MIT EL 00-007

Energy Laboratory

Massachusetts Institute
of Technology

Symposium Summary
The Future of Diesel: Scientific Issues
2000 Air Pollution Symposium

December 2000

SYMPOSIUM SUMMARY

The Future of Diesel: Scientific Issues

2000 Air Pollution Symposium

Symposium Chair: Dr. Robert Slott, MIT
Program Committee:
Praveen Amar, NESCAUM
John Heywood, MIT
Diane Mundt, HEI
Robert Sawyer, UC-Berkeley

Sponsored by the MIT Energy Laboratory

Held at
Endicott House
Dedham, Massachusetts
July 13-14, 2000

Proceedings prepared by Renee J. Robins, MIT

Energy Laboratory Publication No. EL 00-007
December 2000

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The Summer Air Symposium is a continuation of conferences established in 1993 for the purpose of informing decision makers on scientific aspects of important air pollution issues. Participation is limited to invited members of the scientific, regulatory, industrial, and public interest communities. The small size of the group promotes discussions that have led to important progress on ideas for improvements in air pollution control. The conference is co-sponsored by a variety of organizations (see Appendix I).

The objective of the 2000 Symposium was to discuss scientific aspects of diesel engines and fuel, including:

- what is known about the science;
- uncertainties and their magnitude; and
- what research is needed.

Widespread Diesel: Diesel engines are in widespread use for a number of reasons. They are the most economical engines to own and operate due to their high power density. They are highly reliable and very durable, with an effective infrastructure for fuel distribution. Models are available in a wide power range, and the engine can be modified to operate with alternate fuels.

Diesel Pollution: Diesels have become a large part of the NO_x pollution problem. NO_x from gasoline-powered vehicles has declined due to emission controls, and stationary-source NOx has also decreased substantially in most parts of the country. However diesel emissions have been essentially uncontrolled for the last thirty years while use of diesel vehicles has been increasing. Diesels also contribute substantially to ambient concentrations of particulate matter (PM), although the variation in emission rates for the in-use fleet is large. It is known that in-use diesel NO_x emissions are high from a variety of consistent data and corollary information, however uncertainties remain, such as fleet activity and how representative test cycles are. There are tradeoffs between fuel economy, PM, and NO_x in injection timed engines.

Heavy duty diesel trucks dominate heavy duty diesel vehicle emissions, however transit buses and school buses have localized exposures that are of concern. Off-road emissions are more distributed. Construction is the major source, followed by locomotives, agriculture, marine, and commercial.

Diesel Regulation: On June 2, 2000, EPA published proposed Phase 2 rules. These rules attempt to regulate vehicle and fuel as a system, aiming for 90% reduction in PM, NOx, and HC emissions in new vehicles. EPA anticipates very low emissions from these requirements *if* sulfur levels in fuel are reduced. New federal diesel truck emission standards have been proposed by U.S.EPA, and these will reduce both NOx and PM by 98% from uncontrolled levels. Off-road diesels are as important as buses and trucks, because they emit as much NOx and twice as much PM, and new off-road emission standards are being developed. Greater than 97% reduction in off-road emissions, compared to uncontrolled levels, is achievable. Defining the certification process is as important as the emission standard set, because that is how it is determined whether the standard is met or not.

In Europe, where diesel is a popular choice for automobiles and light duty vehicles, regulations for 2005-2008 are similar to the US for PM but not for NOx. Some European governments are requiring diesel particulate filters for all trucks starting in 2005. NOx limits for 2005 are not stringent, but 2008 limits will require a NOx emission control device. The EU 2005 standards are probably the last time diesel engines will face less stringent regulations than gasoline-powered light duty cars and trucks. Japan's current standards are less stringent than Europe for both NOx and PM, and less stringent for US standards for PM but similar for NOx. New long-term standards are currently under discussion. They are not anticipated to be as stringent for PM but similar for NOx compared to future US and European requirements. In general, there is more emphasis on CO_2 and greenhouse gases in Europe (and to a lesser extent Japan) whereas in the US, the emphasis is on conventional pollutants.

Issues: Active after-treatment for both NOx and PM may be needed in the future. There are interesting and promising developments with respect to after-treatment, but no proven devices. The control of NOx is the more difficult problem. The fundamental constraint is that there is no catalyst available to facilitate the dissociation of NOx. Selective catalytic reduction is feasible, as are NOx traps that store NOx as nitrate, and plasma systems.

Fuel changes are a key enabling technology. Current California requirements call for 15 ppm sulfur in diesel fuel used in transit buses as of 2002. EPA's proposed Phase II rules call for a sulfur cap of 15 ppm for highway diesel fuel by 2006. This is in contrast to 350 ppm sulfur in current US on-road fuel. Engine manufacturers are calling for ultra-low sulfur fuel, arguing that 15 ppm isn't low enough. However oil companies question whether this can be accomplished. Concerns about ultra-low sulfur fuel include whether enough refineries can upgrade fast enough to meet supply needs, and how contamination and measurement affect the ability to meet standards.

Health concerns will continue to drive further regulation of emissions from diesel engines. EPA has been assessing diesel health risk for 12 years. Diesel exhaust contains carbonaceous particles with some organics adhered, gaseous phase organics, and some metals. All of these have associated toxicological issues. In California, the Multiple Air Toxics Exposure Study (MATES II) found that ~70% of all cancer risk in the South Coast Air Basin due to outdoor air pollution is attributable to diesel PM. MATES II estimates that outdoor toxic air pollution accounts for less than 1% of cancer due to all risk factors. There is a growing interest in the size distribution of particulates. Particulates smaller than 100 nm are low in mass but high in number, and toxicologists need to determine how important they are.

Control of emissions from in-use vehicles is expected to get increasing regulatory attention. Retrofit programs can significantly reduce PM, HC, CO, and toxic emissions. There is also the potential for NOx reductions. California is planning to retrofit 1.25 million engines, mostly mobile and some stationary.

1.0 INTRODUCTION: BOB SLOTT, MIT ENERGY LABORATORY

The Summer Air Symposium is a continuation of conferences established in 1993 for the purpose of informing decision makers on scientific aspects of important air pollution issues. Participation is limited to invited members of the scientific, regulatory, industrial, and public interest communities. The small size of the group promotes discussions that have led to important progress on ideas for improvements in air pollution control. The conference is co-sponsored by a variety of organizations (see Appendix I).

The objective of the 2000 Symposium was to discuss scientific aspects of diesel engines and fuel, including:

- what is known about the science;
- uncertainties and their magnitude; and

what research is needed.

2.0 WHERE ARE WE NOW? (*Moderator: Praveen Amar, NESCAUM*)

To put the current debate about diesel in perspective, Praveen Amar related some anecdotes from a history of air pollution control compiled by NESCAUM (Northeast States for Coordinated Air Use Management) . In 1952, a Stanford Research Institute study concluded that the diesel contribution to air pollution was small, and no further work was recommended. One year later, an auto company wrote that exhaust gases dissipate quickly in the atmosphere and were therefore not a problem.

2.1 The Importance of Diesel in Today's Economy

John Fairbanks, US Department of Energy

John Fairbanks presented a thorough review of where and why diesel is used, and his perspective of its role in the future. He gave examples of the extensive use of diesel in commerce in the US and in Europe, including food and produce trucks, farm equipment, logging trucks, school buses, liquid carriers, transit buses, construction equipment, mining equipment, light rail, fire trucks, and ships. This widespread use is in part because only diesel engines can supply the torque that these varied jobs require. Emphasizing the importance of diesel, he noted that 60% of the cost of seafood at the dock is the fuel cost of taking the fishing boats out to sea and back.

There are a number of reasons why diesel is in such widespread use. It is the most economical engine to own and operate due to its high power density. It is highly reliable and very durable, with an effective infrastructure for fuel distribution. Models are available in a wide power range, and the engine can be modified to operate with alternate fuels.

Fairbanks discussed some of the more recent improvements in the technology, which was originally patented in 1892. After posing the question of whether diesel combustion is a mature technology or an engine with considerable potential for improvement and growth, he noted that in the past 25 years, average diesel engine efficiency has increased 30% while simultaneously the durability was increased by a factor of four. Construction materials have advanced from rather straightforward aluminum, steel, and iron to more complex alloys with much improved casting techniques and ceramics.[1] Computer modeling of components and their mechanical and thermal interactions is a major design advance. The biggest advance has been electronic control of the combustion process with fuel injection, and, more recently, microprocessor control.[2] These advanced fuel injection systems have significantly reduced NOx (nitrogen oxide) emissions and noise.

[1] For about 50 years, the primary coating in diesel engines was chromium deposited by electrodeposition or a packed bed system. Now multi-element nitrides and carbides are deposited by high velocity oxygen-fueled systems and plasma spray.

[2] Microprocessor control involves the exact amount of fuel injected precisely when required, including rate shaping of the injection charge, primarily by pilot injection.

Light trucks are the fastest growing area in vehicle sales, currently accounting for approximately 50% of passenger vehicle sales. The big question, he suggested, is whether diesel engines should be used in non-commercial light trucks. The reasons to do so include reduced fuel use (and corresponding reduction in the US balance of payments), reduced carbon dioxide (CO_2) emissions, enhanced engine durability and higher resale value, and excellent low-power torque. However, there are disadvantages, including the perception of excess emissions, more stringent emission constraints, smell, noise, and cost differential. It is his view that diesel engines are inordinately blamed for air quality problems, undoubtedly influenced by black clouds from pre-1994 models. He also pointed out NRDC's (Natural Resources Defense Council) "No More Dirty Diesel" campaign against New York City buses as a big problem for diesel's image. The publicized link between diesel exhaust and asthma that NRDC has made part of its campaign needs to be combated with scientific evidence.

