demonstrated that the particle number measurement method is a far more sensitive indicator of particle emissions performance than even the revised particulate mass measurement. Indeed particle number is sufficiently sensitive to indicate changes in the fill state of a DPF following regenerations. There is no evidence that the mass method is sensitive enough to indicate this."

The PMP process resulted in the creation of a methodology to measure solid particles, called the Solid Particle Number (SPN). The SPN provides the basis for certifying compliance with PN limits in the Euro 5b and Euro 6 light-duty vehicle standards.

For the reasons explained below, however, the EU measurement method under-counts the actual number UFPs and other particles.

⁶³ <http://www.unece.org/fileadmin/DAM/trans/doc/2006/wp29grpe/PMP-2006-17-01e.pdf>.

⁶⁴ Ibid.

Here's how this situation developed: A key concern for the PMP is to ensure repeatable results, which was critical because the methods would be used for certification testing across many different engines. To improve repeatability of the measurements, the PMP requires the removal of volatile particles by heating the exhaust, essentially removing the “wet” organic carbon fraction of the particulate. Much of this volatile particulate exists as nucleation mode particles/droplets (i.e., less than 50 nm in diameter) and contributes significantly to the total number of particles present in the exhaust stream. These “wet” particles are not counted using the PMP methods.

Similarly, the PMP does not measure solid particles that are less than 23 nm in diameter. Setting this threshold for solid particle size made sense at the time, because it was based on the testing limitations of the instruments available to test labs at the time the standard was developed.⁶⁵ But this, too, results in an undercounting of particles in the exhaust stream—and neglects a size range that often contains metal ash particles and semi-volatile particles.

Today, instrumentation exists that allows for the measurement of particles as small as 10 nm, which could be an important component of a U.S. PN limit and a future, revised European PMP methodology, as will be discussed in more detail in Section 4 below. The PMP approach demonstrated that although the measurement technique was not perfect and ignored the contribution of solid and volatile particles less than 23 nm, it offered a robust and repeatable measurement method that required the use of the best available control technology, such as DPFs that would capture ultrafine and volatile particles. As new measurement instruments and methods developed in the future, that would allow for quantification of sub-23 nm solid and volatile particles, those methods could be deployed in future revisions of the test procedure.

The European PN limit

All new direct injection vehicles in Europe must meet, or will soon have to meet, PN limits, in addition to PM mass standards. For diesel-fueled, compression-ignition light-duty vehicles, the PN limit went into effect in September 2011. As of that date, they had to meet a PN limit of 6×10^{11} /km on the NEDC test cycle. Starting in September 2014, all new gasoline-fueled, spark-ignition light-duty vehicles equipped with direct injection will also have to meet a PN limit in Europe, although the initial PN limit for GDI-equipped vehicles will be an order of magnitude higher, i.e., 6×10^{12} /km. In September 2017, GDI-equipped LDVs will have to meet the same 6×10^{11} /km as the diesel LDVs.

⁶⁵ Andersson J., Giechaskiel B., Muñoz-Bueno R., Sandback E. And Dilara P. “Particle Measurement Programme (PMP) Light-Duty Inter-Laboratory Correlation Exercise (ILCE_LD) Final Report”. 2007 EUR 22775 EN, p. 122.

Starting in January of this year, new heavy-duty vehicle engines in Europe also became subject to PN limits. New heavy-duty diesel engines now have to meet an 8×10^{11} /km PN limit on the World Harmonized Stationary Cycle and a 6×10^{11} /km PN limit on the World Harmonized Transient Cycle.

It is important to note that implementing these PN limits was the culmination of work that began years before, when the European Commission first started down the path towards PN limits by initiating the PMP Process, by releasing the Impact Assessment for Euro 5 regulations in 2005 and by adopting Regulation 715/2007, which anticipated the need for a PN limit that would follow the outcomes of the PMP process. Because they were still waiting for the outcomes of the PMP, neither the 2005 Assessment nor Regulation 715/2007 included a specific PN limit number. However, the Commission forecast the eventuality of a PN limit, when it stated:

“...As soon as the results of the UN/ECE Particulate Measurement Programme are going to be available, a PM number standard will be introduced. The standards would be set so that they broadly correlate with the petrol and diesel mass standards of the current proposal. . . The use of a particle number standard is a means to ensure that emissions of ultra fine particles are controlled and that developments in filter technology continue to focus on the removal of ultra fine particles.”

EPA's Tier 3 Standards

On March 29 of this year, EPA proposed its much-anticipated Tier 3 fuel and vehicle emission standards.⁶⁶

Assuming it is finalized as proposed, Tier 3 would create a national set of exhaust and evaporative emission standards for passenger cars and light-duty trucks in the 2017 model year, largely by harmonizing the agency's emission standards with California's already-finalized LEV III standards. Tier 3 will also reduce the sulfur levels in gasoline from today's refinery cap of 80 parts-per-million (ppm) and average of 30 ppm to an average of 10 ppm nationwide by 2017. However, the Tier 3 proposal does not tighten FTP PM emission limits beyond the 3 mg/mile level. As discussed below, LEV III reduces the PM emissions limits to 1 mg/mile in 2025.

In its report, “LEV III and Tier 3 Exhaust Emission Control Technologies for Light-Duty Gasoline Vehicles,”⁶⁷ the Manufacturers of Emissions Control Association (MECA) agreed with EPA's assessment that achieving the proposed Tier 3 exhaust and evaporative emission standards is both technically feasible and cost-effective. The report outlined the technologies that would

⁶⁶ <http://www.epa.gov/otaq/documents/tier3/420f13016a.pdf>.

⁶⁷ <http://www.meca.org/galleries/default-file/LEV%20III%20Tier%203%20white%20paper%20final.pdf>

likely be used to comply with Tier 3, including advanced three-way catalysts, exhaust hydrocarbon adsorber materials, high cell density substrates, emission system thermal management strategies, secondary air injection systems, advanced carbon canisters, advanced low fuel permeation materials, and air intake hydrocarbon adsorber materials.

Indeed, the report points out that more than two million SULEV and PZEV certified light-duty vehicles have already been sold in the U.S. since they were first introduced more than ten years ago. These vehicles already include variations of the technologies listed above, and form a technology base that will be further optimized to allow all light-duty gasoline vehicles to achieve the Tier 3 emission standards.

It is worth noting that reducing sulfur in gasoline enables vehicle emission control technologies to perform more efficiently. Thus, reducing gasoline fuel sulfur levels from the current 30 ppm national average to a 10 ppm average will ensure the use of the most cost-effective emission control strategies for future Tier 3 vehicles; will provide immediate reductions in emissions from the large, existing fleet of light-duty gasoline vehicles that travel America's highways; and will help these vehicles meet upcoming fuel economy and greenhouse gas emissions standards.

California LEV III Standards and the Advanced Clean Cars Program

In January 2012, California adopted its Advanced Clean Cars program. This program includes tighter criteria pollutant standards for light-duty vehicles as part of their LEV III regulations, greenhouse gas (GHG) standards for model years 2017-2025, and revised zero emission vehicle (ZEV) requirements. The LEV III requirements cover passenger cars and light-trucks up to 8,500 lbs GVWR, medium-duty passenger vehicles up to 10,000 lbs, and medium-duty trucks up to 14,000 lbs GVWR. The standards phase-in from 2015 to 2025 and require that a manufacturer's light-duty fleet average meets a combined NMOG + NO_x emissions limit of 30 mg/mile (or SULEV) by 2025 with a 150,000 mile durability requirement. The LEV III standards set tighter PM FTP emissions limits for both diesel and gasoline vehicles of 3 mg/mile starting in 2017 and 1 mg/mile starting in 2025.⁶⁸

The final LEV III package did not include the original proposal to offer automakers an optional compliance pathway that included a new solid particle number (SPN) standard that was in the 2010 proposal. This proposal had been intended to provide more flexibility to auto makers who might want to coordinate their vehicle certifications with Europe. Further, it was proposed in recognition that UFPs and high particle numbers had potential adverse health impacts. In addition, CARB staff noted that a SPN standard was actually a simpler, faster, and more precise

⁶⁸ For more information about the LEV III program, see the MECA white paper, "EV III and Tier 3 Exhaust Emission Control Technologies for Light-Duty Gasoline Vehicles," available online at <http://www.meca.org/galleries/default-file/LEV%20III%20Tier%203%20white%20paper%20final.pdf>.

measurement method than the gravimetric approach used to measure PM mass, as will be discussed in greater detail in Section 4 below.⁶⁹ As in Europe, the SPN limit was not designed to be technology-forcing. Rather it was anticipated that it would be set at the level that guarantees the use of a wall flow filter or alternate technology that might be used to meet the PM mass-based standard. The LEV III program includes a mid-term review of the 2025 1 mg/mile PM standard in 2015, which affords another opportunity to consider the adoption of a SPN limit to require control of UFP emissions.

