NESCAUM

101 Merrimac Street, 10th Floor
Boston, MA 02114
Tel (617) 259-2000
Fax (617) 742-9162

NESCCAF

Ultrafine Particles: Issues Surrounding Diesel Retrofit Technologies for Particulate Matter Control

By Phil Johnson and Paul J. Miller
NESCAUM/NESCCAF

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Problem Statement

Some diesel retrofit technologies greatly lower the mass concentrations of $PM_{2.5}$ (fine particulate matter ≤2.5 microns (µm) in diameter) in diesel exhaust. They may, however, increase ultrafine particle (UFP; liquid or solid particles <0.1 µm in diameter) number concentrations under some conditions along roadways and other sites where diesel engines operate. This is a public health concern because UFP in high number (count) concentrations may have adverse health effects. At the same time, efforts to reduce mass-based $PM_{2.5}$ are needed because of the known health effects that are significantly associated with $PM_{2.5}$ mass concentrations.

Along roadways, vehicles powered by diesel engines produce $PM_{2.5}$ that includes a UFP fraction.[1] While arising from the same diesel engine sources, potential exposures to $PM_{2.5}$ and UFPs differ with location. UFP counts are highest at and near roadways, and drop off within several hundred meters at a much more rapid rate than $PM_{2.5}$ mass levels (Levy et al., 2003; Zhang et al., 2004). Because of this rapid drop off, on-road commuters can have their greatest exposure to UFPs during commute times, even if the time spent in traffic is a relatively small part of the day. Those living, working, or otherwise spending time near major roadways or other sources of diesel emissions will also be exposed to higher concentrations of UFPs than the general population. In light of these potential exposure venues, efforts to reduce $PM_{2.5}$ mass emissions in diesel exhaust need to consider the implications of potential increases in UFP number that may result from some diesel retrofit technologies.

This paper provides contextual information on UFPs, $PM_{2.5}$, and the influence of diesel retrofit technologies. It is arranged in three parts: 1) UFP health concerns; 2) $PM_{2.5}$ health concerns; and 3) studies of the impacts on UFP number in response to diesel retrofit measures aimed at reducing mass-based $PM_{2.5}$. Based on our review of the available information, we present at the end of this paper some conclusions and recommendations with regard to UFPs and diesel retrofit technologies.

[1] Throughout this paper, $PM_{2.5}$ concentrations will be expressed in mass units, while UFP concentrations will be expressed in particle count units.

1. Ultrafine particle health concerns

There is a strong possibility of adverse health impacts associated with UFPs, with further study being warranted. Some researchers hypothesize that the ultrafine particle constituent of $PM_{2.5}$ is especially dangerous because of its physical structure. It has been noted that the surface area of UFPs provides a suitable base for adsorbed or condensed exogenous chemical materials. The extremely small size of UFPs enables their transport and of materials on their surfaces into the gas-exchange (alveolar) portion of the lung, bypassing deposition onto surfaces of the lung's conductive airways. UFPs have also been found to penetrate the airway surfaces and pass into human blood to be carried to extrapulmonary organs, leading to possible systemic effects (Donaldson et al., 2001; EPA, 2004; Frampton, 2001; Lippmann et al., 2003). A few studies have directly evaluated the effects on cardiovascular health by UFPs. Delfino et al.'s (2005) recent review concludes that redox-active components in UFPs from fossil fuel combustion likely reach cardiovascular target sites. High UFP exposures may lead to systemic inflammation through oxidative stress responses to reactive oxygen species (ROS), thereby promoting the progression of atherosclerosis and precipitating acute cardiovascular responses ranging from increased blood pressure to heart attacks.

Combustion-related emissions sources dominate the carbonaceous fraction of ambient $PM_{2.5}$ in many populated areas. Carbonaceous material encompasses a significant fraction of $PM_{2.5}$ mass and comprises the majority of UFP number concentration in uncontrolled diesel exhaust. Toxicological findings connect combustion particles with a variety of responses in the airways of laboratory animals and humans, including inflammation, cellular injury, and increased permeability. Polycyclic aromatic hydrocarbons (PAHs), for example, adsorb onto particles and play a toxicological role in generating ROS, oxidative stress, and inflammation once inhaled. In this way, organic UFP target airway epithelial cells and macrophages – the primary defense of the deep lung – and damage cellular proteins, lipids, membranes, and DNA (Li et al., 2003; Nel, 2005; Sioutas et al., 2005). Epidemiological studies investigating surrogates of motor vehicle exhaust, proximity to traffic sources, and intracity gradients indirectly implicate elemental and organic carbon, as well as other mobile source emissions, in adverse health outcomes (Hoek et al., 2002; Ito et al., 2004; Jerrett et al., 2005; Kinney et al., 2000; Schlesinger et al., 2006). These studies have found associations between mobile source emissions and health outcomes, indirectly suggesting the potential role of carbonaceous $PM_{2.5}$ and UFP (Sioutas et al., 2005). Uncontrolled mobile source emissions are rich in carbonaceous material and UFP, but these source emissions also contain co-varying pollutant gases, such as CO, NO_2, SO_2, and semi-volatile organics, that could be responsible for health findings.