Turning to efforts to improve the performance of diesel vehicles, he showed the progression of light truck emission standards and highlighted a joint DOE/Detroit Diesel program to improve engine and emissions performance and reduce cost. There are some tradeoffs in decreasing emissions, however, and engineering challenges exist. Yet he argued the case for a more efficient engine (diesel) based on the carbon balance: carbon in equals carbon out, and since exhaust carbon is in the form of hydrocarbons (HC), particulate matter (PM), carbon dioxide (CO_2), and carbon monoxide (CO), it is beneficial overall to reduce the consumption of fuel (carbon in).

With respect to the association of air pollution with mortality, he countered a number of arguments against diesel. He referred to a Harvard School of Public Health study showing the relationship between ambient fine particles and the death rate. Then he showed particulate size distribution from a 1.9 liter diesel engine vs. gasoline engines, pointing out that whereas the gasoline engine emitted fewer particles, they were smaller in size. He also pointed out that there have been many deaths due to fire and explosion in gasoline-powered vehicles (he cited 5000/year in France), but none related to diesel because of its lower flammability. Similarly, deaths from carbon monoxide poisoning are only related to gasoline vehicles. Finally, he noted that benzene, a carcinogenic air contaminant, is present in diesel fuel, but that diesel only contributes 3% of ambient benzene whereas gasoline sources account for the remaining 97%.

Discussion

The discussion focused largely on just how much regulators should be concerned about diesel emissions. The relative contribution of diesel to PM and NOx was questioned. Diesel currently contributes more, but Fairbanks noted that filters are not yet used, and post-treatment devices including NOx absorber catalyst and urea injection are being developed. Responding to a suggestion that DOE is in a state of denial about the toxic consequences of diesel exhaust given the predominant emphasis on CO_2 in his presentation, he noted some British measurements of diesel toxics to be below levels of concern when certain control technology was applied. With respect to the regulation of sulfur content in diesel fuel, Fairbanks noted that despite some engine companies advocating 0-15 ppm (parts per million), the question is whether it can be produced in large enough quantities. DOE will probably support 15 ppm.

2.2 NOx and PM Emissions, Predictions of Emission Inventory Models and Diesel's Share

Alison Pollack, ENVIRON International Corporation

Alison Pollack described the EPA and ARB models that are used to predict emissions from on-road mobile sources. Over the years EPA has developed a series of models called MOBILE; MOBILE5 is the current model. The California Air Resources Board (CARB) has its own model; the most recent official release is called the Motor Vehicle Emissions Inventory or MVEI7G. Both agencies have been working on major revisions to their models for the last several years. EPA's new model, expected around the end of 2000, is called MOBILE6. CARB's new model, EMFAC2000 (for "Emissions Factor"), was approved by the CARB Board but has not yet been finalized.

These models are used in a variety of regulatory and non-regulatory settings. They are used, for instance, to determine baseline emission inventories, to determine the need for new emission control programs, and in transportation conformity for planned transportation projects. The models provide gram per mile emission factors, which are then multiplied by vehicle miles traveled (VMT). MOBILE5 and Part 5 (which estimates PM emissions) group all heavy duty diesel vehicles (HDDV) in one category. In MOBILE6, they will be disaggregated by weight classes. MOBILE6 will also make separate estimates for transit, intercity, and school buses.

The basis for MOBILE5 HDDV emission factors is engine dynamometer testing. Twenty-two vehicles, covering model years 1979-1984, were tested in a joint Environmental Protection Agency (EPA)-industry study in 1984; some manufacturer certification testing is also factored in. Conversion factors are used to translate work-specific factors (grams per brake-horsepower-hour or g/b-hp-hr) to grams per mile (g/mi). These are then aggregated across weight classes using sales-weighted averages and composited across model years using age and mileage accumulation distributions to derive fleet average emission factors for a given calendar year. There are correction factors for speed (speed vs. emissions is a U-shaped curve with higher emissions occurring at very low and very high speeds) and for altitude. MOBILE5 does not include any deterioration rate adjustments for tampering effects.

MOBILE6 revisions will incorporate new certification test data for HDDV emission factor estimates, but EPA likely will still rely on the older engine dynamometer testing. In MOBILE6, EPA is updating the factors used to convert g/b-hp-hr to g/mi, and also HDDV age and mileage accumulation distributions. MOBILE6 methodology documentation can be obtained at http://www.epa.gov/OMSWWW/m6.htm; beta and final versions of the model will also be posted on this web page.

The current release of the California model takes a similar approach and is based on the same 1984 dynamometer study and EPA's dated speed corrections. It has an emissions deterioration factor for tampering and malmaintenance, and adjusts for California clean diesel fuel, out-of-state vehicles, and heavy duty truck inspection and maintenance (I/M) program effect.

The most significant change in EMFAC2000 HDDV emissions estimate is the use of chassis dynamometer testing for determining basic emission rates. Another significant change is that the model includes both idle and running emissions. As in the case of MOBILE6, there will be further disaggregation into weight classes. EMFAC2000, like its predecessor MVEI7G, will estimate not just emission factors but total emissions for the whole state and for each county or air basin. To do this, it uses VMT/speed/idle data by weight class, hour of day, and day of week. These changes result in a significant increase in estimated NOx emissions and a decrease in estimated PM emissions. Recent actions not yet reflected in the model include the HDDV consent decree and proposed 2007 highway heavy-duty emission standards and fuel changes, as well as recent CARB bus standards. A beta version of the EMFAC2000 model and associated documentation is available at http://arbis.arb.ca.gov/msei/msei.htm.

She then turned to the issue of uncertainties in the models. These are assumed to be large, but have not been quantitatively estimated. The basic emission rates are based on very limited data. The effect of deterioration and I/M are uncertain, as are speed correction factors (based on very old data) and idling emissions. The NOx/PM emission tradeoff also adds uncertainty. More model validation based on tunnel studies or some other source of real-world data are needed.

Finally, she discussed models for off-road emissions. EPA's NONROAD model is in development. CARB's model is called OFFROAD. These estimate "traditional" nonroad sources such as construction equipment, pleasure boats, lawn and garden equipment, and light industrual/commercial equipment. The models do not estimate emissions from aircraft, locomotives, and commercial marine; there are separate guidance documents for estimating emissions from these sources. The NONROAD and OFFROAD models estimate emissions by multiplying estimates of equipment population, activity levels, and emission factors, and are even more uncertain than the on-road models. This is due to the many diverse diesel applications, few measurements, and little data with respect to equipment populations, use, and activity.

Concluding with some inventory data, she showed a national 1996 off-road diesel NOx inventory broken down by equipment category. The inventory shows the largest source to be construction equipment, followed by diesel locomotives. For PM, construction equipment also dominates, followed by industrial sources.

Discussion

The discussion focused on the uncertainties in the data used for inventories, and the obstacles to coming up with better emissions estimates. Some additional uncertainties in emission rates were pointed out, including brake and load effects. There are, or course, many sources of uncertainty beyond what was specifically mentioned. Some data are beginning to be available about the effect of deterioration on diesel emissions. An analysis by CARB and EPA found that deterioration is a significant factor in PM emission rates, although it is not as much a factor for other emissions. If it were included in the model, it would be expected to raise the PM amounts substantially.

The most critical issue for improving estimates is judged to be more data -- especially from chassis dynamometer testing -- however the constraint is cost. There is no clear way to do this kind of testing more economically. EPA continues to use the engine dynamometer data because there aren't enough consistent chassis dynamometer data yet. It was noted that sample bias is a problem; getting a representative sample of in-use heavy duty diesel vehicles is difficult, for vehicles tested are taken out of service for the day, often at an economic loss to the owner. Other possible approaches include remote testing with sensors, but this too will not come cheaply. Some initial reports about remote NOx sensing for trucks showed good correlation between NOx emissions and fuel use, suggesting another possible approach for estimating emissions. All told, EPA staff have estimated the cost of getting necessary data for improved inventories to be $150 million. A consent decree between EPA and truck manufacturers[3] has a provision requiring manufacturers to conduct in-use testing, but EPA and the companies are still debating the details of this requirement.

2.3 Issues in NOx Measurement and Monitoring

Robert Sawyer, UC Berkeley

Diesels are becoming a bigger part of the NO_x problem. NO_x from gasoline-powered vehicles has declined 75% due to emission controls, and stationary-source NOx has also decreased substantially in most parts of the country. Diesel emissions have been essentially uncontrolled for the last thirty years while use of diesel vehicles has been increasing. Total diesel fuel consumption has increased approximately 5% per year, which corresponds to a doubling in 15 years. This is twice the growth rate of gasoline consumption. Diesel now amounts to 25% of fuel used in on- and off-road vehicles.

We know that in-use diesel NO_x emissions are high from a variety of consistent data and corollary information, including chassis dynamometer measurements, tunnel studies, and remote sensing. Uncertainties remain, such as fleet activity and how representative test cycles are. Current estimates put diesel NO_x emissions at about five times that of gasoline engines on an equivalent fuel basis. Presenting a summary of tunnel data, Sawyer pointed out how consistent the numbers were from five separate tests. The heavy duty emissions data ranged from 34 to 59 grams NO_x per kilogram of fuel. In California, diesels account for about 50% of the heavy-duty truck fleet, but 83% of VMT and 86% of fuel use. Heavy duty diesel trucks account for approximately 50% of total on-road NO_x emissions, even though they are a small fraction of vehicles.

Providing some background information, he pointed out that the section in the 1990 Clean Air Act Amendments calling for a 90% reduction of mobile source emissions spelled out light duty vehicle requirements but left regulation of heavy duty vehicles to EPA's discretion. Furthermore, the first emission standards for diesel vehicles in 1985 (1990 for NOx) were fifteen years behind the regulation of gasoline vehicle emissions. With respect to current requirements, Sawyer commented that the 2004 requirement of 2.5 g/bhp-hr NO_x + HC seemed achievable without resorting to after-treatment. However, the proposed 2007-2010 limit of 0.2 g/b-hp-hr is a truly huge reduction.