Tier 3/LEV III Evaporative and Refueling Standards

The most stringent evaporative emission control regulations are enforced in the United States. Vehicles certified to California's PZEV low emission vehicle standards must demonstrate near-zero evaporative emissions from the fuel system at 0.054 g/test using canisters with advanced carbon adsorbers, low fuel permeation tanks and hoses within a vehicle's fuel system. Since the 2001 model year, U.S. vehicles have had to employ on-board refueling and vapor recovery (ORVR) systems to insure that refueling emissions do not exceed 0.2 g/gallon of fuel dispensed. Today, all new passenger vehicles manufactured in North America are equipped with ORVR systems. The function of the automobile evaporative emission control system is to block or capture the above sources of vaporized hydrocarbons and prevent their release into the atmosphere. This reduces the formation of secondary organic aerosol particles and volatile organic compounds (VOC) that contribute to the formation of ground level ozone and smog. The LEV III and Tier 3 standards will extend these requirements across the entire light-duty and medium-duty passenger vehicle fleet (<14,000 lbs GVWR) by 2022. The evaporative controls required by LEV III and Tier 3 represent the best available controls and should be considered by other regions of the world that are experiencing high ozone and secondary organic aerosol particulates caused by mobile sources. The EURO based regulations for evaporative emissions are much less stringent than U.S. or California regulations. It is worth noting that the U.S. has also established evaporative limits for non-automotive applications including motorcycles, small and large off-road spark-ignited engines, and marine engines. More information about technologies used to control evaporative emissions to meet future LEV III and Tier III standards may be found in MECA's evaporative emission control technology report.⁷⁰

⁶⁹ http://www.arb.ca.gov/msprog/levprog/leviii/meetings/051810/lev_iii_pm_and_bc_v2.pdf. The gravimetric approach is codified at 40 C.F.R. Part 1065. For SPN measurement, CARB proposed using the European PMP protocol for solid particles >23 nm.

⁷⁰ MECA, Evaporative Emission Control Technologies for Gasoline Powered Vehicles, December 2010, available at <http://www.meca.org/galleries/default-file/MECA%20Evap%20White%20Paper%20Final.pdf>.

State and federal funding for diesel retrofits

Federal Funding

Diesel retrofit programs have enjoyed strong, bi-partisan support in Congress and several states. In 2010, Congress reauthorized the Diesel Emissions Reduction Act (DERA) program in a lame duck session of Congress that was typified by partisan rancor. However, all sides came together to reauthorize the program that had funded almost \$500 million in diesel retrofits, idle reduction projects, emerging technology investments, and other clean diesel programs since it was first passed in 2005 as part of the Energy Policy Act in 2005.

Although the current DERA is authorized for \$100 million/year, it has never been close to fully funded. In the past four years, it has received \$60 million, \$50 million, \$30 million, and \$20 million. In the current White House budget for fiscal year 2014, DERA is slated to receive only \$6 million. A coalition of industry, labor, environmental, and public health organizations (including MECA) has called for Congress to maintain the current \$20 million appropriation.

As DERA funding for retrofits diminishes, another potential source of federal funds for cleaning up the existing fleet of diesel vehicles is through the Congestion Mitigation and Air Quality (CMAQ) program administered by the Department of Transportation. The CMAQ program provides over \$300 million per year for states to maintain the highway infrastructure. Some of this money may be directed by state transportation agencies towards retrofitting the diesel vehicles and equipment that are used on state infrastructure projects funded with CMAQ money.

State Retrofit Funds

Two states have led the way on providing state dollars for retrofit programs: California and New Jersey. Other states and cities, such as Rhode Island, New York City, Chicago, and others, have adopted clean construction mandates to clean-up construction equipment and other diesel vehicles that are used on state funded construction projects. In jurisdictions with clean construction mandates, a small portion of each construction grant may be required to help defray the cost of retrofitting vehicles that are used on these projects. This helps accelerate the clean-up of in-use construction equipment that will contribute to the PM inventory for years to come.

California

California has two programs that fund diesel retrofits: the Carl Moyer Memorial Air Quality Standards Attainment Program and Proposition 1B Goods Movement Emission Reduction Program.

The Carl Moyer program targets airborne particulate matter, ozone, carbon monoxide, nitrogen oxides, sulfur dioxide and lead that result from diesel fuel emissions by providing financial incentives to retrofit or replace older polluting vehicles that typically operate in non-attainment areas. The funds are applied to the incremental costs of replacing or retrofitting the engine with emission control devices, and the implementation happens through administration by the California Air Resources Board and the various Air Quality Management Districts in the state. The state funds are distributed to the districts each year when they select projects to fund based on the program guidelines. The program is offered to early emission reduction projects that are implemented ahead of California's increasingly stringent emissions standards. Carl Moyer Program is slated to receive \$141 million annually through 2015.

The Proposition 1B: Goods Movement Emission Reduction Program connects CARB with local air districts throughout the state to award grants and loans to reduce emissions from trucks, ships, and locomotives involved in goods movement. While most of the authorized \$19.925 billion in Proposition 1B bonds is dedicated to road infrastructure, roughly \$1 billion is dedicated to emissions reduction incentives.

From 2007 through the end of December 2012, CARB has received \$587 million and allocated a total of \$569 million to 9 local agencies for emission reduction projects. Another \$393 million will be disbursed for emission reduction projects at the local level when it is raised through bond sales.⁷¹ Proposition 1B is expected to pay out \$70 million to local agencies in the first half of 2013, with the majority of the funds dedicated to improving emissions from ships at berth.

In addition, Proposition 1B also authorized \$200 million for retrofitting and replacing school buses, through the Highway Safety, Traffic Reduction, Air Quality, and Port Security Bond Act of 2006.

New Jersey

Signed in 2005, New Jersey's Diesel Retrofit Law targets diesel PM emissions from publicly owned vehicles including school and commercial buses, solid waste vehicles, and publicly-owned on and off-road vehicles. In addition to requiring the installation of retrofit devices on these vehicles, it provides \$160 million over 10 years to fund the purchase costs and installation costs for these devices. The program is funded by the state's corporate business tax.

Texas

The Texas Emissions Reduction Plan (TERP) was established in 2001 to provide voluntary incentives for projects to reduce NO_x emissions in non-attainment areas across the state. Within TERP, the Emission Reduction Incentive Grant (ERIG) program has funded vehicle

⁷¹ California Air Resources Board. <http://www.arb.ca.gov/bonds/gmbond/gmbond.htm>.

replacement grants for on-road and off-road diesel vehicles and idle reduction infrastructure, however, no funding has gone towards vehicle retrofit projects. The ERIG program was most recently funded in the amount of \$40 million over the last two years to cover the incremental costs of vehicle replacements, engine repowers, and potentially retrofit of add-on devices that achieve at least a 25% reduction of NO_x emissions from the level at which the engine was certified. To date, no funds have gone towards retrofits, despite their relatively high cost effectiveness. The state sources their funds from various vehicle registration surcharges.