In sum, UFP physical and chemical properties, as well as presence in combustion-related emissions, present a potential role for this constituent in contributing to observed $PM_{2.5}$-related health outcomes. Overall, however, research has not determined which specific physical characteristics and chemical components of $PM_{2.5}$ are responsible for adverse health effects. The complex task of separating particle size from other particle characteristics such as chemical composition, number concentration, and surface area has limited the interpretation of study results. Whether health associations are caused by particle physical size alone, by the combined effects of chemical and biological components of particles, specific organic compounds, or gases is unknown (Schlesinger et al., 2006).

2. $PM_{2.5}$ health concerns

Over the past few decades, a growing body of experimental and observational evidence has implicated mass-based $PM_{2.5}$ ambient exposure with adverse health outcomes. Toxicological, clinical, and epidemiological research has centered mainly on respiratory and cardiac effects ranging from minor irritation to exacerbation of chronic disease and even premature death. In support of the current $PM_{2.5}$ NAAQS, numerous epidemiology studies using mass-based $PM_{2.5}$ air pollution data have found associations between short- and long-term exposure to $PM_{2.5}$ and adverse health outcomes. These include lung function decrements, exacerbation of lung disease, respiratory and cardiac mortality, cancer, and developmental and immunological effects (EPA, 2005).

The majority of studies relying upon mass-based $PM_{2.5}$ monitoring data, however, provide little causal understanding of the properties of particulate matter that potentially play a role in eliciting adverse health effects. Ambient $PM_{2.5}$ has diverse physicochemical properties ranging from the physical characteristics of the particles to the chemical components in or on the surface of the particles. Chemical components of ambient $PM_{2.5}$ that might contribute to adverse health effects include acidity, a variety of trace metals, reactive organic species, and biological agents. Physical characteristics of particles including size, number, shape, and surface area might also be responsible for adverse health outcomes (EPA, 2004; NRC, 1998). It may be that no single etiologic toxic agent is responsible for the entire spectrum of adverse health effects observed in health studies. Instead, different agents, individually and in combination, could contribute to health outcomes by stimulating different mechanistic pathways. A complete understanding of the pathways by which very small concentrations of inhaled ambient $PM_{2.5}$ can produce pathophysiological changes leading to health effects remains to be more fully researched (Lippmann and Ito, 2000; Lippmann et al., 2003; Schlesinger, 2000; Utell et al., 2002).

3. The impacts on UFP number in response to diesel engine retrofit measures

Reducing $PM_{2.5}$ mass through diesel retrofit technologies does not necessarily mean a concomitant reduction in total UFP number, and UFP number may increase by a factor of 10 or greater with some technologies that reduce overall $PM_{2.5}$ mass. Measurements of UFP number, however, can give contradictory results regarding an increase or decrease in UFP number (e.g., the change in UFP number can depend on any condition that affects condensation processes, such as the dilution conditions used in the measurement method). Even if an increase in UFP number occurs, there appear to be retrofit technologies that do not show this effect. Therefore, current studies provide a mixed picture on the extent of increased UFP number from diesel retrofit technologies.

Figure 1 shows idealized distributions of particulate matter weighted by size and mass in diesel engine emissions (Kittelson, 1998). For the mass weighted distribution (dashed profile line), most of the mass is in the accumulation mode range from 0.05 to 1.0 µm in diameter, as indicated by the area under the curve for the various size ranges. The coarse mode (>1.0 µm in diameter) contains about 5-20 percent of the particle mass while the UFPs in the nuclei mode (<0.05 µm in diameter) are typically 1-20 percent of the mass. By contrast, the nuclei mode is more than 90 percent of the particle number distribution (solid profile line). The nuclei mode consists of volatile organic and sulfur compounds formed during exhaust dilution and cooling, along with solid carbon and metal compounds from the combustion process (Kittelson, 1998).