---

[3] EPA charged seven truck manucturers with equiping their heavy-duty diesel vehicles with illegal devices that enable the engines to pass the EPA emissions testing, but are turned off during the vehicles' typical highway driving. EPA charged that these "defeat devices" resulted in those engines emitting substantially more NOx than was allowed. An $83.4 million civil penalty was imposed on the seven manufacturers, and a consent decree required a number of actions by the companies representing over $1 billion in investments. Further details are available at http://es.epa.gov/oeca/ore/aed/diesel.

Turning to possible NO_x control strategies, he detailed the tradeoffs between fuel economy, PM, and NO_x in injection timed engines. Adjusting the engine for maximum fuel economy results in higher NO_x, and vice versa. High temperatures are needed to get particulate levels down, but this also increases NO_x formation. A report on inspection and maintenance indicates that by screening for and fixing smoky trucks, fleet NOx emissions increase. The conclusion is that exhaust treatment will be needed to meet the 2007-2010 regulations.

New technology will be devoted to reducing the fuel economy/NO_x tradeoff. However, the existing fleet needs to be addressed through a good heavy duty I/M program for PM and NO_x. Otherwise operators will continue to adjust their engines to maximize fuel economy. Acknowledging that both NO_x reductions and fuel have value, he pointed out that drivers only "see" the value of the fuel used. He expects that the development of on-board monitoring of NO_x in the next decade will be useful in engine control strategies, as well as in demonstrating in-use compliance and potentially for NO_x trading. The latter will help drivers internalize the cost of their NO_x emissions.

Discussion

There are other pollutants that go along with NO_x, so the tradeoffs are more complicated. Most toxics should be reduced with after treatment, however. It was also noted that ozone is not the only consideration for NO_x emissions. Particulate nitrate is a problem in California, so ambient ozone can't alone determine the appropriate level of NO_x emissions. The I/M issue is an important one, and the tradeoff between smoke and NO_x is problematic. The only solution might be to combine I/M with a particulate filter retrofit program, although it would be difficult to implement. I/M programs must also be designed to ensure that drivers don't simply re-tune their engines to the better fuel economy/higher NO_x timing once they have passed their inspections. Regular I/M combined with random on-road testing could address this issue. The state of New Hampshire is looking at economic incentives such as basing truck registration fees based on engine type and emissions. Anything above \$1000 to \$2000 per ton of NO_x would provide sufficient incentive for truck drivers to adjust and maintain their trucks.

The potential for controlling train emissions was questioned, since generally the larger the source the more cost effective to control and the easier it is to implement the regulations. Sawyer added that trains are a more efficient way to move freight, but he wouldn't go so far as to advocate switching freight from trucks to trains.

2.4 Issues in PM Measurement and Monitoring Including Diesel/Gasoline Split

Eric Fujita, DRI

Eric Fujita began by identifying some of the unresolved issues related to vehicular PM emissions:

- What is the chemical component of gas/diesel particulate emissions and how do they vary by size?
- How do rates, chemical composition, and particulate size distribution change with operating conditions and malfunctions?
- What is the evolution and fate of ultrafines in the atmosphere?
- Are emission measurements relevant to exposure? Can we determine urban exposures with ambient measurements?
- How much do diesel and gasoline vehicles contribute to ambient PM in urban areas?

He showed trends in PM emission rates based on measurements taken in highway tunnels. Under hot stabilized operation, gasoline vehicles are very clean. However, emissions are much higher in cold start mode[4] and for high emitters. Tunnel measurements indicate that the amount of diesel emissions have been reduced over time. PM emission rates measured on a chassis dynamometer also show a decreasing trend.

The variation in emission rates for the in-use fleet is large. Gasoline engine "smokers" are quite a bit higher even than Phase I emissions from other vehicles. In Phase I, elemental carbon emissions are higher whereas organic carbon is predominant from high emitters. For diesel, the predominant constituent is elemental carbon. (Chemical

[4] Cold start mode is "Phase I" of the Federal Test Procedure dynamometer certification test for gasoline light duty vehicles.

marker species have been identified to be able to assess the fraction of PM that comes from hardwood and softwood combustion and meat cooking.) Results of ambient PM source apportionment for the Denver area were presented. For $PM_{2.5}$, motor vehicles contributed one-third of the total, with gasoline vehicles responsible for more than half of that. Diesel contributed approximately half the elemental carbon, and the organic carbon came mostly from gasoline vehicles. With respect to the Denver emission inventory, diesel and dust emissions seem to be overestimated when compared to the ambient apportionment.

The trend in elemental and organic carbon for the Los Angeles area shows elemental carbon has a clear downward trend while organic carbon shows increases at most sites from 1982-1993. Fujita questioned whether gasoline vehicles are responsible for this organic carbon trend. PM emission trends based on mobile source inventories show clear decreases for gasoline vehicles, whereas tunnel studies showed no change. Diesel emissions peaked around 1990, with a slight decrease after that in the inventory numbers, whereas tunnel studies showed a clear downward trend.

In California, the Multiple Air Toxics Exposure Study (MATES II) found that ~70% of all cancer risk in the South Coast Air Basin is attributable to diesel PM. (He noted that 65% of total carbon wasn't identified and so had no risk assigned to it.) When the emission rates for specific PAHs (polycyclic aromatic hydrocarbons) in gasoline and diesel emissions were examined, diesel was found to have mostly lower levels of gas-phase PAH as well as particle-phase. Turning to tunnel studies, he said that particle size distribution from one such study showed background particles averaging 100 (nanometers). At the tunnel inlet, they found ultrafines (~10 nm) mixed with the background distribution. At the tunnel outlet, there were virtually all ultrafines. He made the point that while ultrafine particles can account for most of the particles by number, they do not account for a large part of the total mass. He gave some information about factors affecting particle emission rates and composition.

In summary he noted that PM mass emission rates of diesel vehicles have decreased significantly over the past 25 years. Particulate emission rates from on-road spark-ignition vehicles are low during steady hot-stabilized conditions, with occasional spikes in emissions contributing much higher concentrations of ultrafines. Cold starts, hard accelerations, and high emitters account for most of the on-road spark-ignition (SI) gasoline vehicle emissions, and trends in ambient concentrations suggest that this contribution has not declined. PM from SI vehicles contains a higher fraction of particulate PAHs and these emissions are comparable to or exceed diesel vehicles on a per-mile basis, but are underestimated in current inventories relative to diesel emissions. A greater fraction of semi-volatile organic compounds exists in the particulate phase near the source. But as of yet, the relative contributions of gasoline and diesel vehicles to ultrafine particles exposures have not been evaluated.

Discussion

The impact of the unassigned elemental carbon in the MATES II study was questioned. Since it wasn't assigned to any source, it can be assumed that the absolute risk values attributed to specific sources are accurate given the inherent uncertainties, but that there is additional risk that hasn't been accounted for. So the *fraction* of total risk from diesel might be lower. The distinction between elemental carbon and organic carbon was questioned. The distinction is an operational one. The relevant question is what happens to semi-volatile compounds during their residence time in the atmosphere.

2.5 Issues in Dilution Sampling of Fine PM from Diesel Exhaust

Larry Jones, EPA

The measurement of ultrafine particles is a primary problem, and improved procedures to properly characterize diesel particles in the environment are needed. It has been found that particle size distribution is strongly influenced by the formation of ultrafine particles as exhaust gases are diluted by ambient air. Factors affecting ultrafine particle formation include humidity, the dilution ratio, and residence time. Therefore EPA researchers have used a full-size truck with specialized equipment to sample the exhaust plume eleven meters behind the truck's exhaust stack. The objective is to develop a dilution system to obtain more accurate particle distribution data. The test facility is a 1990 model truck. A diluter system is used for sampling fine PM. In the stack, researchers observe particles centering around 100 nm, which is typical. But they don't have measurements of fine particles in the 10 nm range. Comparing the dilution system with ambient air enables them to examine the dynamics involved. As the truck accelerates, there are higher particle counts. In cruise mode, the counts are lower. A similar effect was observed for PAHs. Another issue is the impact from smoking trucks, oil-burning, and engine wear. PAHs are increased by engine wear. They are making improvements to the test facility to better address these issues.

Next, he discussed some European data based on samples taken with a dynamometer and plume samples taken with a chase vehicle following behind the test vehicle. Other laboratory studies using dilution systems show the influence of dilution ratios on nanoparticle counts; the bigger the dilution ratio, the smaller the number of particles nucleated at the peak size. Nucleation of sulfuric acid followed by growth in the particle size due to sorption of volatile organic compounds is also strongly affected by ambient temperature. More particles at the peak size are nucleated in the plume at colder ambient temperatures.

Showing the progression of tightening emission standards, he discussed changes in diesel engine technology. Newer engines emit less mass and smaller size particles. Oxidation catalyst with low sulfur fuel have shown significant reduction in the number and size of particles. Finally, he addressed dioxin/furan data. Dioxins and furans are found in diesel PM, but the amount emitted is small compared to other sources. However, more on-road diesel emissions research is currently planned by EPA to confirm these preliminary findings.

Preliminary conclusions are that we can adequately characterize diesel particles. Particulates smaller than 100 nm are low in mass but high in number, and toxicologists need to determine how important they are. Future EPA research plans include testing various control systems, installing nanoparticle measurement systems, and comparing on-road nanoparticle and dioxin/furan emissions with and without low sulfur fuel in the presence of catalytic controls and/or traps.

Discussion

EPA has chemical composition studies underway, but the data are not yet available. Others noted that preliminary studies of diesel nanoparticles showed that the majority of 25 nm particulate mass consisted of hydrocarbons (alkanes, alkenes, and cyclic compounds), and that polycyclics were below detection levels. They also found that these particles were enriched with heavy hydrocarbons relative to undifferentiated hydrocarbons in the range of a molecular mass of thirty or higher. Additional on-road tests at EPA are planned to identify hydrocarbon emission species in modern, new technology engines.