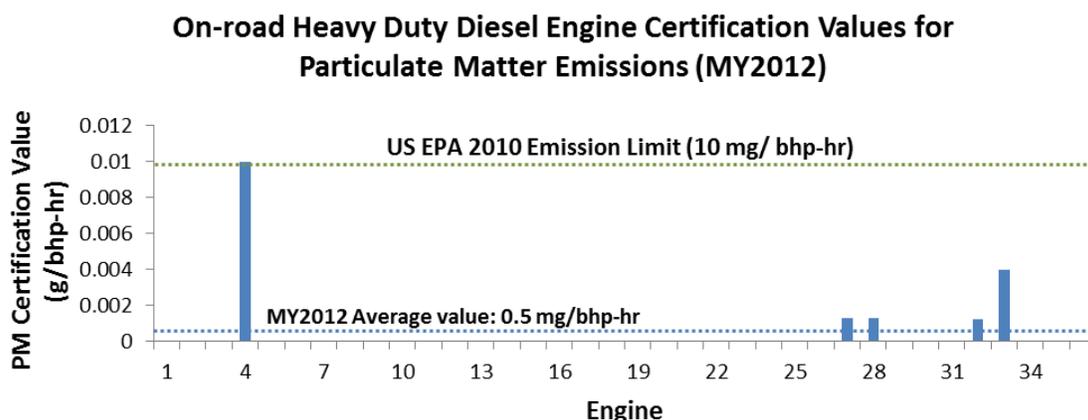
Section 4 - Making the Case for the Regulatory Control of UFPs

Using Particulate Filters creates Surplus PM Emission Reductions

Our analysis of EPA certification data and other information is clear: using wall-flow particulate filters of the type used by engine manufacturers to comply with EPA's 2010 highway diesel standards and the interim Tier 4 Nonroad Diesel standards has led to significant and unrecognized emissions benefits compared to the standards. This compliance margin is creating bonus emission reductions, which translate directly into surplus health benefits—over and above what EPA estimated when it finalized these standards in 2001 (Highway Diesel) and 2004 (Nonroad Diesel).

These unrecognized emission benefits stem from the fact that DPFs are extremely efficient at reducing particulate emissions. The efficiency of these filters can be seen by comparing PM emissions rates from EPA certification data against the relevant EPA standard.

As shown in Figure 29, the average certified PM emissions rate for model year 2012 on-road diesel engines equipped with DPF and SCR emissions controls is 0.5 mg/bhp-hr, 90% lower than the standard of 10 mg/bhp-hr. In fact, only eight of the forty engine certifications show any PM emissions above the mass detection threshold of the test procedure, hence 32 engines are certified at zero PM emissions. In plain English, it is clear that today's DPFs are delivering significant emission benefits above and beyond EPA's most stringent PM standards.



Engines shown at zero emissions are emitting at rates below the mass detection limits of the certification procedure

Note: Certification data for one manufacturer were removed because all of the data for the engines certified by this manufacturer appear to be outliers and do not represent the state of the art in DPF performance. The datum for engine #4 was not removed because this manufacturer has certified many other similar engine configurations, so certification data from this manufacturer cannot be considered, as a whole, to be non-representative of the state of the art. If engine #4 were to be excluded, the average PM certification level would drop from 0.5 mg to 0.2 mg.

Figure 29. PM emissions certification values for on-road heavy duty diesel engine

The certification data in Figure 29 are comparable to the result of the HEI Advanced Collaborative Emissions Study (ACES) Phase II, which found that 2010 heavy-duty engines tested emitted PM at a rate that was 84-97 percent lower than the EPA PM standard. Further, the ACES results showed that particle numbers of the 2010 engines were 41 percent lower than the 2007 engines—and 99 percent lower than the 2004 engines as shown in Figure 30, below.⁷²

Total (solid +volatile) Particle Number Emissions

•2010 FTP Particle Number was 41% & 99% below 2007 and 2004 technology engines, respectively

•DPF active regeneration frequency with 2007 technology engines was 1 to 3 times per 16-hour cycle
 •No DPF regeneration was encountered with the 2010 engine, even after 3 consecutive 16-hour cycles. This led to even more reduction (72%) in particle number for 2010 vs. 2007

The lack of active DPF regeneration and the presence of SCR led to a substantial reduction in particle number with 2010 vs. 2007 & 2004 technology engines

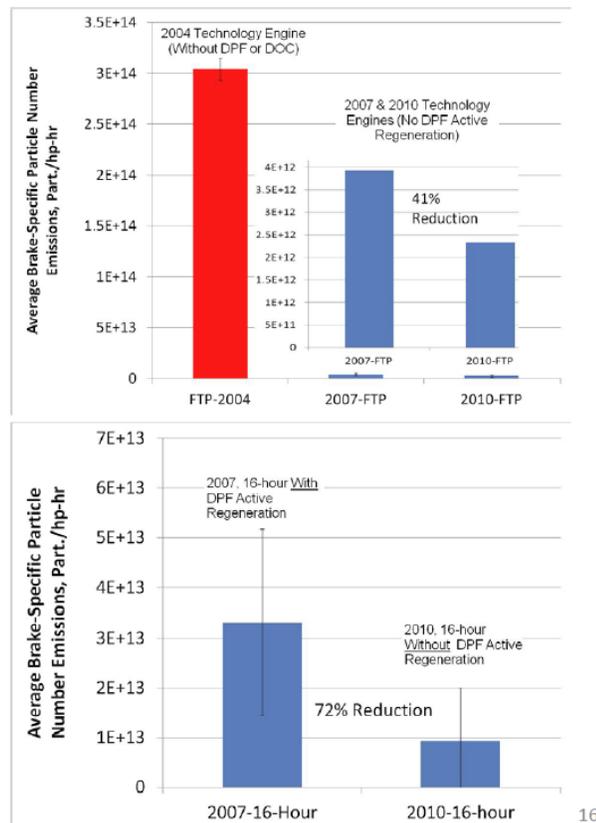


Figure 30. PN emissions from ACES Phase II test results for 2010-compliant engines

This phenomenon has been seen in nonroad engines as well. As shown in Figure 31, model year 2011 nonroad engines with DPFs have an average PM emissions rate of 3.7 mg/kw-hr, 82% lower than the interim Tier 4 (Tier 4i) standard of 20 mg/kw-hr for these engines.⁷³

In other words, just as in the highway diesel sector, the use of a DPF is consistently providing significant emission benefits in the nonroad diesel sector, which translates into surplus health

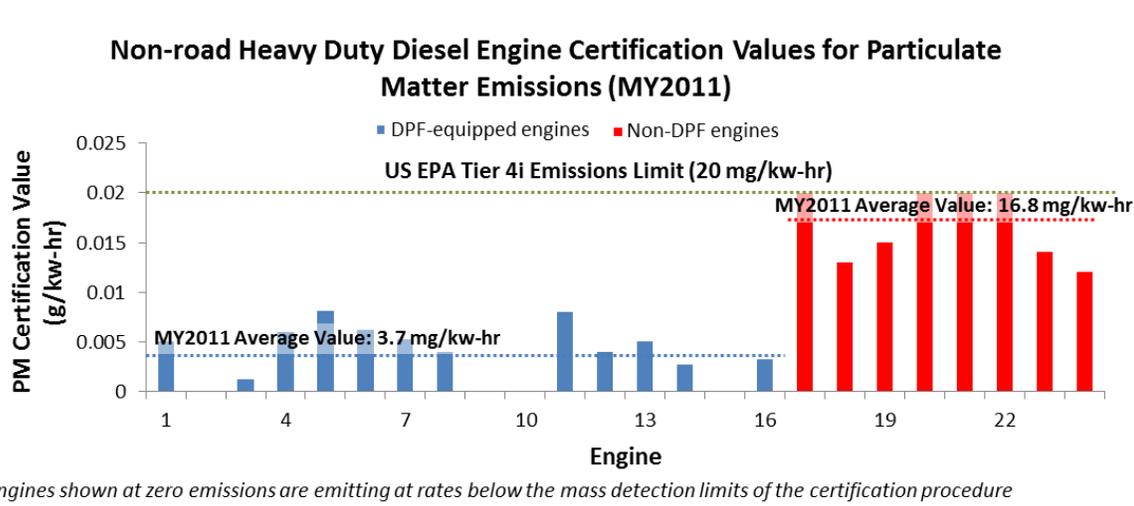
⁷² Khalek, I., Southwest Research Institute, “Update on Phase II” presentation to CRC MSAT Workshop, February 2013.