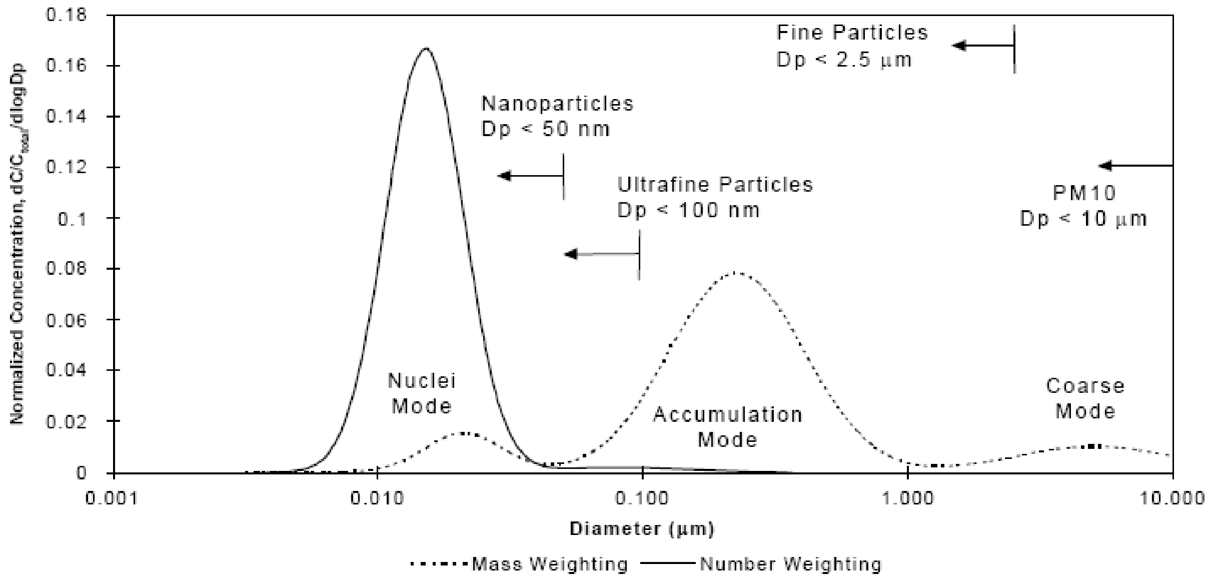

Figure 1. Idealized mass weighted (dashed line) and number weighted (solid line) distributions of particulate matter in diesel engine exhaust (Kittelson, 1998).

Burtscher (2005) has described how diesel particulate traps or filters can increase UFP number even while decreasing overall $PM_{2.5}$ mass. Without a filter, the volatile materials in diesel exhaust can condense upon solid particles, leading to decreases in overall particle numbers while particle mass increases. The presence of a diesel particulate trap will remove the solid particles, leaving the volatile materials without a solid surface to condense upon in the exhaust. This allows the uncondensed volatile material (e.g., sulfuric acid and unburned hydrocarbons) to pass through the filter. While total mass is reduced by the filter, particle number in the smaller size ranges can increase as the volatile material that otherwise would have condensed onto a solid substrate remains in the gas phase where nucleation can enhance formation of UFPs.

The formation of UFPs in diesel exhaust under real world conditions is highly variable and sensitive to a number of factors, including engine operation, engine thermal history, roadway grade, interaction with other traffic, background aerosol, dilution conditions, and ambient temperature. There is a greater tendency to form UFPs in the nucleation mode under real world driving conditions than can be consistently duplicated in laboratory tests (Kittelson et al., 2002).

On-road studies of UFP in diesel exhaust. In an on-road study of truck diesel exhaust, Kittelson et al. (2006a) compared the control performance of two diesel exhaust aftertreatment technologies – a continuously regenerating trap (CRT™) and a catalyzed continuously regenerating trap (CCRT™).[2] The study found that the two technologies were very effective in removing particles larger than 0.02 µm in diameter (equivalent to 20 nanometers (nm)). By contrast, the CRT increased UFP number for sizes below 0.02 µm, while the CCRT decreased it. When the researchers looked at particles collected in the laboratory from a CRT-equipped engine, they found that the particles were composed mainly of sulfates (Grose et al., 2006).

[2] The CRT consists of a diesel oxidation catalyst (DOC) followed by an uncatalyzed filter. The CCRT consists of the same DOC with a catalyzed filter.

Therefore, the carbonaceous PM component is greatly reduced by a CRT even though UFP number due to sulfates may increase. Kittleson et al. (2006a) attributed the decrease in sulfate with the CCRT to application of a washcoat to the filter portion of the CCRT that could store significant amounts of sulfates. The researchers also suggested that the UFP number could eventually increase with running time of the CCRT as the washcoat surface becomes saturated with sulfates, but this may occur only after thousands of miles if using low sulfur diesel and lubricating oil. For the UFP comparisons, changes in particle number were relative to a diesel engine with no control running on 15 ppm sulfur fuel (Figure 2). An additional on-road study by this research group concluded that a modified CCRT with a special catalytic coating to trap sulfate species coupled with low sulfur fuel and a uniquely formulated low sulfur lubricating oil could result in a diesel engine with virtually zero PM emissions indistinguishable from background ambient PM levels within the experiment's detection limits (Kittelson et al., 2006b). With a catalyzed trap arrangement and ultralow sulfur diesel fuel, an inhalation exposure study of the diesel exhaust using mice showed either complete or near complete elimination of health hazards associated with resistance to infection, inflammation, and oxidative stress relative to diesel exhaust from circa 2003 diesel fuel (371 ppm sulfur) with no filter trap (McDonald et al., 2004).