3.0 REGULATIONS IN THE US, EUROPE, AND ASIA (*Moderator: Blair Martin,EPA*)

3.1 US Regulations and Their Consequences: Reducing the Impact of Diesels on Air Quality and Public Health

3.1.1 Reducing the Impact of Diesels on Air Quality and Public Health: *Tom Cackette, CARB*

Tom Cackette discussed the California perspective and experience regulating diesel emissions. He stated that diesel exhaust is unhealthy because it is a major contributor to ambient NOx (which is a precursor to ozone and to secondary fine particulates) and also contains diesel particulate matter and over 40 substances identified as toxic air contaminants. Diesel's cancer risk is high. On a California statewide basis, diesel cancer risk dominates cancer risk from all other toxic contaminants (~70%). According to forecasts, on- and off-road diesel engines will account for 98% of California statewide directly-emitted PM and approximately two-thirds of mobile source NOx (split between on- and off-road). Therefore, reducing diesel emissions is a priority.

He noted that heavy duty diesel trucks dominate heavy duty diesel vehicle emissions, however transit buses and school buses have localized exposures that are of concern. Off-road emissions are more distributed. Construction is the major source, followed by locomotives, agriculture, marine, and commercial. These forecasts are based on the assumption that vehicles will meet current emission standards, and indicate that total emissions will decrease despite continued increasing VMT. These decreases will result from existing control measures, including new engine emissions standards, California's diesel PM control plan, transit bus fleet rule, and other measures and incentives. However, they still need to do more given the toxic risk and the need to assure ozone attainment and reduce secondary $PM_{2.5}$ formation. California's diesel control plan includes adopting after-treatment-based standards (including off-road), requiring ultralow sulfur diesel fuel, retrofitting existing vehicles, implementing in-use compliance programs, and requiring on-board diagnostics. New federal diesel truck emission standards have been proposed by U.S.EPA, and these will reduce both NOx and PM by 98% from uncontrolled levels. Off-road diesels are as important as buses and trucks, because they emit as much NOx and twice as much PM, and new off-road emission standards are being developed. Greater than 97% reduction in off-road emissions, compared to uncontrolled levels, is achieveable.

None of this can be achieved, however, without fuel changes. Currently, requirements call for 15 ppm sulfur in California diesel fuel used in transit buses as of 2002. This is in contrast to 350 ppm sulfur in current US on-road fuel. Switching to natural gas is an option to reduce emissions, particularly for transit bus fleets. Retrofit programs can obtain immediate decreases in PM emissions. The California goal is to retrofit all in-use diesels with particulate filters, and requirements are in place to begin school bus retrofits in 2001 and transit buses retrofits in 2003. The state has allocated over one hundred million dollars to pay the incremental cost of low emission heavy duty engine technologies. Finally, he noted that currently, there are essentially no vehicles with diesel engines in the light duty sector. Proposals to introduce diesel engines into the light and medium duty truck sector would substantially increase PM emissions in the mid-2000s before the effect of more stringent standards lowered these emissions again.

3.1.2 The Future of Diesels: Scientific Issues: *Bob Larson, EPA OTAQ*

The growing popularity of diesel calls for stricter controls. The Phase 1 diesel standards currently in place to take effect in 2004 will require 2.4 g/hp-hr combined NOx and HC. The rules also contain additional test procedure requirements. With this standard in place, total diesel emissions are forecasted to decrease until 2015, when they will begin to grow again because increases in VMT will more than compensate for the effect of cleaner vehicles. He also noted that diesels contribute to urban air toxics, and that NOx and PM emissions vary by location.

On June 2, 2000, EPA published proposed Phase 2 rules. These rules attempt to regulate vehicle and fuel as a system, aiming for 90% reduction in PM, NOx, and HC emissions in new vehicles. With these requirements taking effect, the reduction in total diesel emissions is predicted to continue until at least 2030. (He showed graphs illustrating the continued reduction in emissions with the Phase 2 requirements vs. the increase in emissions starting around 2015 if the proposed standards are not adopted.) The program's main features include simultaneous regulation of vehicle and fuel; 2007 effective date for the PM standard; the NOx standard to be phased in from 2007 to 2010, and a sulfur cap of 15 ppm for highway diesel fuel by 2006. EPA anticipates very low emissions from these requirements *if* sulfur levels in fuel are reduced. Larson showed typical current fuel sulfur levels for highway diesel (350 ppm), non-road diesel (1500-3000 ppm), California diesel (130 ppm), Swedish and UK city fuel (10 ppm), and others.

He emphasized the importance of controlling the sulfur content in diesel fuel. The two goals for changing the fuel are to (1) enable technology to meet the proposed heavy-duty diesel standards and (2) to help light duty trucks to meet Tier II standards. There are three technologies most commonly expected to be used: catalyzed trap, NOx adsorber, and compact urea selective catalytic reduction (SCR). Larson explained how these technologies work. Traps can be catalytic or continuously regenerating, with two ways to regenerate the filter.

Next he showed a schematic of a diesel vehicle equipped with after-treatment. EPA is very optimistic about PM traps functioning well. They have been screening NOx adsorbers from different manufacturers and demonstrating performance. EPA is also investigating the fuel sulfur impact on NOx adsorption and on durability. He noted that whereas the 2007 rule is estimated to add 4.4 cents per gallon in fuel costs, it is also predicted to reduce maintenance costs by about one cent per gallon. The net additional vehicle costs range from $980 to $1500 for the various vehicle classes.

Turning to non-road engines, he noted that it is anticipated that by 2007, more than 50% of mobile source NOx emissions will be from non-road sources, and similarly over 70% for PM mobile source emissions. He explained the three tiers of standards that have been adopted. Tier 3 has NOx but not yet PM standards. EPA is looking at adopting a transient test procedure because steady-state operation is uncommon for off-road equipment. Finally, he noted that there is a series of related rulemakings, including the air toxics rule, Tier 2 and gasoline sulfur regulations, etc. EPA's action plan states that the final non-road rule will be issued in late 2001.

3.1.3 Clean Diesel Technology: Linkage to Fuels and After-treatment: *Glenn Keller, EMA*

Glenn Keller began by reviewing why diesel engines are popular, emphasizing that they have the lowest life costs of any powertrain due to their fuel efficiency, reliability, and durability. He also noted the low greenhouse gas emissions. Referring to the White House announcement of the 21st Century Truck Initiative to develop revolutionary technologies to increase fuel economy and safety of trucks and buses, he noted that diesel will play a role in line-haul trucking, hybrid engines, heavy duty applications, etc. Asking what would happen if all diesels disappeared, he discussed the inadequacy of other potential fuels/engines to replace it. Gasoline, compressed natural gas (CNG), liquid petroleum gas (LPG), and methanol cannot cover the full power range needed, and there is no infrastructure to supply these fuels. Looking to the impact of regulations, he said that the 2007 proposal is a 90% decrease from 2004 levels, so future diesels will be significantly cleaner than today's.

Discussing future regulation of off-road diesel equipment, he said that Engine Manufacturers Association (EMA) is investigating the feasibility of EPA Tier II (2001-2004) and Tier III (2005-2008) requirements. The combination of standards and test procedure rules is critical. He described how EPA's control emphasis has shifted over time from PM to NOx to both. Meeting these changing requirements has involved extensive engine systems changes, and in the future a fuel change in combination with after-treatment devices will be necessary. The new systems approach encompasses three main elements: engine controls, after-treatment, and fuels. The industry goal, he said, is to achieve clean diesel technology, and he noted that the future standards are technology-forcing for after-treatment. *Ultra low* sulfur fuel is necessary; 15 ppm isn't sufficient. EMA is advocating 5 ppm as the level necessary to enable technology, and for durability considerations as well. The ultra low levels are necessary to meet the "useful life" requirements that apply to manufacturers.

He discussed the effect of fuel sulfur on PM filters, With 150 ppm sulfur in the fuel, PM levels actually increase when a catalyst is used. Fuel sulfur contributes to PM directly (sulfates, carbon, soluble organics), and indirectly (sulfates). The sulfur in the fuel poisons the after-treatment controls, and it also ends up in the air. He provided additional arguments why 5 ppm is needed, including that it enables NOx adsorber control technology, it produces the lowest ambient sulfate emissions across the entire fleet, and it enhances the durability of the engine as well as emissions control devices. A 50 ppm limit (which he said is the oil industry's position) will jeopardize NOx control and compromises PM filter operation among other problems.

The estimated costs are a 4-7 cents per gallon increase for 50 ppm sulfur, and only another 2 cents/gallon to go down to 5 ppm. Technologically it is feasible. 5 ppm could make 2007 diesel engines cleaner than today's CNG engines, and would also contribute to reductions from non-road engines. In summary, he said that fuel changes are required to comply with the technology-forcing regulations. The sulfur content of non-road fuel must also be reduced.

3.1.4 Highway Diesel Fuel: Mike Leister*, Marathon Petroleum*

Mike Leister began by stating Marathon Petroleum's support for a 90% reduction in fuel sulfur. Marathon supports EPA's proposed PM and HC standards, but it proposes reducing NOx by 80% (rather than the EPA's 90% goal). The company questions what the actual ozone impact of EPA's proposal will be, which Leister asserted was not modeled. He noted that diesel fuel is Marathon's second largest product, and outlined his company's concerns:

- He stated that the NOx standard of 0.2 lacks both a rationale and analysis.
- He questioned why the NOx standard is phased in over so many years if it's such an urgent problem and if fleet turnover is slow in the first place.
- Agreeing with EMA's position, he said that 15 ppm won't work for NOx adsorbers.

- Another problem is manufacturing sufficient quantity of fuel that meets the standard.
- The diesel distribution system is shared with jet fuel, home heating fuel, and others that have a sulfur concentration orders of magnitude greater, making contamination an issue.
- He also said that there are still many questions about the health effects of diesel emissions.
- Another concern is the accuracy of measurement. They can only measure fuel sulfur to within plus or minus 6-7 ppm.
- There are questions about how to measure PM, as well as the issue of speciation.
- Sulfur in lubricating oil can add 5-8 ppm.
- They can't issue a standard without defining a certification process, because that is how it is determined whether the standard is met.
- He questioned whether diesel de-sulfurizing facilities can be built at the same time as Tier II gasoline facilities.
- He questioned the requirement for off-road diesel.