⁷³ Nonroad engine emissions data excludes marine and locomotive engines.

benefits when the technology is used. These bonus health benefits come at no extra cost beyond those that were originally used to justify the regulations.

However, it is important to note that this over-compliance—and the surplus environmental and health benefits that come with it—is not universal. Already, some nonroad engines have been certified to the Tier 4i standard without DPFs. These engines typically use engine control strategies, combined with diesel oxidation catalysts and SCR, to comply with Tier 4i. These engines consistently lack the surplus emission reductions of their DPF-equipped brethren, as shown in Figure 31 below.

Nonroad engines without DPFs that are certified to the same Tier 4i PM standard of 20 mg/kw-hr standard show emissions rates that average 16.8 mg/kw-hr—more than four times the rate of DPF-equipped engines. Significantly, this provides little margin of error for emissions degradation as the engine goes through the normal wear and tear of its useful life, including the rugged nonroad duty cycles, cold starts, excess idling, and imperfect maintenance that are common in the world of agricultural, construction, and other nonroad engine sectors.



Note: Certification data for one manufacturer were removed because all of the data for the engines certified by this manufacturer appear to be outliers and do not represent the state of the art in DPF performance

Figure 31. PM emissions certification values for nonroad heavy duty diesel engines certified to Tier 4i standard

It is important to note that engine manufacturers always demand a compliance or safety margin when certifying engines and vehicles to a full useful life standard. This compliance margin accounts for normal manufacturing and application variability, and insures that the engines will continue to emit below the limits set by the standards. Due to varying levels of manufacturers' acceptable risk and the different technologies, typical compliance margins may range from 20-50% below the allowable limits. These compliance margins will always insure a certain level of over-compliance relative to the standards. For the purpose of the following

analysis, we relied on the certification data summarized in Figures 29 and 31 to select reasonable values of additional emission reductions that are being demonstrated by DPF technologies deployed in the field.

Surplus emission reductions create quantifiable surplus environmental and health benefits

There are real-world benefits from using DPFs that go well beyond EPA's estimates for its 2010 highway diesel and Tier 4i nonroad diesel standards. As will be detailed below, we estimate that the per vehicle surplus emission reductions from on-road HD vehicles range from 1.2 kg for Class 3 vehicles to 11.6 kg of PM per Class 8 vehicle over the vehicle's useful life. Using EPA estimates of health benefits from reductions in directly emitted PM_{2.5} of \$320,000 to \$730,000 per ton,⁷⁴ the value of these surplus emission reductions are as much as \$9,400 per vehicle for those equipped with DPFs. Multiplying the per vehicle benefits by the heavy-duty vehicle population results in an estimated \$19.1-\$43.5 billion of extra environmental and health benefits associated with DPFs over the life of the fleet— benefits that can be added to EPA's original estimates of the health benefits of the 2007 and 2010 heavy-duty engine standards. These benefits—which represent fewer asthma emergencies, fewer cancers, fewer lost work days, and fewer premature deaths—will be lost if engine makers backslide away from their current DPF-based strategy and switch to a reliance on engine-based strategies for controlling PM.

In reaching the estimates in Table 1 and discussed in this section, we used vehicle activity, vehicle population, and EPA emissions data to estimate the extra PM benefits from on-road heavy-duty diesel engines that are achieved by using a DPF. This information is summarized in Table 3 below. Here, the estimated PM reductions assume a 9 mg/bhp-hr reduction from the use of DPFs relative to the 10 mg/bhp-hr standard, as shown in Figure 29. This is consistent with the 90% compliance margins discussed above.

⁷⁴ U.S. EPA Technical Support Document, Estimating the Benefit per Ton of Reducing PM_{2.5} Precursors from 17 Sectors, January 2013. Figures represent cost of PM_{2.5} emitted in 2016 with a 7% discount rate.

Table 1. On-road heavy duty fleet populations and activity information used for estimated surplus PM benefits

Class	GVWR (lbs)	Population ⁷⁵ (vehicles)	Useful Life ⁷⁶ (miles)	Conversion Factor (bhp-hr/mile)	Est. PM Reduction (mg/mile)	Value of PM reduction (per vehicle)	
						@\$320,000/ton	@\$730,000/ton
LHDDE	14,001-19,500	1,888,000	110,000	1.23	11.1	\$430	\$980
MHDDE	19,501-33,000	2,957,000	185,000	2.25	20.3	\$1,321	\$3,015
HHDE	33,001+	3,499,000	435,000	2.97	26.7	\$4,101	\$9,357
Total		8,344,000				\$19.1B	\$43.5B

Based on 9 mg/bhp-hr of surplus PM emission reductions due to DPF usage

The avoided health impacts are central to explaining the dollar value of the surplus emission reductions generated by DPFs. Using EPA estimates for mortality and morbidity,⁷⁷ we estimate that the full introduction of DPFs in the on-road heavy duty fleet will result in the avoidance of up to 780 premature deaths, nearly 50,000 lost work days, roughly 25,000 incidents of exacerbated asthma, and hundreds of hospital and ER visits annually.

Table 2. Estimated reduction in health impacts due to the bonus PM reductions delivered by the use of DPFs in on-road heavy duty vehicles

Health Impact	Annual Rate
Premature Deaths	349-780
Lost Work Days	48,965
Incidents of Asthma Exacerbation	24,897
Hospital Admissions	207
Respiratory-related ER Visits	199

The nonroad sector also provides additional emission reductions that can be quantified in terms of both surplus environmental and health benefits. Given the diversity of the nonroad sector – the NON-ROAD 2008a model lists 89 distinct equipment groups – seven of the largest groups by total fleet activity were selected as illustrative examples. These comprise 50 percent of the estimated population of nonroad diesel engines in the U.S. EPA NONROAD2008 emissions model.

⁷⁵ PC and LT data source: National Transportation Energy Data Book, ed. 31., 2012.

MDV-HHDDE data source: Polk Quarterly Commercial Vehicle Report for 2011.

⁷⁶ Per EPA required Useful Life for emissions controls as given in federal emissions standards.

⁷⁷ U.S. EPA Technical Support Document, Estimating the Benefit per Ton of Reducing PM_{2.5} Precursors from 17 Sectors, January 2013. Table 35.

We have analyzed these groups by average rated load, lifetime activity, and other factors, and have been able to estimate the surplus PM reductions that would accompany the use of DPFs, as well as the dollar value of the environmental and health benefits that would accrue from those surplus PM reductions. Across these seven nonroad equipment groups, the value of the surplus PM reductions is as much as \$10,100 per engine. Over the entire population of equipment in these groups, the total value of the surplus emissions benefits of DPFs is estimated at \$5.6 - \$12.9 billion over the life of these engines. To calculate these amounts, we used a similar methodology as for the highway benefits calculation—i.e., multiplying the per vehicle benefits by the vehicle population to estimate the total benefits from full introduction of DPFs in the nonroad fleet. The costs of a catalyzed diesel particulate filter (CDPF) for a nonroad vehicle have been estimated by EPA as part of their Regulatory Impact Analysis (RIA) Control of Emissions from Nonroad Diesel Engines that was released with the Tier 4 nonroad rule.⁷⁸ The agency estimated the system costs for CDPFs to range from \$493 for a 76 hp engine to \$2,031 for a 503 hp engine. The costs represent the costs to the buyer and include the total direct costs and warranty costs in 2002 dollars. Adjusted for inflation, these costs are \$597 and \$2,458 in 2010 dollars.

Table 3 summarizes the engine, horsepower, and activity used to estimate the surplus emissions benefits expected from these seven equipment groups on a per engine basis. Table 4 summarizes our estimates of the underlying annual reductions in mortality and morbidity associated with these emissions benefits. The estimated PM reductions are based on the observed average difference in PM certification values of 13 mg/kw-hr shown in Figure 31.