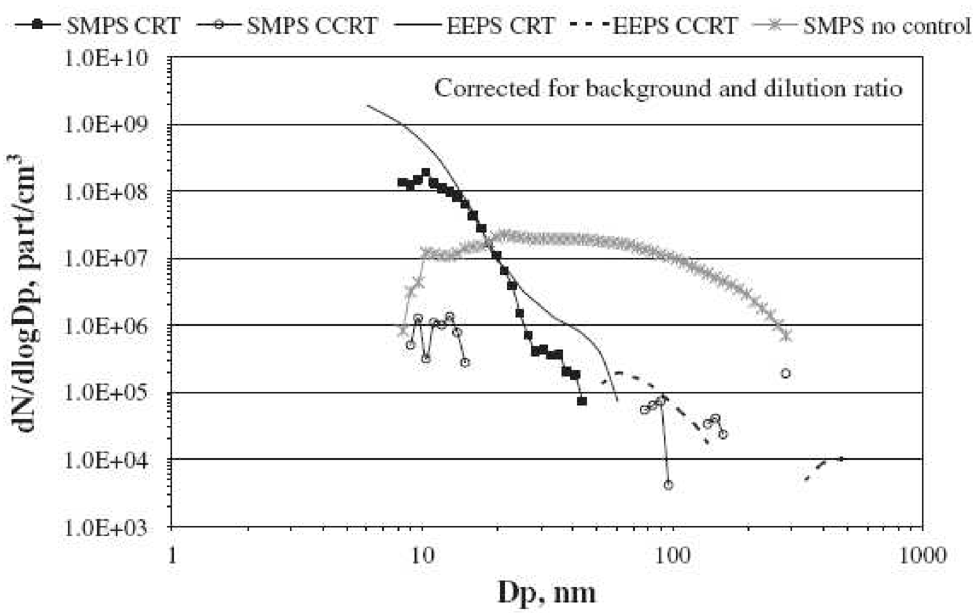

Figure 2. SMPS and EEPS size distributions for the CRT, CCRT, and uncontrolled case. SMPS and EEPS refer to different PM measurement methods. Note that the SMPS method substantially undercounts particles <0.01 µm (10 nm) in size relative to the EEPS method. The figure indicates the CRT produces higher UFP number than the CCRT and the uncontrolled engine. The CCRT produces the lowest UFP number (Kittelson et al., 2006a).

An additional salient observation from the on-road testing is that a CRT without a filter catalyst on a diesel engine running on 15 ppm sulfur fuel and low sulfur lubricating oil (0.152% sulfur by weight) produced essentially identical UFP numbers below 0.02 µm as a diesel engine with no control running on current US market fuel (350 ppm sulfur) and lubricating oil (~0.5% sulfur by weight). The CRT engine reduced total $PM_{2.5}$ by over 90 percent (Kittelson et al., 2006b). This suggests that changing current market lubricating oil to low sulfur oil for use with CRT-equipped engines operating on 15 ppm sulfur fuel can greatly reduce total $PM_{2.5}$ mass without increasing UFP number below 0.02 µm relative to uncontrolled diesel engines running on US market fuel containing 350 ppm sulfur. The study indicated that the UFPs are likely sulfate-based, and showed that if a particulate filter is employed in the system that is treated with a catalyst containing a sulfate-trapping component, even the UFPs are reduced below ambient background levels.

Laboratory studies of UFP formation in diesel exhaust. In addition to the on-road studies, two laboratory dynamometer studies have shown that a CRT decreases both $PM_{2.5}$ mass and particle number across all particle sizes down to about 0.03 µm by >90 percent (Lanni et al., 2001; Chatterjee et al. 2002). Toback et al. (2005) obtained similar results with a mobile test cycle of school buses equipped with a variety of control technologies running on a test track. The range of the PM size in these measurements, however, did not extend below 0.03 µm (30 nm), so any increase in UFP number below this size relative to an uncontrolled diesel engine would not be observable. Figure 3 displays an example of the reductions in PM down to about 0.03 µm in diameter observed in one laboratory study (Chatterjee et al., 2002).