Noting that the US economy runs on diesel (over 80% of US freight is transported by trucks), he said revolutionary changes are problematic given the potential for dramatic economic and political impacts. He did agree about the impact of diesel sulfur on controls and particulates, but he stated that removal is costly and needs to be optimized as part of an engine-fuel-after-treatment system approach. He pointed out that sulfur is naturally present in crude oil in a variety of compound sulfur-hydrocarbon species. Reviewing how diesel is produced, he showed the processing that would be involved in going from 50 ppm to 30 ppm to even lower levels. Desulfurization will be a negative return investment for refiners. While some will comply, others will move certain production streams into other markets, and some will simply get out of the refining business. Therefore the per-gallon costs start to dramatically increase at higher volumes. Marathon predicts supply will be limited to 2300 million barrels per day (MBPD).[5] He stated that EPA and EMI cost studies based on an "average" refinery are based on faulty logic.

Marathon predicts an initial significant reduction in supply, followed by an increase in price and eventual new supply coming on line. Leister also predicted cheating and bypassing of emission controls. The industry fears EPA will backstep and issue waivers after some companies have already made investments. This gives everyone an incentive to wait until the last minute to make the investment in upgrading their refinery. Rather than rushing the rule, he suggested giving the engine manufacturers and the oil industry four years lead time in order to allow the market to work with the regulations.

3.1.5 US Regulations and the Future of Diesel in Light Duty Application: *Reg Modlin, DaimlerChrysler*

Reg Modlin began with an anecdote about "The Perfect Storm," in which three storm systems came together to form a deadly super storm. He said that in the world of diesel companies, fuel quality, fuel economy, and emission regulations constitute three elements coming together to make the perfect storm, and we shouldn't be steering policy right into the center of it. Daimler Chrysler's view is that diesel has a place in the future motor vehicle fleet because it is the best alternative for improved fuel economy and reduced CO_2 emissions in the near- to mid-term. However, health-based regulations effectively bar diesel in the light duty segment, making a technology deemed necessary elsewhere in the world a nonviable option for the United States. He noted the apparent conflict between health-based emission restrictions and energy policies, but countered that marketplace realities must be acknowledged. Any new technologies must meet customers' desires in order for sales to occur. Advanced powertrains can't be counted on in the near- to mid-term. Fossil fuel powered internal combustion engines will remain the choice for vehicles for the foreseeable future.

The Program for a New Generation of Vehicle (PNGV) illustrates the policy/marketplace conflict. PNGV goals were set in 1993 beyond the then-existing technological limits. The 10-year program seeks mature, affordable technologies by 2004. Illustrating this challenge is Daimler-Chrysler's D-C concept vehicle ESX-3, a direct injection diesel with an

[5] Current highway diesel demand is close to 2,000 MBPD. Some estimates place 2007 highway diesel demand at 2,600 MBPD, based on approximately a 3% growth annual rate plus the movement of a small amount of off-road diesel demand to highway diesel.

electric motor with a fuel efficiency of 72 miles per gallon (mpg) (gasoline equivalent). For the vehicle to be viable, it needs a zero-sulfur fuel in order to achieve Tier 2 standards.

Reviewing the challenges, Modlin said that existing tailpipe regulations appear to allow some flexibility for light duty diesel -- but these phase out by 2007, which doesn't allow a sufficient time span to develop and market a vehicle cost effectively. In addition, the requisite fuel won't be ready by 2004. The proposed sulfur cap of 15 ppm is not adequate to support after-treatment technologies. What this means is that new diesel engines are effectively choked out of the market by 2004 unless better fuel becomes available. He added that customers require improved cetane for better start up, reduced smoke and noise, and a smoother ride. US cetane levels are very low. (He also noted that the proposed regulations neglect to set limits on aromatics.)

In conclusion, he said that diesel offers the only option to significantly improve fuel economy in the near term, but the timing and stringency of emissions and fuel regulations are inconsistent and counterproductive. Fuel quality must improve beyond the current proposals.

3.1.6 Discussion of US Regulations and Their Consequences

It was noted that there is a trend towards fewer refineries and more imports of finished petroleum products in the US. What stands in the way of a major overhaul in US refining capacity? Leister said that it all comes down to money and financing. In Europe, governments have used financial incentives. A participant pointed out that we don't really have a systems approach. For example, on-road and off-road fuel sulfur will decline, but EPA won't regulate sulfur in home heating oil. This raises the concern about contamination in the pipeline. There is already a conflict in maximizing diesel vs. gasoline refining. A participant asked why not a massive overhaul of the oil-producing business in the US in order to clean the fuel supply. Fuel price fluctuations in the past year suggest that consumers could adjust to the cost of phasing in new fuels if industry were in agreement rather than in opposition.

With respect to Modlin's point about cetane content, a participant asked whether emissions increase with increased cetane levels. (Emissions decrease slightly as cetane increases, but the change does not appear to be statistically significant.) Leister noted that taking aromatics out of diesel fuel reduces the molecules that provide the most power. The point is that with every regulation, unintended consequences loom large. Concurring with this point, Modlin said that Daimler-Chrylser could have made their concept car 80 mpg, but they had to balance fuel economy with customer requirements and other concerns.

There was some discussion of the best way to get in-use compliance. A few participants suggested a "not-to-exceed" provision is the only realistic near-term alternative. There are a lot of unknowns in terms of test procedures, a big uncertainty for engine manufacturers.

3.2 Where Europe and Asia are Going with Diesel

3.2.1 Diesel Engine Status in Japan: *Katsuhiko Yokota, Isuzu*

Katsuhiko Yokota began with an overview of air quality in Japan. The air quality trend in Japanese urban areas has shown no improvement for several years. There were reductions in suspended particulate matter concentrations in the early 1990s, but no improvement since 1993 at both roadside and general ambient monitoring stations. Reviewing Japanese heath effects research, he described studies conducted by the Japan Auto Research Institute. They conducted long-term inhalation experiments of diesel exhaust on small animals, and the results suggested cancer risk at high concentrations. They also investigated the relationship between chronic obstructive pulmonary disease (COPD) and diesel exhaust, and found no effect at low concentrations but symptoms at medium and high concentrations. A $PM_{2.5}$ study is underway.

He showed a schematic indicating possible paths over the next decade for regulating various vehicle classes, and the Japanese decision-making process. The Central Council for Environmental Pollution Control makes recommendations to the Director General of the Environmental Agency. Following publication of recommendations, a technology assessment-like hearing is undertaken and standards are set.

Next, he compared Japanese, European, and US standards for heavy duty diesel vehicles. Japan's current standards are less stringent than Europe for both NOx and PM, and less stringent for US standards for PM but similar for NOx. New long-term standards are currently under discussion. They are not anticipated to be as stringent for PM but similar for NOx compared to future US and European requirements.

Reviewing various technologies including after-treatment and correlating fuel requirements, he showed two ways that future emission standards can be met by using after-treatment. Many of the technologies, including various diesel particulate filters (DPFs), the oxidation catalyst, and de-NOx catalyst, have low-sulfur fuel requirements. He further detailed a control approach including DPF and a de-NOx catalyst that is projected to approach the EPA 2007 standard if low-sulfur fuel is used. Japanese low sulfur gasoline is currently 10-15 ppm. In diesel, it is still 500 ppm but will be reduced to 50 ppm by 2005.

Finally, he described the proposed Tokyo environmental initiative. One-half of total NOx in Tokyo comes from automobiles (39% diesel, 12% gasoline), and diesel contributes one-third of suspended particulate matter. In "Step 1," there were five proposals, none of which have been carried out (they have only been discussed). "Step 2" contains nine action plans to reduce diesel emissions, including limits on the use of vehicles not satisfying gasoline engine emission limits and obligatory retrofitting of DPFs on heavy duty diesel trucks and buses. He noted that the cost of retrofitting a single vehicle with a diesel particulate filter (DPF) depends on the vehicle type. A two-ton garbage truck, for instance, would cost $8000.

Summarizing his points, he said that diesel exhaust gases seem to have harmful health effects, and these emissions should be dramatically reduced worldwide. Engine modifications should be required as well as after-treatment. The proposed Tokyo Environmental Initiative would require retrofitting of diesel vehicles and replacement with gas, CNG, and LPG vehicles. All considered, diesel vehicles have a bright future.

3.2.2 The European Framework: *Klaus Peter Schindler, Volkswagen*

Klaus Peter Schindler began with the development of European regulations of exhaust gases and particulate emissions. The first European legislation was in 1988. The steps are characterized by Euro 1 (1992) through Euro 4 (2005). He predicted that light duty truck standards will merge with those for passenger vehicles.

Cars in Europe also have to meet CO_2 requirements. Car manufacturers were forced to adopt a voluntary target of 140 g/km by 2008 (a 25% reduction from 1995 levels). Diesel engine contributions constitute a big part of meeting this goal. (He noted that of the Volkswagen group's sales in 1998 in Europe the diesel share was 39%) European measures to reduce CO_2 emissions include commitments of the European automobile industry, consumer information, official monitoring, and taxation/tax incentive schemes.

Volkswagen continues to work on improving internal combustion. They are also developing an oxidation catalytic converter, which requires improved fuels. If this approach isn't sufficient to meet the target PM emission levels, they will turn to particulate filters. If they can't lower PM emissions through internal combustion improvements, they will apply NOx exhaust gas after-treatment, which requires sulfur-free fuel (no more than 10 ppm).

He showed some data comparing regular diesel fuel with "Swedish" diesel fuel. The latter has produced great reductions in emissions, so they conclude that fuel improvements can have immediate positive impacts on air quality, whereas new technology requires time for introduction and fleet turnover.