⁷⁸ U.S. EPA Final Regulatory Impact Analysis Control of Emissions from Nonroad Diesel Engines, May 2004. Table 6.2-13

Table 3. Nonroad fleet populations and activity information used for estimated PM benefits

Equipment Group	Population	Avg Rated Load	Avg Lifetime Activity	Estimated PM Reductions	Value of PM reductions (per engine)	
		HP	kw-hr/engine	mg/kw-hr	@\$270,000/ton	@\$620,000/ton
Agricultural Tractors	1,429,898	132	507,434	13	\$1,963	\$4,508
Crawler Tractor/Dozers	96,481	260	1,139,122	13	\$4,407	\$10,121
Rubber Tire Loaders	138,912	241	1,048,294	13	\$4,056	\$9,314
Excavators	125,539	171	654,132	13	\$2,531	\$5,812
Tractors/Loaders/Backhoes	334,926	93	323,712	13	\$1,252	\$2,876
Skid Steer Loaders	521,210	55	171,650	13	\$664	\$1,525
Combines	288,475	190	677,319	13	\$2,621	\$6,018
Total	2,935,441				\$5.64B	\$12.9B

Table 4. Estimated annual reduction in health impacts due to the use DPFs in seven nonroad sectors

Health Impact	Annual Rate
Premature Deaths	86-196
Lost Work Days	12,238
Incidents of Asthma Exacerbation	2,692
Hospital Admissions	53
Respiratory-related ER Visits	51

The surplus emission reductions of the Highway Diesel and Nonroad Diesel Rules are at risk

As manufacturers of nonroad engines begin to certify engines to the final Tier 4 standard (Tier 4f), it is expected that SCR will be the preferred method of NO_x control. However, it is unclear whether manufacturers will continue to rely on DPFs as their preferred method of PM control.

Some engine manufacturers have indicated that using SCR will enable them to meet the Tier 4f PM standards without the use of a DPF. Already, seven nonroad engines in the 2011 certification data set do not use a DPF to meet Tier 4i standards. Among this group of engines,

the average PM certification value is 16.8 mg/kw-hr, 13.1 mg/kw-hr higher than the average certification value of a DPF-equipped engine of 3.7 mg/kw-hr.

Hence, it is reasonable to assume that engines using SCR - but foregoing DPFs - to comply with the Tier 4 final standards will likely emit PM at rates very close to the 20 mg/kw-hr certification limit and significantly higher than DPF-equipped engines.

In other words, using current emissions certification data as a guide, engines that do not use DPFs to meet the PM standard would be likely to emit 4-5 times as much PM in their actual use as engines that use DPFs. Both engines would meet the PM standard in the controlled tests of the certification process, but the DPF-equipped engines would provide much cleaner operation—and improved environmental and health benefits—in the real world of actual use.

As certification data becomes available for the final Tier 4 standard, it is expected that some engines equipped with DPFs under Tier 4i will be certified without DPFs. If this happens, this will provide a true apples-to-apples comparison of the PM emissions benefits of engines with and without DPFs.

Using Gasoline PM filters will create surplus emissions and health benefits under Tier 3

Based on the current market projections and available technology options, it is clear that GDI-equipped engines are likely to be the dominant strategy that will be used to meet the matrix of LEV III, Tier 3, and the EPA/NHTSA greenhouse gas and fuel economy standards. Although a number of technology options exist to meet the future LEV III and Tier 3 PM emission standards, for certain classes of vehicles, GPFs may represent the most cost effective PM reduction strategy, in terms of emission reductions and likely performance over a vehicle's useful life, for reasons that have been discussed in Section 2 and above. Indeed, it may be reasonable to assume a similar level of high compliance margin and additional emission reductions, which have been seen with the deployment of DPFs in the highway and nonroad diesel sectors, will repeat in the light duty vehicle sector through the potential use of GPFs on passenger cars.

Calculating the likely environmental and health benefits from a GPF approach is difficult, because PM certification data from light duty vehicles is available only for the small number of diesel-fueled vehicles. (This prevents us from directly calculating the current average PM emissions from the full light duty fleet, as was done for highway diesel engines above.)

However, CARB has reported PM emissions data from tests of GDI engines conducted by both CARB and U.S. EPA. These tests indicate that GDI engines currently emit PM at rates near the 3

mg/mi LEV III standard⁷⁹. Based on these data, we can assume that a typical contemporary GDI engine emits PM at a rate of 3.8 mg/mi.

For the purposes of calculating emissions benefits, it is reasonable to assume that GPFs will provide the same 90% additional reduction in PM emissions that has been the norm with DPFs in the highway sector. This, in turn, would produce bonus PM emission reductions of 2.6 mg/mi⁸⁰ for light duty cars and trucks. For Class 2b and medium duty vehicles, there is insufficient data available to estimate PM emissions from GDI engines in these vehicle classes. Thus, we have assumed the same 90 percent compliance margin for these vehicles that we have seen from the other vehicles.

As seen in Table 5 below, we calculate that the total value of the potential surplus emissions benefits of GPFs in the light and medium duty fleets is estimated at \$35.1 - \$80.0 billion beyond the benefits attributed to the Tier 3 standard. Further, as shown Table 6, these surplus benefits are estimated to reduce premature deaths by nearly 900 per year and save 56,000 lost work days.

Given that EPA's Tier 3 proposal estimates annual benefits of \$8 - 23 billion in 2030 and between 820 and 2,400 annual avoided premature deaths for the currently-proposed program, this presents a significant environmental and health opportunity.

⁷⁹ California Air Resources Board, LEV III Technical Support Document – Appendix P, 2011. CARB reported an average PM emissions rate for nine GDI engines of 3.9 mg/mi and EPA reported an average PM emissions for two GDI engines of 3.3 g/mi. In aggregate, the average PM emissions rate is 3.8 g/mi.

⁸⁰ Calculated as 3.8 mg/mi * (1-0.9) = 0.4 mg/mi emissions rate, producing a 2.6 mg/mi reduction from the 3 mg/mi standard.

Table 5. On-road light and medium duty fleet populations and activity information used for estimated PM benefits

Class	GVWR	Population ⁸¹	Useful Life ⁸²	Annual VMT	Est. PM Reductions	Value of PM reductions (per vehicle)	
	lbs	units	miles	miles	mg/mile	@\$320,000 / ton	@730,000 / ton
Passenger Cars	-	130,892,000	150,000	10,650	2.6	\$138	\$314
Light Trucks	≤8,500	91,822,394	150,000	15,474	2.6	\$138	\$314
Class 2b Trucks⁸³	8,501-10,000	7,729,606	150,000	15,474	7.2	\$381	\$869
MDVs	10,000 - 14,000	3,127,000	150,000	13,476	9.0	\$476	\$1,086
Total		233,571,000				\$35.1B	\$80.0B

Table 6. Estimated reduction in health impacts due to the use GPFs in the light-duty on-road fleet

Health Impact	Annual Rate
Premature Deaths	396-887
Lost Work Days	55,665
Incidents of Asthma Exacerbation	28,304
Hospital Admissions	236
Respiratory-related ER Visits	226

⁸¹ PC and LT data source: National Transportation Energy Data Book, ed. 31., 2012.

MDV-HHDDE data source: Polk Quarterly Commercial Vehicle Report for 2011.

⁸² Per EPA required Useful Life for emissions controls as given in federal emissions standards.

⁸³ Data for Class 2b trucks are scarce. Figures presented here are based on vehicle population distributions given in Oak Ridge National Laboratories study of Class 2b trucks. ORNL/TM-2002/49.

Adopting a PN limit in the U.S. would guarantee surplus environmental and health benefits

In setting the first-ever PN limits, EU regulators set the standards at levels that would guarantee the use of PM filters or equivalent control strategies—and at a level that would prevent backsliding on PN emissions if vehicle manufacturers elected to use emission control strategies other than particulate filters.