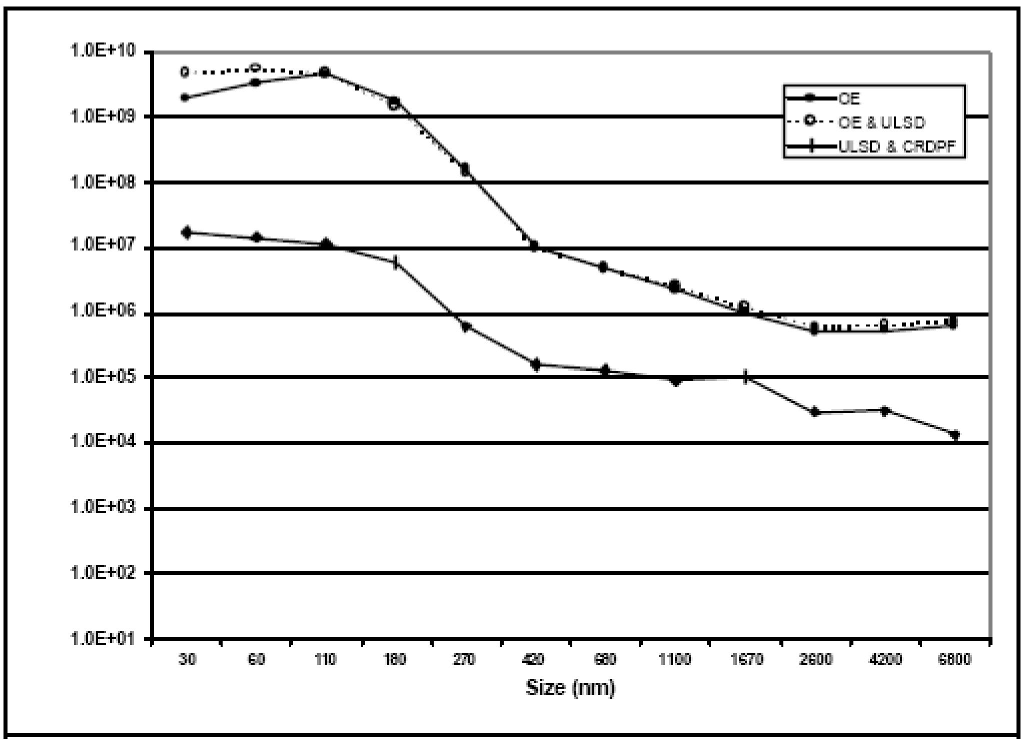

Figure 3. Particle number distributions in diesel engine exhaust from dynamometer test cycles. The figure shows the difference in PM number between an engine with no control (OE) run with and without <30 ppm sulfur diesel (ULSD) and a CRT diesel engine (CRDPF) with ULSD. The CRT results are from dynamometer testing of a bus after 12 months of on-road operation. The smallest PM size bin is ~0.03 µm (30 nm) (Chatterjee et al., 2002).

In another laboratory dynamometer study, an increase in UFP number was seen for particle sizes below about 0.01 µm for a CRT-equipped diesel engine relative to an engine with no control running on 11 ppm sulfur fuel (Holmén & Ayala, 2002). The UFP results changed, however, with different exhaust dilution conditions used in the test. Relative to a diesel engine with no control, a constant volume sampler (CVS) technique gave a higher UFP number at particle sizes below 0.01 µm for a CRT engine, while the test results using a minidiluter indicated a lower UFP number (Figure 4). This indicates that the dilution conditions in the sampling methods can affect the UFP number results.

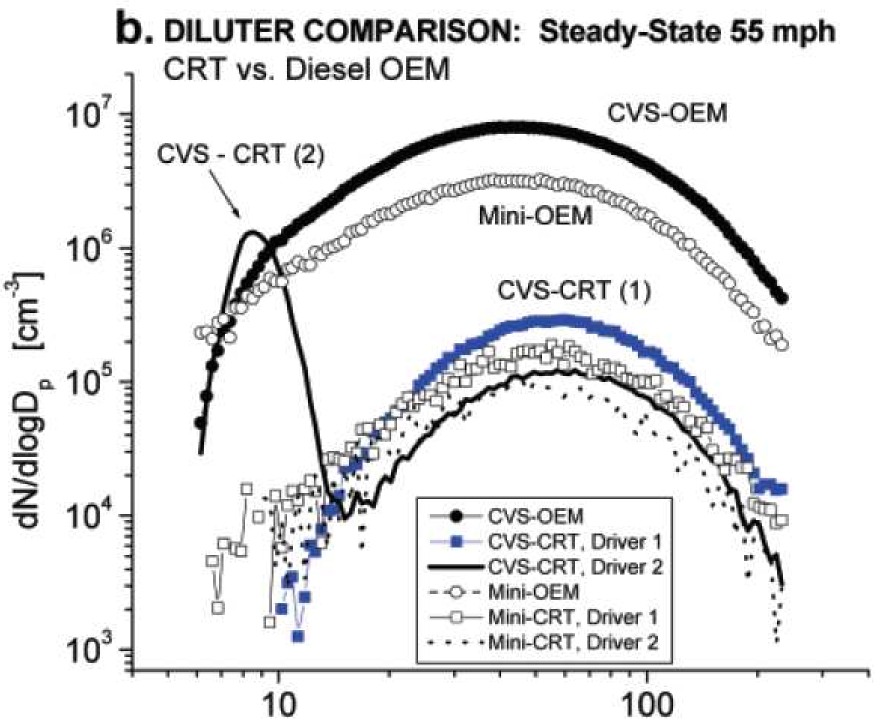

Figure 4. Comparisons of UFP number results using two different dilution methods – a constant volume sampler ("CVS-") and a minidiluter ("Mini-"). The CVS method indicates higher UFP number with a CRT diesel engine that is not seen with the minidiluter technique (Holmén & Ayala, 2002).

Using a minidiluter sampling technique, a study by Frank et al. (2006) found that the particle number and size distribution were approximately the same for particles above ~0.02 µm from an uncontrolled diesel engine and a diesel engine with a diesel oxidation catalyst (DOC) without a trap, while the DOC had higher UFP number for particles below 0.02 µm. Diesel engines with a CRT and a CRT combined with exhaust gas recirculation (to reduce NO_X in addition to PM) had significantly lower UFP numbers across all size ranges (Figure 5). All the engine tests used diesel fuel with sulfur content less than 30 ppm.