The Worldwide Fuel Charter (a paper of vehicle manufacturers worldwide) calls for 10 ppm sulfur and other specifications such as minimum cetane number of 55. He contrasted this proposal with Euro 2005 specification. He showed Volkswagen's reduction strategy for the Golf and Passat models to meet Euro 4 without after-treatment, and for a concept car that is bigger and heavier which would require after-treatment.

Concluding, he acknowledged that diesel engine combustion produces NOx and PM, which is a problem that needs to be solved. However, the diesel engine is and will remain the most efficient powertrain system and is needed to fulfill the CO_2 commitment. Progress is being made towards after-treatment, and new improved fuels are a necessary element of the strategy to reduce diesel emissions.

3.2.3 Diesel Exhaust Emission Control in Europe: *Jacques Lemaire, Rhodia*

Diesel is a popular choice in Europe for automobiles and light duty vehicles. In France, a favorable tax differential, fuel efficiency, and vehicle durability contribute to its popularity. Since Europe imports all its crude oil, optimizing its use is very important. But the public is becoming more aware of diesel emissions. To balance pollution control and fuel economy, the European Union (EU) established ambitious and unprecedented standards that simultaneously address emissions and fuel quality in two stages (2000 and 2005). For heavy duty vehicles, they effectively require the use of a particulate trap. Comparing heavy duty diesel regulations, he noted that US and European regulations for 2005-2008 are similar for PM but not for NOx. Some European governments are requiring diesel particulate filters (DPFs) for all trucks starting in 2005. NOx limits for 2005 are not stringent, but 2008 limits will require a NOx emission control device.

Ozone is less a public concern in Europe. Rather, the media and public perception focus on the image of diesel as a dirty engine with offensive odors. Lung cancer risk is not a primary health concern, but asthma risk is. Most PM debate focuses on short peak exposures for children and other at-risk individuals. The trend has been to shift focus to particle size and number rather than mass emissions only. All considered, he noted that diesel-drivers love diesel engines and non-drivers hate them.

Starting this year, Peugeot is selling a car with a particulate ceramic filter regenerated by a cerium based fuel-borne catalyst. He showed a schematic of the system it uses. The engine with the filter emits exhaust with the same concentration of particulate matter as the ambient air.

In conclusion, he said that US and European standards for cars and light trucks are closer than ever. The EU 2005 standards are probably the last time diesel engines will face less stringent regulations than gasoline-powered light duty cars and trucks. The major European problem with PM is an urban problem, but there are no urban bus standards or retrofit initiatives in place. DPFs are now in commercial application on passenger cars, with measured control efficiency at close to 100%. Sulfur lower than 50 ppm is being sought by the Engine Makers Association and the German government supports 10 ppm, but strong opposition from southern European countries is expected.

3.2.4 The Future of Diesel -- A European Perspective: *David Rickeard, Exxon-Mobil*

"Auto-Oil 1" mandated specific reductions in vehicular emissions by 2000, 2005, and 2007. They anticipate dramatic reduction in emissions of diesel particulates due to these requirements. They also set standards for fuels for 2000. Euro 4 has set sulfur at 50 ppm and aromatics at 35 ppm, but so far they haven't set other specifications. The report on the "Auto-Oil 2" program has been drafted but not released yet.[6]

Most diesel fuel is used by commercial vehicles, but there is also a strong passenger car market. Emission levels are tightening but CO_2 is also under pressure. To emphasize diesel's good economy, he showed some data from a life cycle (well to wheels) energy efficiency calculation of various vehicles/fuels. Diesel was the most efficient by a big margin, at nearly 30% overall efficiency. LPG, the next highest, was around 24%.

He then discussed the diesel vehicle of the future. He believes that many light duty diesel cars will meet Euro 4 without advanced after-treatment. For heavy duty, there is more uncertainty with respect to hardware, and several options are being pursued. The technology is developing rapidly, however some of the new technologies are sulfur-sensitive. Therefore the appropriate sulfur level is important in order to enable future hardware.

He pointed out that although non-sulfur fuel changes can also change emissions in the existing fleet, the 2005 and newer model year vehicles won't show lower emissions. This is because in Europe the certification fuel is based on

---

[6] The Auto-Oil process was a 'tripartite' program between the European Commission and the two industries. It formed the basis for the Commission's' recommendation to the Parliament when they debated and decided on the Euro 3 and Euro 4 regulations.

the market average. Vehicles certified in 2005 will have just the same emissions as if the fuel had not been changed. In sum, sulfur is the key component since reducing sulfur allows new vehicle technologies to be used. He contrasted enabling fuels (which affect the current and future fleet) with non-enabling fuels (which only affect the current fleet).

He reviewed the challenge of decreasing sulfur. The cost in cents/gallon seems small but it corresponds to significant costs for individual refineries. Therefore decisions should be based on sound science and cost efficiency. The cost of further decreasing sulfur increases dramatically as the concentration of sulfur decreases. We need to choose the level on the basis of the need to enable new technology.

Next he turned to the issue of the size and number of particles (in contrast to total mass). There is a growing interest in the size distribution of particulates. He discussed some of the issues related to sulfate formation with respect to various fuel and control options. For example, some PM filters can increase the formation of sulfates. There is a strong need for better understanding these issues.

Summarizing his talk, he said that currently planned measures will dramatically decrease vehicle emissions in Europe through 2025. Diesel vehicles will continue to be important. Fuels have an important role in enabling new technologies.

3.2.5 Where Europe and Asia are Going with Diesels: *Mike Walsh, Consultant*

Mike Walsh began by noting the two forces at work: conventional pollutants and greenhouse gases (GHGs). In the US, the emphasis is on conventional pollutants, whereas in Europe and to a lesser extent Japan, there is more emphasis on CO_2 and greenhouse gases. Walsh highlighted the global warming concern. In Europe, there is more acknowledgment of the problem. The US has a higher fraction of CO_2 emissions from the transport sector, but Europe is close. Europe has adopted a “voluntary” agreement to lower CO_2 emissions, and the increased penetration of diesels plays an important role in this. He noted that Europeans tax gasoline at higher rates than diesel fuels. The ozone problem is not perceived to be as bad as in the US, despite the fact that the standard was exceeded 60 days in southern Europe (10 days in northern Europe)..

The trend in at least one country in Europe (England) is that overall PM_{10} emissions from gasoline vehicles are declining as diesel PM_{10} increases. To counter this, Europe has moved fairly aggressively to control diesel vehicles and fuels. The tightest HDV standards in the world are contained in Euro 3, 4, and 5. Germany is pushing for lower sulfur (10 ppm maximum) fuel.

It was expected that particulate filters would be needed to meet 2005 diesel passenger car standards, but engine improvements have been such that this might not be so. To comply with heavy duty standards, filters and NOx after-treatment will likely be needed. Individual countries can encourage early adoption of low-sulfur fuel with tax incentives. (Germany in particular is pushing for lower sulfur requirements for diesel in order to assure the feasibility of the new standards.) Sweden has had low sulfur fuel (less than 10 ppm) for many years. An ongoing issue is the comparison of carcinogenic potential of diesel vs. gasoline emissions. With particle filters, they are dramatically closer. Since particle filters do a good job across the size distribution, this is another reason that this technology is being pushed.

The European Environment Commissioner, Margot Wallstrom, has issued a European “call for evidence” on very low sulfur fuel. It is intended to look at incremental benefits and refining costs, the potential linkage to advanced technologies, and the impact on other fuel parameters. The overall impact on greenhouse gas emissions as well as logistical and investment implications will also be examined. The Eurpoean Commission will evaluate the comments received and determine whether to propose tighter sulfur requirements.

He then summarized Japanese developments. Diesel car and truck standards were tightened last year, but are still relatively weak. Low sulfur fuel is planned for 2005, but the requirements are vague. It will certainly be no higher than 50 ppm. The Tokyo government and courts are pushing for faster action. (He noted that courts recently found the government and a private highway owner liable for a class action by asthmatics). A major retrofit program has been proposed for Tokyo, and the government is going to issue a major report on diesel toxicity. He showed details of the Japanese standards.

Finally, he reviewed the situation in some other Asian countries where there is some movement away from diesels. Hong Kong recently adopted a tax incentive for 50 ppm sulfur fuel, and is shifting its taxi fleet from diesel to LPG. South Korea and Beijing are shifting to CNG buses. In India, the Supreme Court is trying to ban diesel buses, and Taiwan tried to ban the sale of diesel cars.

In conclusion, he said that Europe pushes on fuel efficiency and decreased CO_2, but allowed more lenient NOx standards. The drivers for further reduction will be lower sulfur fuel, diesel NOx standards as strict as gasoline NOx standards, and the use of PM filters.

3.2.6 Discussion

Taxation policies in Europe, which affect drivers' vehicle choices, were discussed at some length. In some countries, diesel has a tax advantage. Schindler noted that in Germany the purchase tax is actually higher, but the fuel tax is lower. An automobile owner would have to drive 12,000 km per year to make it cheaper. Walsh noted that the OECD (Organization for Economic Cooperation and Development) has determined that lower diesel fuel prices may result in more driving of diesel cars, thereby offsetting the potential reduction in CO_2 that diesels might otherwise provide. Given the frustration of US engine manufacturers with regulation and given the real progress that has been made in Europe using tax policy to encourage sulfur reductions, it was questioned why the US fuel industry isn't advocating this approach for the US. Walsh replied that the utility of tax policy on all aspects of vehicles is a lesson we can learn from Europe, but added the big distinction that fuel in the US is cheap. In Europe, it's accepted that taxes constitute the dominant part of fuel prices. The European acceptance of taxes as mechanisms of social or environmental policy is very different from the situation in the US.