Figure 32 presents test data from the EU PMP inter-laboratory testing effort for light duty vehicles, and highlights the fact that particulate filters are highly efficient at controlling both particulate mass and particulate number emissions.

Further, this data confirm

what has been shown in the EPA certification data presented above, i.e., that PM filters provide reductions well beyond what is required for compliance with existing U.S. and EU standards for PM mass.

As seen in these tests, engines equipped with particulate filters produced PN emissions of less than 1×10^{11} particles/km, significantly lower than the European PN limit of 6×10^{11} particles/km. At the same time, PM mass emissions from these vehicles ranged from approximately 0.2-0.9 mg/km, also well below the PM standard of 4.5 mg/km for Euro 5b and Euro 6b. The simultaneous reduction in PM and PN is due to the basic design of the wall-flow

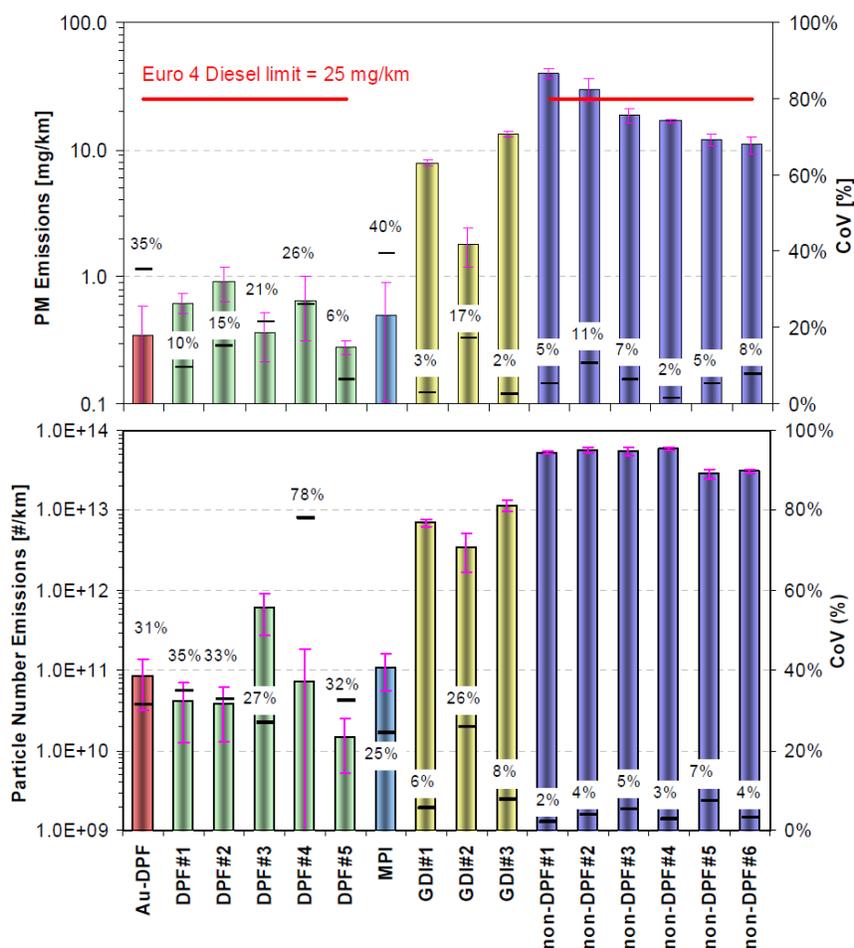


Figure 32. PM Mass and PN Emissions from various engine/exhaust emission control technologies⁸⁴

⁸⁴ Andersson et al., Particle Measurement Programme (PMP) Light-duty Inter-laboratory Correlation Exercise (ILCE_LD) Final Report, 2007 EUR 22775 EN.

particulate filter and its ability to provide PM reductions almost independent of particle size. In essence, the high level of PN control from a particulate filter is achieved through a similarly high level of PM mass reductions. Hence, establishing a PN standard based on the performance of particulate filters is expected to result in PM reductions and corresponding surplus health benefits as those currently provided by DPFs.

U.S. regulators have struggled with the efficacy of setting particle number standards because the National Ambient Air Quality Standards (NAAQS) for particulate matter are derived from ambient air monitoring that is based on mass concentration. Furthermore, the epidemiological and toxicological studies that are the basis for estimating the health effects also rely on data that is derived from concentration or mass-based exposure levels. Diesel particles, and specifically ultrafine PM, have very little mass although they contribute significantly to the total number of particles in the exhaust.

It is relatively easy to measure the size and number of particles in the exhaust even at very low mass concentrations. Converting the particle number to a particle mass may provide an elegant means to quantify the mass at very low levels because one is not relying on extremely sensitive analytical techniques as may be required to measure very low mass levels of soot on a collection filter. However, the challenge has been to establish agreement on what the density of soot is, given the complex make-up of soot particles and the differences in compositions across engine and fuel types.

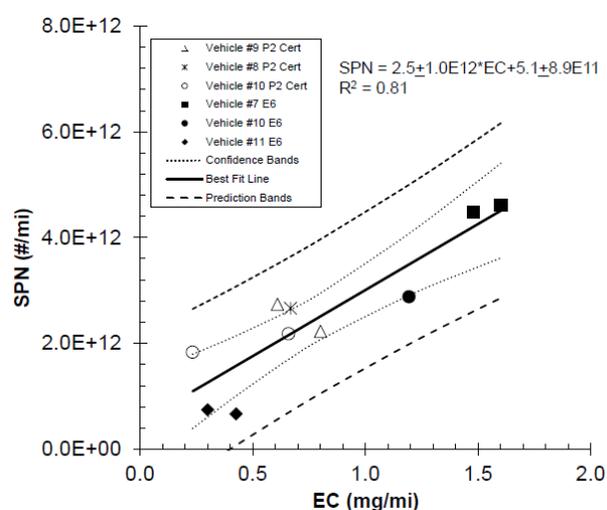


Figure 33. Correlation between Solid Particle Number and Particle Mass⁸⁵

Several researchers have investigated the correlation between PM mass and particle number. As summarized by CARB staff,⁸⁶ these investigations are in reasonable agreement and indicate a correlation between solid particle number (SPN) and elemental carbon (EC) mass. Figure 33 depicts this correlation and provides an estimate of 2.5×10^{12} particles per mg EC. At 1 mg/mile, the 90% confidence interval is 1.5 to 4.5×10^{12} per mg EC with an average value of 3.0×10^{12} particles per mg EC. This correlation suggests that PN limits can be equated to PM mass emission limits. This conclusion is corroborated by the findings of Maricq and Xu, who concluded that the “level of accuracy, the possibility of second by second transient PM mass

⁸⁵ California Air Resources Board, LEV III Technical Support Document – Appendix P, 2011.

⁸⁶ Ibid

measurement, and freedom from hydrocarbon artifacts make the calculation of PM mass from particle size distribution measurements an attractive alternative to filter based measurements.”⁸⁷

This suggests that PN limits can be used to guarantee the health benefits of using DPFs to meet PM mass emission standards. To illustrate this concept, the Euro 6 PN limit of 6×10^{11} particles/km was converted to an equivalent PM mass of 0.54 mg/mile using the correlation above.⁸⁸

It is worth noting that these correlations are approximate and are only intended to help illustrate the potential PM benefits that may be associated with a PN standard equivalent to the EU standard. Notwithstanding the foregoing, the potential benefits appear to be significant and bear further consideration by EPA, CARB, and others.

The PN limit imposes an effective PM mass limit that is 93% below the PM mass-based standard, compared to the 7.3 mg/mile PM mass-based standard for Euro 5b. Table 7 extends this illustration to several EU and U.S. on-road emissions standards. First, it shows the estimated PM mass emission reductions that should result from European PN limits in the light-duty and heavy-duty sectors. Then, since the U.S. does not currently have a PN limit, Table 7 also provides estimates of the PM benefits that would result if a PN limit was adopted for the U.S. light-duty and heavy-duty vehicle sectors.