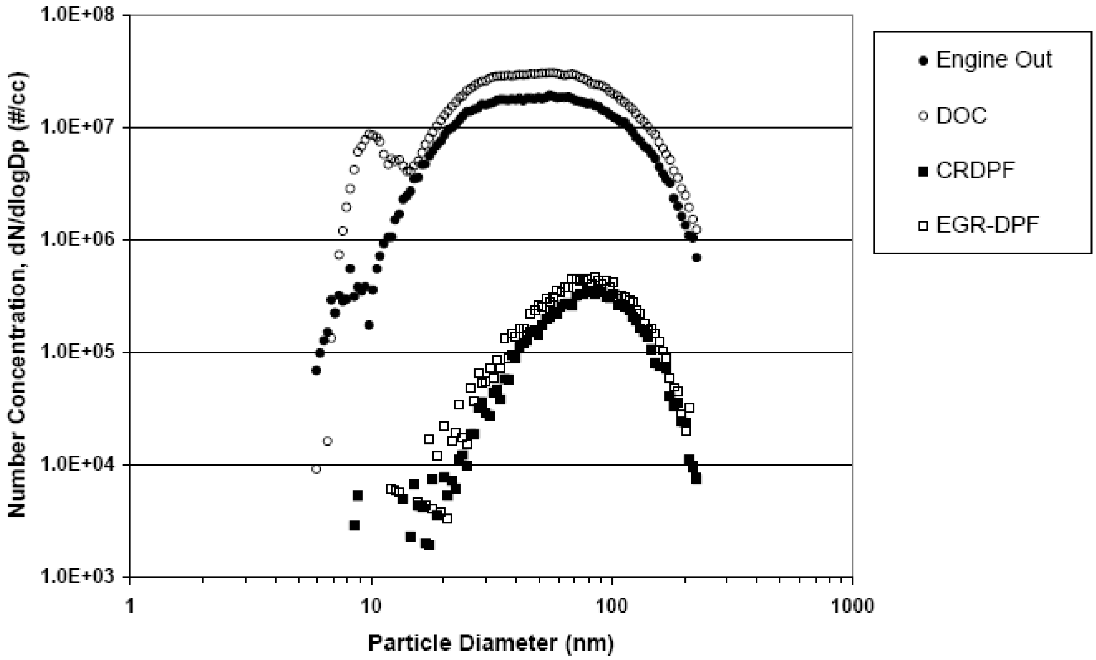

Figure 5. "CRDPF" is an engine equipped with a CRT and "EGR-DPF" is an engine with a CRT using exhaust gas recirculation. The CRT engines had lower UFP numbers across all particle sizes than the diesel engine with no controls and the engine with a diesel oxidation catalyst only (no trap). The test method used a minidiluter (Frank et al., 2006).

Additional work has been done to replicate on-road UFP measurements in the laboratory with the finding that it is difficult to match on-road size distributions in individual laboratory test conditions, but better agreement was possible with composites of several laboratory test conditions (Kittelson et al., 2006c). This work also concluded that the presence of UFPs in the smallest size ranges found near roadways has not changed since the late 1960s, indicating that this is a longstanding phenomenon irrespective of diesel retrofits. The researchers further found that while engines continue to produce UFPs, engine improvements in recent years have led to a reduction of volatile emissions such as sulfuric acid and heavy hydrocarbons that can form UFPs during exhaust dilution and cooling.

The effect of sulfur content in diesel fuel. In general, further lowering the sulfur content in diesel fuel below 500 ppm does not continue to lower measured PM in the diesel exhaust, but it is necessary for the efficient operation of the catalysts used in PM control technologies. The results of Frank et al. (2006), however, indicate a changing profile in PM size distribution with changing sulfur content of the fuel. All diesel fuels used in the Frank et al. (2006) study had a common mode above ~0.05 µm (50 nm). Below ~0.05 µm in diameter, a diesel engine with no control exhibited a strong second mode of increasing UFP number with decreasing sulfur content, but this second mode nearly disappeared at the lowest sulfur content level (<30 ppm). The strongest bimodal behavior (i.e., increasing UFP number with diesel sulfur content) appeared limited to the 162-615 ppm sulfur content range (Figure 6).