The role of various technologies in different countries was discussed. Walsh clarified that the shift away from diesels in Asia is for buses and passenger cars, not heavy duty vehicles. It was questioned why there isn't more attention to diesel hybrids in Europe. Schindler responded that given Europe's greater experience with diesel, they don't see a need to pursue hybrids if they can meet the standards with diesel alone. Europeans are satisfied with a small diesel vehicle instead of a big hybrid. The issue of two-stroke engines in highly polluted Asian cities was raised. The presence of these vehicles varies significantly from city to city. In Delhi, two-stroke vehicles comprise 70% of the urban fleet and are a major pollution problem, but this is not the case in Beijing, for instance.

Other aspects of fuel regulations were raised, such as other countries' experience regulating lead in fuel. Japan phased it out long before the US, however Europe moved more slowly. Some European countries eliminated it several years ago, some just now, and others still have a few years to go before final phaseout. The role of cerium as a fuel additive was also questioned. Cerium can increase filter efficiency as a fuel-borne catalyst. The Peugeot car carries cerium on board. The Health Effects Institute (HEI) is reviewing the impact of cerium added to fuel.

Participants questioned the continued concern about diesel carcinogenicity in light of other particulate non-cancer mortality risk. Lemaire replied that Europeans are more concerned about the acute effect of pollution peaks, whereas the US is more focused on cancer risk. Schindler added that cancer risk is very important in Germany, and raising cancer arguments provides an advantage to regulators.

Finally, the point was made that pollution control engineers should think hard about likely failure modes and deterioration mechanisms in order to pursue technologies that fail in an acceptable manner. Vehicle manufacturer requirements would help in this regard.

DAY 2

4.0 THE ROAD TO CLEAN DIESEL: THE ISSUES *(Moderator: John Heywood, MIT)*

John Heywood noted that the focus of Day 2 is looking to the future. He noted the importance of everyone being educated about the various issues and technologies, particularly given that specialists are increasingly narrowly focused. It is also important in policy discussions to make distinctions between prototype technologies that are being developed and robust technologies that are ready for the market. In any reasonable time frame and scale, the gasoline engine is the only apparent real alternative to diesel. Contrasting the two, he said that they complement each other and showed a comparison across various critical cost parameters. For example, SI gasoline engines have good power density but lower fuel efficiency whereas diesel engines are more efficient. Diesel fuel is lowest cost, but catalytic technologies to control NOx emissions are not yet available. His recently completed assessment of future automotive technologies indicates that over the next 20 years, the SI gasoline engine will narrow the efficiency gap, and that the likely changes will result in the SI gasoline engine taking on many of the characteristics of diesel. Meanwhile, diesel catalyst technologies are promising but not yet ready for production.

Finally, he set the stage for the morning's presentations by explaining some fundamentals. He said that the emissions problem goes hand-in-hand with why diesel engines are attractive. We want a small, highly efficient engine. The diesel combustion process accomplishes this by injecting fuel directly into the cylinder just before combustion, which requires rapid mixing of fuel and air. This contributes to noise and soot formation. Because this is mixing-controlled combustion, most of the fuel burns in a stoichiometric flame. This is a high temperature process and therefore produces high amounts of NOx. The engineering challenge is to fix the latter while maintaining the former. There are hopeful ways to do this, but we are a fair way from practical reality.

4.1 Diesel Engine Design Improvements and Future Potential

Pat Flynn, Cummins

Pat Flynn began by clarifying that in internal combustion engines, temperature does not relate to engine efficiency. Instead, it is the expansion ratio the heated gas can go through. He plotted indicated thermal efficiency as a function of effective expansion ratios (EER). A diesel engine operates at higher efficiency and higher EER than SI engines. In SI engines, efficiency under light load can be quite low with greater efficiency under high load. For diesel engines, on the other hand, there isn't such an efficiency range associated with load. He contrasted a large 250 horsepower (HP) passenger car which would be expected to last at least 100,000 miles with a truck needing 500 HP. If they ran a gasoline engine at 250 HP, he said it wouldn't last 10 hours. The gasoline engine lasts 100,000 miles because it's only putting out 25 HP and never goes to the high temperatures. A truck burning gasoline needing 500 HP would need a 40 liter engine, which would simply be too big. A diesel engine of that power only has to be 12-15 liters.

So, he summarized, high expansion ratio power plants are needed. If a truck burns 2-3 times the purchase cost of the engine in fuel each year, efficiency is very important. Diesel provides it at lower operating cost and CO_2 emissions but we must control for PM and NOx.

He showed a few charts detailing the evolution of engine emission control. Engines used to emit 15 grams / HP-hr of NOx. Emission improvements came with retarded timing, reduced friction, higher compression ratios, and variable injection timing, among other innovations. Some of these were at some expense to fuel economy. For 2004 standards, Exhaust Gas Recirculation (EGR) will be used to cool the flame temperature. This is not at the expense of indicated efficiency but possibly worsened brake thermal efficiency. 2004 requirements call for a cumulative 90% reduction in PM and an 85% reduction in NOx from early emission levels, but new 2007 proposals would require an additional 90% reduction in NOx and PM, and the controls must operate for hundreds of thousands of miles. These will require active after-treatment systems, involving mechanical systems (valves and injectors) inside the hot environment of the engine. There is little experience with these systems. One attempt at PM traps was not successful.

Another complicated aspect for after-treatment systems is that diesels operate with a lean oxygen rich exhaust stream. However, diesel NOx after-treatment needs a rich, oxygen depleted operating environment with an introduced chemical reductant. The regeneration of an after-treatment device to remove sulfur will need to operate in an even hotter environment. Engines must be certified to go anywhere in the US, and exhaust temperatures during northern winters are not hot enough to do the job. There are interesting and promising things with respect to after-treatment, but no proven devices.

He showed a schematic of a flame, and explained Cummins' analysis of where and when things happen in the engine. Most fuel is burned in a two-stage process involving a rich pre-mixed reaction followed by a peripheral diffusion flame. The initial cooler burn releases a lot of particulates, but the thin surrounding high-temperature diffusion flame forms NOx and consumes particulates. Their observations show that there are three critical temperature ranges in which different chemical processes occur.

He showed fuel NOx as a function of gross indicated fuel consumption and how this relates to flame temperature. There are two curves, one corresponding to complete and one to incomplete combustion. Engineers can cool the combustion process to a point of lower NOx emissions, but the lower limit is 5.5 grams NOx/kg fuel, because below this the process shifts to the incomplete combustion curve. This translates to 1.5 gm/b-hp-hr NOx, and this is why after-treatment is needed in order to further reduce NOx emissions.

Turning to fine particulates, he showed the number/size distribution data from the HEI report.[7] New engines decrease the mass, but increase the number of fines. Another experiment under "roadway chase conditions" showed that condensation of fine particulates depends on ambient conditions. The nanoparticle component appears to consist mainly of volatile materials; ultrafines are condensates formed after the exhaust gases pass out of the tailpipe. They further found that low sulfur fuel combined with an oxidizing catalyst effectively prevents nanoparticle formation.

Summarizing, he said that carbon particulate formed during combustion would require removal with actively controlled particulate traps. Elimination of fine particulates formed by condensation at the tailpipe exit requires removal of sulfur from fuel and oil. His conclusions are that active after-treatment for both NOx and PM will be needed in the future, but much research and development is needed in order to reach the ambitious target of 90% efficiency over 435,000 miles.

Discussion

Flynn clarified that emissions control system maintenance must be paid for by the engine seller through 435,000 miles, because manufacturers must warrantee the emissions of engines for that specified useful life under existing emissions regulations. It is difficult to project a reasonable time frame to accomplish these hypothetical goals, but there are good opportunities. He clarified that the chemical composition of the ultra-fine particles from diesel combustion consists of a mix of higher molecular mass hydrocarbons, water and sulfates.

4.2 Emission Control Systems and Fuel Requirements for Mobile Sources

Tim Johnson, Corning

Corning is one of the original catalytic converter companies. In the early 1980s it invented the diesel PM filter. Since then, the companies watched as opportunities came with each step change in the regulations and then disappeared, as engine companies did an excellent job of developing engine technologies that obviated the need for catalytic converters. He is optimistic based on this track record that the proposed stringent reductions can be met.

[7] Bagley, S.T., K.J. Baumgard, L.G. Gratz, J.H. Johnson, and D.G. Leddy. 1996. *Characterization of Fuel and Aftertreatment Device Effects on Diesel Emissions*. Health Effects Institute (HEI), Research Report No. 76. See also Kittelson, D.B., P.A. Kadue, H.C. Scherrer, and R. Lovrien. 1988. *Characterization of Diesel Particles in the Atmosphere*. Final Report, Coordinating Research Council.

Johnson showed US 2007 vs. Euro 4 & 5 regulations. He showed details of improvements to the Deutz 2013 prototype engine, which comes close to Euro 4 without traditional emission control equipment. He then reviewed the options for further reductions. Leading PM technologies include continuous regenerating filter systems and catalyzed soot filters. The efficiency depends on how "dry" the PM is. Leading NOx technologies include SCR, NOx adsorbers, and non-thermal plasma. He discussed issues related to each of these.

Next, he discussed particle formation in some detail. Particle form is dependent on the HC content of the fuel, however the particle size distribution of soot in the cylinder is independent of fuel. Nanoparticles are aerosols of H_2SO_4 and HCs, and their concentration depends on time, temperature, and dilution ratios. The current theory is that nanoparticles precipitate as sulfuric acid and then grow with HC adsorption. The relevant point is that there are two types of particles: solid PM, and nanoparticles which are droplets.

He then explained how PM filters use porous ceramics and a catalyst to collect and burn the solid PM. Filters are very efficient and can clean the exhaust to ambient levels, but they are strongly dependent on sulfur levels in the fuel. Filters are also very efficient at destroying toxic emissions (PAHs, etc.). Johnson Matthey tested the durability of filters in use on various vehicles, and analyzed their performance using dynamometers. In Department of Energy (DOE) consortium work, at 150 ppm sulfur, filters have little effect on PM. Even at 30 ppm sulfur, emissions exceed requirements (the bulk is H_2SO_4). Their analysis shows that 15-20 ppm sulfur is the maximum level that can achieve the 2007 requirements. Therefore, Johnson concluded, there is some logic to the EPA proposal.