The U.S. heavy duty on-road sector currently uses DPFs for compliance with PM mass emission limits and, as certification data show, currently demonstrates an average PM emissions rate of 0.5 mg/bhp-hr (0.62 to 1.49 mg/mi). This is similar to the 0.5 mg/mile emission rate estimated using the PN correlation described above and shown in Figure 33. Hence, Table 7 indicates the approximate PM benefits that would be lost if this sector moved away from DPFs and complied solely with the upper limit of the PM mass standard (10 mg/bhp-hr).

⁸⁷ Maricq, M. and Xu, N., The effective density and fractal dimension of soot particles from premixed flames and motor vehicle exhaust, *Journal of Aerosol Science*, 2004, at 1272.

⁸⁸ Assumes the SPN is primarily elemental carbon which typically comprises 60% of total PM mass. Hence, the total PM mass is the SPN mass divided by 0.6.

Table 7. Estimated PM mass emission reductions from a PN limit for various emissions standards

Emission Standard	Basis	PM Standard	PN Standard*	Effective PM limit***	PM Reduced	PM Reduced
		mg/basis	SPN/basis	mg/basis	mg/basis	% of standard
Euro 5b LD CI	mile	7.3	9.7E+11	0.54	6.8	93%
Euro VI HD	bhp-hr	7.5	4.5E+11	0.25	7.2	97%
Euro 6b LD	mile	7.3	9.7E+11	0.54	6.8	93%
US 2010 HD	hp-hr	10.0	4.5E+11	0.25	9.8	98%
US Tier 3 LD(est)	mile	3.0	9.7E+11	0.54	2.5	82%
ARB LEV III LD	mile	3.0	9.7E+11	0.54	2.5	82%
ARB LEV III MD1	mile	8.0	9.7E+11	0.54	7.5	93%
ARB LEV III MD2	mile	10.0	9.7E+11	0.54	9.5	95%
US Tier 4 Final (75-750 HP)	kw-hr	20.0	6.0E+11**	0.33	19.7	98%

*Hypothetical PN standards for U.S. sectors are assumed to be equal to the PN standard for the corresponding EU sector (e.g. EU light duty PN limit = U.S. light duty PN limit, EU heavy duty PN limit = U.S. heavy duty PN limit).

**Assumes PN standard is equivalent to EU PN standard for HD on-road trucks (6×10^{11} SPN/kW-hr)

***Assumes SPN is primarily elemental carbon which typically comprises 60% of total PM mass. Hence, the total PM mass is the correlated SPN mass divided by 60%.

In summary, all of this is significant when considering the shift towards using SCR and engine control strategies—rather than SCR and DPFs—to meet upcoming EPA standards. Should this trend continue into on-road HD engines and GDI-equipped light-duty vehicles, the potential surplus emission reductions and health benefits that would come from using PM filters in both sectors would be lost.

Particle Number Standards as a Complement to Mass Standards

The adoption of a PN limit as a *complement* to mass-based PM standards would add a simple, fast, and accurate measurement to the current regulatory regime. (It is worth noting that the adoption of a PN limit is not recommended as a *replacement* for mass-based PM standards.⁸⁹). However, as we approach lower and lower PM mass levels, developing better measurement

⁸⁹ It is also worth noting the recent study by the Health Effects Institute, Understanding the Health Effects of Ambient Ultrafine Particles, January 2013. HEI concluded that the current evidence does not support a conclusion that “exposure to UFPs alone can account...for the adverse effects...of PM_{2.5}.” HEI raised a number of important research questions that should be considered. Nevertheless, the existence of these open questions does not negate the utility of using a PN limit as a *complement* to the mass-based PM standards.

methods will increasingly become more important. Adding a PN limit to complement mass-based PM standards would help ensure the environmental and health benefits of these standards.

Several researchers have noted that the ever decreasing PM mass emissions standards are beginning to brush up against the limits of gravimetric measurement techniques.^{90,91,92,93} Swanson et al. noted that measuring PM mass levels at 10 percent of the EPA 2010 heavy duty standard introduces uncertainties of 5-70 percent in a gravimetric measurement. Further, subtle influences such as electrostatic charges and filter erosion can contribute to errors that can be ten times the expected uncertainty levels.

New measurement methods can reduce or eliminate this uncertainty. A number of new measurement methods have been proposed, based on particle size and number measurements. These particle size based measurements, referred to by Liu et al. as Integrated Particle Size Distribution (IPSD), show good agreement with gravimetric methods and have two additional advantages. First, the IPSD method has a lower threshold of detection for mass, meaning that this technique can resolve mass emissions for particulate matter that would typically be reported as “zero” by gravimetric methods. This enables a better accounting of PM emissions inventories from ultra-low emission engines. Second, the basis of the technique involves measuring the size and number of particles, which may be a more atmospherically relevant means of evaluating the emissions of these very small particles.⁹⁴ The challenge with particle size and number measurement methods is that they must be correlated back to gravimetric methods to provide mass emissions per current PM standards. However, the fact that there is a strong correlation between PM mass (as elemental carbon) and particle number appears to be very clear (as shown in Figure 30). Further, CARB staff has noted that a SPN standard is actually a simpler, faster, and more precise measurement method than the gravimetric approach used to measure PM mass.⁹⁵ As PM standards drop to 3 or even 1 mg/mi,

⁹⁰ Bushkuhl, J., Silvis, W., Szente, J., and Maricq, M., "A New Approach for Very Low Particulate Mass Emissions Measurement," SAE Technical Paper 2013-01-1557, 2013, doi:10.4271/2013-01-1557.

⁹¹ Z. Gerald Liu, Victoria N. Vasys, Melissa E. Dettmann, James J. Schauer, David B. Kittelson & Jacob Swanson "Comparison of Strategies for the Measurement of Mass Emissions from Diesel Engines Emitting Ultra-Low Levels of Particulate Matter", 2009, Aerosol Science and Technology, 43:11, 1142-1152.

⁹² Kyriakis, N., Vouitsis, I., Samaras, Z., "Study on Emission Control Technologies for Heavy Duty Vehicles, Volume 2 – Measurement Techniques and Sampling Procedures for Low Level Particulates", Study for European Commission, ETD/00/503430, July 2002.

⁹³ Swanson, J., Kittleson, D., Dikken, D., "Quantification of Uncertainty and Techniques for Improving Filter Mass Measurements", American Filtration and Separations Society Annual Conference, May 2009

⁹⁴ Liu, Z., 2009.

⁹⁵ http://www.arb.ca.gov/msprog/levprog/leviii/meetings/051810/lev_iii_pm_and_bc_v2.pdf. The gravimetric approach is codified at 40 C.F.R. Part 1065. For SPN measurement, CARB proposed using the European PMP protocol for solid particles >23 nm.

particle number may become a more reliable and effective way of regulating PM emissions and correlating these with mass-based health studies.

Conclusions and Recommendations

Over the past decade, regulators in the United States, California, and Europe have taken major steps to reduce the human health impacts from car, truck, bus, nonroad diesel engines, and other transportation-related pollution. In the United States, the Environmental Protection Agency (EPA) has implemented a series of diesel rules that have dramatically reduced sulfur levels in diesel fuel and led to a new generation of engines equipped with highly-efficient diesel particulate filters (DPFs), selective catalytic reduction and other emission-cutting strategies. Implementing these rules is making the belching black smoke of an old diesel truck or tractor a thing of the past.

In March 2013, EPA proposed a new Tier 3 program of fuel and emission standards for these light-duty vehicles, which will lower the sulfur content in gasoline from today's average of 30 parts-per-million (ppm) to 10 ppm and introduce new tailpipe emission standards for all new cars, light trucks, and sport-utility vehicles, starting in the 2017 model year. Once implemented, this will be another important step forward for clean air and public health.

All of this great progress has occurred against the backdrop of an increasing understanding of the strong evidence linking particulate matter emissions from vehicles with a wide range of adverse health impacts.

As we look ahead, we see some clouds forming on the horizon that deserve attention.