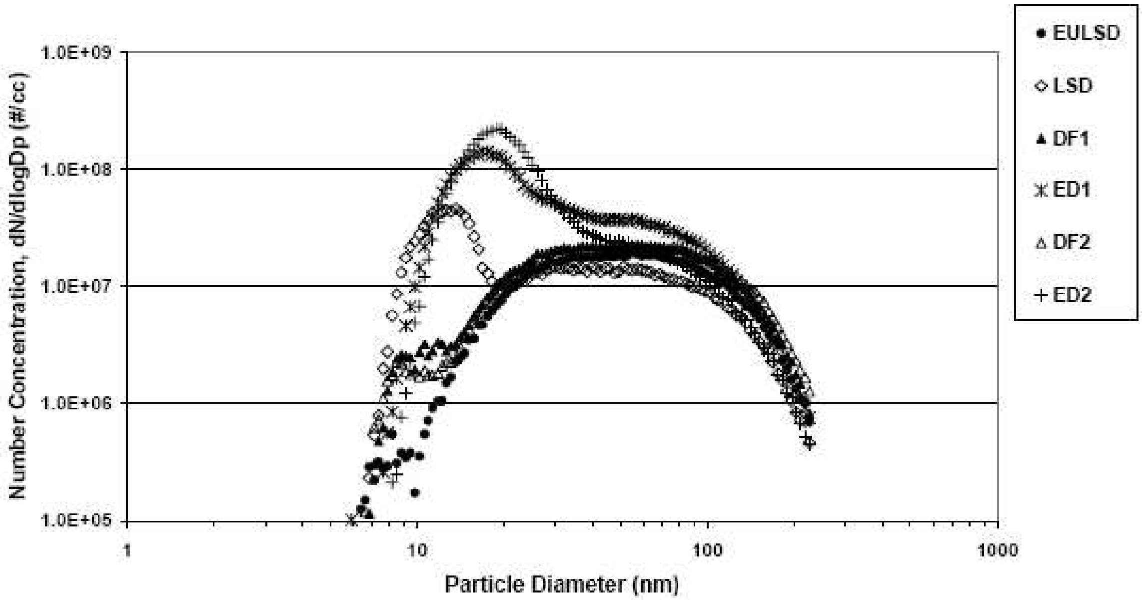

Figure 6. Profile of PM size distribution in diesel exhaust from an engine with no control. EULSD is <30 ppm sulfur; LSD is ~150 ppm sulfur; DF1 and DF2 are diesel with >400 ppm sulfur; ED1 and ED2 are 7 percent by volume ethanol blends with DF1 and DF2, respectively. The highest sulfur content diesel fuels (DF1 and DF2) and the ultralow diesel fuel (EULSD) display less bimodal character in the PM size distribution than the fuels with intermediate sulfur content (Frank et al., 2006).

A similar result was seen by Ristovski et al. (2006) in which an engine with no control operating at high engine load and 500 ppm sulfur diesel produced 74 percent of the particles in the exhaust in a size range smaller than 0.05 µm whereas only 43 percent of the particles were below this size when using 50 ppm sulfur diesel (Figure 7).

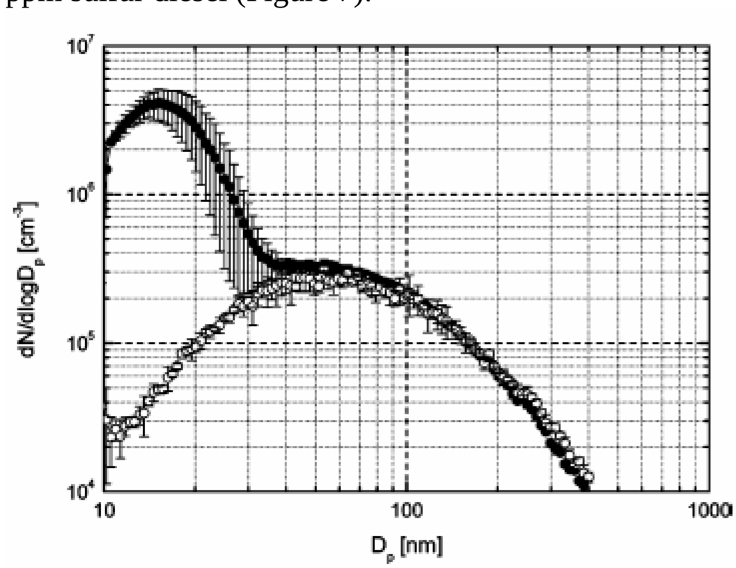

Figure 7. The size profile distribution shown in the figure indicates higher particle number below ~0.04 µm (40 nm) for low sulfur diesel (500 ppm S) (full circle profile) relative to the particle number for ultralow sulfur diesel (50 ppm S) (open circle profile) for a diesel engine with no control (Ristovski et al., 2006).

A study in Copenhagen during the introduction of ultralow sulfur diesel also found a similar effect (Wåhlin et al., 2001). In a “real world” experiment, ambient PM measurements taken during the winter of 2000 in a Copenhagen street canyon showed a significant decrease (~50 percent) in PM particles below 0.1 µm compared to measurements taken at the same location during the winter of 1999. The decrease was especially large for UFP diameters below 0.03 µm. The large drop in UFP levels coincided with a decrease in diesel fuel sulfur content from ~500 ppm to <50 ppm. These results suggest that the introduction of ultralow sulfur fuel can have an added benefit in reducing UFP numbers at smaller diameters (<0.03 µm).

With respect to ultralow sulfur diesel and CRT engines, studies indicate that the particle physical characteristics change relative to higher sulfur content diesel and an engine with no control. The carbonaceous component virtually disappears, and the observed particles are mainly spherical sulfate particles (Chatterjee et al., 2002; Grose et al., 2006). Therefore, a CRT efficiently removes the carbonaceous portion of UFPs, an important aspect as this component has been implicated in potential adverse health effects of UFPs. Furthermore, large reductions in other exhaust pollutants occur with ultralow sulfur fuel and a CRT: >90 percent in carbon monoxide; >70 percent in total hydrocarbons; 90-99 percent in carbonyls; 70-80 percent in polycyclic aromatic hydrocarbons; and 70-99 percent in volatile organic compounds (Chatterjee et al., 2002). These significant reductions in other pollutants resulting from ultralow sulfur diesel and CRTs should be considered when weighing the impacts of possible higher UFP numbers.