First, there is a growing concern in the public health community about the contribution of the so-called ultrafine particulates (UFPs, i.e., particles that are finer than 0.1 microns in diameter) to the overall health impacts of PM. Given their small size, UFPs are not a major factor in measurements of overall PM mass, but they constitute the largest contributor to overall particle numbers. This is an especially important issue in urban areas and near busy highways and other major roads, and a topic that deserves additional research and attention.

Second, it is clear that using DPFs creates surplus emission reductions that translate directly into additional, quantifiable health benefits enjoyed by all Americans. Indeed, the DPFs that engine manufacturers and others are using to meet existing heavy duty and nonroad diesel emissions standards in the United States result in additional emission reductions that far exceed the applicable PM standards for highway and nonroad diesel engines—by an average of roughly 90 percent and more than 80 percent, respectively.

The environmental and health benefits of these additional emissions reductions are substantial. Over the life of today's vehicle and engine fleets, these reductions will yield an estimated \$19.1 - \$43.5 billion of additional environmental and health benefits from the highway diesel sector, as well as another \$5.6 - \$12.9 billion in environmental and health benefits from the nonroad

diesel sector. These benefits include the elimination of 349 -780 premature deaths and almost 50,000 lost work days annually from the highway diesel sector and another 86-196 premature deaths and roughly 12,238 lost work days annually from the nonroad diesel sector.

Adding a PN limit in the light-duty sector would create additional, bonus emissions benefits of an additional \$35.1 - \$80.0 billion beyond the benefits of the proposed Tier 3 emissions standards over the life of these vehicles (including another roughly 900 premature deaths and 56,000 lost work days annually).

Some manufacturers are starting to consider new strategies to meet EPA and CARB off-road emission standards that do not include DPFs. Already, several engines have been certified to meet EPA's Tier 4 interim standards without DPFs. EPA certification data shows clearly that, while these engines meet the basic standards, almost all of the surplus emission reductions are lost with this approach.

In addition, approaches that rely on engine-based strategies rather than DPFs are more likely to lead to increased emissions in actual use. These increased emissions are likely to result from a number of factors, including off-cycle operating conditions, poor maintenance, and excess idling. Thus, while this approach may comply with the certification requirements of EPA's standards, it would be a significant step backwards from the perspective of clean air and human health if this approach becomes widespread.

Third, we expect to see an acceleration of the shift towards using direct injection (GDI) and turbocharging in gasoline-fueled light-duty vehicles. Already, more than half of the light-duty vehicles sold in the U.S. have a GDI option—and the number of GDI-equipped models is rapidly increasing. There is ample evidence that engines equipped with GDI emit UFPs and PM that is comparable to the emissions of diesel engines that do not use DPFs. As EPA finalizes its Tier 3 proposal, it will be important that the agency consider the PM and UFP impacts of a shift from port fuel injection (PFI) to GDI and turbocharging, and the opportunities afforded by emerging gasoline particulate filter (GPF) technology.

Our report aims to assist EPA and the California Air Resources Board (CARB) as they consider these clouds on the horizon. We close with recommendations to help the EPA and CARB achieve the maximum environmental and health benefits of their current and upcoming standards, as follows:

EPA and CARB should add a PN limit to its regulatory structure for mobile sources.

Adding a PN limit to EPA's Tier 3, Highway Diesel, and Nonroad Diesel emissions standards would ensure that emissions levels equivalent to today's best available emissions controls technology (e.g., diesel and gasoline particulate filters) are used to reduce both the mass of PM

and the number of UFPs and other particles. Adding a PN limit would complement the existing regulatory regime, and would lock into place the surplus emission reductions that are currently benefiting the health of millions of Americans. For the same reasons, the California Air Resources Board (CARB) should consider adding a PN limit to its LEV-III program in its upcoming midterm review, as well as to its highway and nonroad diesel regulatory programs.

Both EPA and CARB should consider a new set of heavy-duty diesel engine PM standards that would be equivalent in stringency to CARB's 1 mg/mile standard for light-duty vehicles.

Emission testing has shown that, when equipped with a DPF, a PM limit of approximately 1 mg/bhp-hr is a technologically feasible emissions threshold for new heavy-duty diesel engines. This level is seen in certification testing of diesel engines with DPFs, which regularly yields engines that surpass the current PM standard by more than 90 percent. According to our analysis, this compliance margin currently creates an estimated \$19.1 - \$43.5 billion of surplus environmental and health benefits and eliminates 349-780 premature deaths annually in the highway diesel sector—in addition to EPA's original estimates for the Highway Diesel rule. Given that there are DPFs are widespread in the marketplace, there is no question that this technology is widely available and working in the marketplace. The Clean Air Act requires EPA to set emissions standards at the level that is technologically feasible, taking certain economic and other factors into account. EPA and ARB should consider a new round of PM standards that would lock in these unrecognized surplus health benefits.

EPA should increase its in-use compliance monitoring of nonroad diesel engines that are certified without DPFs.

Backsliding on DPFs in the nonroad sector could result in the loss of \$5.6 - \$12.9 billion in environmental and health benefits in just seven of the equipment groups in the nonroad diesel sector over the life of these engines (lost benefits that would include 86-196 premature deaths and roughly 12,238 lost work days annually). Nevertheless, some companies are moving forward with nonroad Tier 4 certification strategies that rely on engine control strategies, rather than DPFs. While these engines may meet the certification requirements in the controlled environment of a testing facility, these engines will not provide the >90 percent margin of surplus extra emission reductions that are common with DPF-equipped engines, and these surplus environmental and health benefits could be lost. Further, there is ample evidence that engine-based strategies are prone to higher in-use emissions than DPF-equipped engines, due to cold starts, extra idling time, poor maintenance, and other factors. Last, given the complex nature of the nonroad diesel engine sector—involving dozens of engine families and a wide array of duty cycles—in-use field testing is especially important. EPA should allocate extra

compliance and enforcement resources to following up with in-use emissions testing of any Tier 4 engines that are certified without DPFs.

EPA and CARB should coordinate activities to develop a methodology for measuring UFP and particle numbers.

Concerns have been raised by both agencies about whether the European Particulate Monitoring Programme (PMP) is suitable for setting a PN limit in the U.S. context. At the same time, the agencies have raised concerns about the ability of their existing framework to measure PM mass emissions at very low levels (e.g., <3 mg/mile). The two agencies should work together to develop a single methodology that could be used to support a PN limit or other UFP standard in the U.S.

Environmental agencies around the world should tighten evaporative emission limits as a way to control secondary organic aerosols.

The California and U.S. LEV III/Tier 3 evaporative emissions programs provide the most comprehensive approach to minimizing evaporative and refueling emissions from gasoline vehicles, a significant source of secondary organic aerosols based particulates. Other major world air quality agencies in major automobile markets should adopt U.S. style evaporative and refueling emission requirements.

Both federal and state governments should play a greater role in accelerating the retirement or retrofitting of older, dirtier diesel engines and the introduction of cleaner diesel replacements.

In 2010, Congress passed the Diesel Emissions Reduction Act (DERA), which authorized \$100 million/year to cleaning up the legacy fleet of older, dirtier diesel engines. Unfortunately, this program has never been fully funded. Over the past two years, it has been funded at only \$30 million and \$20 million, respectively. MECA understands the fiscal constraints facing the 114th Congress, yet strongly urges Congress to maintain the \$20 million appropriation in the coming year and to explore new, additional ways to encourage the accelerated clean-up of the nation's older, dirtier diesels. At the state level, existing retrofit funding programs in California and New Jersey should be fully funded and other states should consider following the model set by these states. With so many older trucks still on American highways and roads, there is a great need for funding incentives to accelerate the retrofitting or retirement of these remaining dirty diesels. As the funding under the federal DERA program diminishes, state transportation agencies should identify ways to allocate a portion of their CMAQ appropriation towards retrofitting the diesel vehicles and equipment that are used on transportation infrastructure projects funded by the state. Furthermore, clean construction mandates represent another

effective means for states that are in PM non-attainment to clean-up construction equipment and other diesel vehicles that are used on state funded projects.