In summary, continuously regenerating traps (CRTs) can reduce $PM_{2.5}$ mass by over 90 percent, thus addressing a class of air pollutants known to adversely affect public health. Measurements show that CRTs significantly decrease PM numbers (>90 percent) uniformly down to a size range of ~0.03 µm. Below this size range, however, the experimental results are mixed. Under some on-road and laboratory measurement conditions, some CRT-equipped engines may produce greater UFP numbers below 0.03 µm in diameter even though total $PM_{2.5}$ mass decreases significantly. Because of the potential role of UFP number in general in contributing to $PM_{2.5}$ health effects, these results are of concern. Measured changes in UFP number, however, can be contradictory in the laboratory depending on the dilution technique used (CVS or minidiluter). As a result, more research is needed to develop a standard measurement method able to reasonably reproduce real world engine operating conditions in the laboratory setting. Even in the face of the laboratory measurement uncertainty, there are on-road measurements suggesting that a CRT with a catalyst-coated filter (in addition to the catalyst before the filter) coupled with ultralow sulfur fuel and low sulfur lubricating oil can reduce virtually all PM emissions across all sizes to levels virtually indistinguishable from ambient background levels (within the experiment’s detection limits). Furthermore, there are significant reductions in other pollutants with adverse health impacts, such as polycyclic aromatic hydrocarbons and the carbonaceous component of UFPs, resulting from the use of ultralow sulfur fuel with CRTs.

4. Conclusions

Over the past few decades, experimental and observational evidence has implicated ambient exposure to mass-based $PM_{2.5}$ with adverse health outcomes. Toxicological, clinical, and epidemiological research has centered mainly on respiratory and cardiac effects ranging from minor irritation to exacerbation of chronic disease and even premature death. The majority of studies relying upon mass-based $PM_{2.5}$ monitoring data provide little causal understanding of the properties of PM that potentially play a role in eliciting adverse health effects. It may be that no single etiologic toxic agent is responsible for the entire spectrum of adverse health effects observed in health studies. Instead, different agents, individually and in combination, could contribute to health outcomes by stimulating different mechanistic pathways.

The physical and chemical properties of various UFPs, as well as their presence in combustion-related emissions, present a potential role for these constituents in contributing to observed $PM_{2.5}$-related health outcomes. The complex task of separating particle size from other particle characteristics such as physical state, chemical composition, number concentration, and surface area has limited the interpretation of study results. Whether health associations are caused by particle physical size alone, by the combined effects of chemical and biological components of particles, specific organic compounds, or gases is unknown.

Measurements show that continuously regenerating traps (CRTs) significantly decrease PM numbers (>90 percent) uniformly down to a size range of ~0.03 µm. Some CRT-equipped engines may produce greater UFP numbers below 0.03 µm in diameter even though total mass of $PM_{2.5}$ decreases significantly. It is important to recognize, however, that there are on-road measurements indicating that a CRT with a catalyst-coated filter (in addition to the catalyst before the filter) coupled with ultralow sulfur fuel and low sulfur lubricating oil can reduce PM emissions across all sizes to levels virtually indistinguishable from ambient background levels (within the experiment's detection limits). Furthermore, there are significant reductions in other pollutants with adverse health impacts, such as polycyclic aromatic hydrocarbons and the carbonaceous component of UFPs, resulting from the use of ultralow sulfur fuel with CRTs.

5. Recommendations

Based on current scientific understanding, no single constituent of mass-based $PM_{2.5}$ may be responsible for all observed health effects. Therefore, we recommend considering adverse health effect impacts as occurring across the full size and speciation profile of $PM_{2.5}$ rather than assuming they are due to just one type of constituent within this diverse mixture. Specifically, reducing mass-based $PM_{2.5}$ by more than 90 percent through the use of CRTs can provide significant public health benefits, and should not be readily dismissed when weighed against potential increases in UFP number (or changes in other emissions, such as NO_X).

While the potential health impacts of increasing UFP number should not be assumed to outweigh the health benefits from reducing $PM_{2.5}$ mass, they should not be ignored either. More study of the health consequences of UFP number should be undertaken, including specific consideration of the sulfur species observed in the diesel exhaust of CRT-equipped engines.

There are additional mitigation measures that should be considered where not already being undertaken. These additional measures include:

- Use of ultralow sulfur diesel fuel (15 ppm)
- Use of low sulfur (~0.15% sulfur by weight) lubricating oil (including synthetics)
- Installation of catalyzed CRTs that contain sulfur trapping sites in the catalyst coating
- Exploration of emerging techniques to remove sulfur, such as sulfur traps

The use of ultralow sulfur diesel fuel and low sulfur lubricating oil with a non-catalyzed CRT can reduce mass-based $PM_{2.5}$ by >90 percent while mitigating increases in UFP number relative to an uncontrolled diesel engine running on current U.S. market diesel fuel (350 ppm). Combining the first three recommendations above can reduce all $PM_{2.5}$, including total UFP number, to levels virtually indistinguishable from background. Additional measures could also emerge, such as sulfur traps, which could further reduce the sulfate component contributing to UFP number.

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