The DOE program also examined sulfur's impact on the ability to regenerate the filter. At all loads, going from 3 ppm to 30 ppm increases the filter regeneration temperatures significantly, perhaps making them more prone to plugging in cold operations. Summarizing his discussion of filter technology, he said that PM filters have been retrofitted on 10,000 vehicles in Europe with minimal operating problems. Very high efficiencies have been obtained including the reduction of toxins.

Next, he turned to the control of NOx, which is the more difficult problem. The fundamental problem is that there is no catalyst available to facilitate the dissociation of NOx. Selective catalytic reduction is feasible, as are NOx traps that store NOx as nitrate, and plasma systems. He detailed these technologies, discussing the relationships between efficiency, size, and temperature, and showed some preliminary results for some of the systems tested. SCR is relatively insensitive to sulfur levels, but urea costs are equivalent to a 2-5% effective fuel penalty. There are other issues with tampering, urea distribution, and customer resistance. Moving on to the other technologies, he said that NOx adsorber catalyst efficiency is very sensitive to sulfur levels. Plasma shows promise for being an excellent sulfur-tolerant oxidizer of NOx. Summarizing the NOx control issues, he said that deNOx catalysts might remove up to 40% of the NOx (with up to a 5% fuel penalty) but this performance is sensitive to high sulfur levels. SCR is the leading technology in Europe, but there is resistance from truckers in the US. Non-thermal plasma technologies show promise, but NOx traps are emerging as the best passive technology.

Discussion

Asked why we can't decrease the rate of sulfur conversion to sulfate in order to meet PM requirements, Johnson explained that sulfate forms on the catalyst, so more catalyst equates with more sulfate. In reference to the catalyst needs for the SCR system and the sensitivity of the catalyst to sulfur, he said that the sensitivity is in the oxidation catalyst, which are not as strongly dependent as NOx adsorbers on fuel sulfur levels. With respect to the role of filter cake formation vs. continuous cleaning, he said that filtration efficiency is relatively independent of filter cake build-up because of the diffusion filtration mechanisms of nanoparticles.

4.3 Emission Control Retrofit Experience with Off-Road Diesel Equipment

Coralie Cooper, NESCAUM

Coralie Cooper discussed NESCAUM's focus on retrofitting the large and durable existing diesel fleet. She began by presenting a broad overview of NOx emissions in the NESCAUM region.[8] Diesel engines, including highway and

[8] NESCAUM covers the six New England states plus New York and New Jersey.

non-road, contribute about one-third of the NOx inventory. Looking at all non-road sources, the non-road diesel NOx emissions dominate. As for PM, non-road diesel will contribute about 60% of all mobile source PM by 2020 according to EPA projections. Furthermore, there is a disproportionate impact in urban areas where diesel engines and emissions are concentrated. Breaking future projected NOx emissions from non-road diesel equipment down by equipment type for the NESCAUM region, construction dominates (40%) followed by agricultural equipment (20%), and then lawn and garden equipment (11%). The figures are similar for PM.

She then discussed implementation issues with retrofitting. In 1998 NESCAUM conducted a pilot program. The issues they encountered included assessing exhaust temperature, checking fuel sulfur level, and avoiding engines that idle a lot. She showed some data which showed the highly transient (as opposed to steady-state) nature of construction equipment operation.

The two filters used achieved 86-95% reduction in PM emissions. The oxidation catalyst achieved 23% reduction in PM. The pilot project was considered successful, and the next step was to retrofit equipment in actual use. So far, they have retrofitted 100 pieces of machinery used in the Boston Central Artery Project with oxidation catalysts. Other NESCAUM projects include retrofitting airport-owned equipment at Logan Airport, urban buses in New York City, and 15 other construction equipment projects. Several Massachusetts state agencies are retrofitting agency-owned non-road equipment. NESCAUM is also working with terminal reconstruction contractors for Delta Airlines. Mechanism to encourage retrofits include Environmental Impact Review of large projects. In the future, they will explore technologies to reduce NOx from non-road diesels, and will continue to retrofit with oxidation catalysts.

Outside the region, other states and cities are also interested in pursuing similar programs, and she identified Denver, Houston, and Atlanta. She detailed EPA's Voluntary Measures Retrofit Program (VMEP), which allows states to get SIP (State Implementation Plan) credits in order to encourage retrofit initiatives based on a third-party verification program.

Concluding, Cooper said that retrofit programs can significantly reduce PM, HC, CO, and toxic emissions. There is also the potential for NOx reductions. Contractual requirements, incentives, and adoption of retrofit policies for publicly-owned heavy duty engines are effective means of getting equipment retrofitted. In-use testing is important to verify the success of programs.

Discussion

The cost of retrofitting construction equipment in Boston's Central Artery is about $1500 per oxidation catalyst installed. The Turnpike Authority has contributed $100,000 towards the effort. There are various motivations for equipment owners to undertake retrofitting. In the Central Artery Project, a requirement in the odor control section of its contract was implemented, aided by a lot of public concern. The Boston City Council applied pressure to contractors and agencies. Cerium additives were required only in the pilot project.

4.4 Diesel Exhaust and Airborne PM: How Low is Low Enough?

Roger McClellan, UNM

Roger McClellan began his presentation by highlighting the difficulties with extrapolating to risk levels that are of concern in establishing public policy and standards. When human data is available it is used. However, when it is not available it is necessary to extrapolate from laboratory animals and cells. Yet people are not just big rats, or just a collection of cells. A second extrapolation issue is how to assess the affects of pollutants at low levels.

He then moved on to some basic definitions. "Hazard" is a qualitative term meaning the potential for an agent or technology to cause adverse effects. "Risk" is a quantitative term, referring to the probability of an adverse outcome in a specific population under specified conditions/experience or use of an agent or technology. Given these definitions, Risk = Exposure x Hazard Potency. McClellan stated that he supports quantitative risk analysis, but both media and policy attention tends to be directed to the hazard side of the equation.

Next, he presented the exposure path:

Sources --> Ambient Concentrations --> Personal exposures --> Dose to target tissue --> Health response

He commented that we're interested in minimizing health effects at the end of this chain, but we target the sources at the beginning of it. This means it is very important to understand the linkages. There has been a strategy to classify agents by likelihood to cause cancer. Those classified as a human carcinogen number under 100. A couple of hundred more are classified as "probable human carcinogens" and perhaps 300-400 are "possible human carcinogens."

The Ames Test was developed in the late 1970s using genetically modified salmonella to detect mutagens. The assumption was that if a compound was a mutagen it was a carcinogen. Diesel exhaust particle extracts showed great activity in the Ames test. This initiated a wave of research on the mutagenicity and carcinogenicity of diesel exhaust extract.

However, the problem remains the bluntness of these tests. He explained that the smaller the exposed population, the higher percentage of excess risk required to detect excess risk. To identify a 50% excess risk would require 400 individuals. With this background, he related the studies that were conducted with diesel exhaust in rats and mice. Researchers exposed rats and mice to whole exhaust at three dilutions and controls. They measured lung burdens based on milligrams of soot and months of exposure. The lung levels at high exposures were higher than expected. Apparently, at low exposures the animals cleared the particles from their lungs, but not in the case of medium and high exposures. Pulmonary inflammatory response, proliferation of lung cells, mutations within the lungs, and alterations of lung functions in the highly-exposed test animals. When they looked at survival rates of control and highly-exposed animals, there was no difference at 24 months, where studies traditionally end. However, 80% of the resultant tumors were observed in the subsequent six months. The data were compelling from four major laboratories around the world: there was no statistically significant effect below 100 mg/m3-hr, and effects at higher exposures were attributed to "overload phenomenon." He said that they now do not think the rat data are relevant to assessing human risks. There was no excess lung cancer observed in the mice at any level of diesel exhaust exposure.

Turning to epidemiological data, he focused on lung cancer. Of 40 studies, about one-half revealed significant excess cancer rates. The relative risk figures determined from these studies congregate around a relative risk of 1.5, or a 50% increase. The use of these studies is problematic, however. One of the best studies looked at US railroad workers, but it is not appropriate for quantitative analysis because of uncertainties over the actual exposures that occurred years ago and the difficulty in teasing out the overwhelming impact of cigarette smoke. A 1999 EPA assessment concluded that "despite the statistical sophistication of the meta analysis, the statistical models used cannot compensate for deficiencies in the original studies and will remain biased to the extent that bias exists in the original studies." HEI's Diesel Expert Panel expressed appropriate concerns about the data. McClellan said that he's not very optimistic about going back and mining the data. He cited the difficulty in determining 1970 exposures in 2000.

Moving on to PM, he showed time trends of ambient pollution and daily mortality counts, and their correlation. In the elderly and children, there are clear signals of impacts. How should these data be looked at? Typically a linear relationship is assumed, but is it really linear at low levels? Are there thresholds? EPA and the EPA Clean Air Scientific Advisory Committee found no bright line distinguishing levels with effects from those without effects, so setting the standard must be a policy judgment. The DC Court of Appeals decision on ozone and PM National Ambient Air Quality Standards (NAAQS) identified constitutional issues of "delegation of authority from Congress to EPA under the Clean Air Act" in its decision to strike down EPA's standards. The court emphasized the need for clear "intelligible principles" for deciding how low is "low enough" or how high is "too high." The case is going to the Supreme Court this fall, and at issue is the need for explicitness about how such decisions are made.

Summarizing current knowledge of the health effects of diesel exhaust PM, he said that small particles are readily respired and may be retained in the respiratory tract for as long as years. These particles contain hundreds of complex organic compounds, extracts of which have been shown to be mutagenic and carcinogenic. Long exposures to high concentrations of particles causes lung cancer in rats by a mechanism that is unlikely to be operative in people with low-level exposures. However, epidemiological studies of certain workers suggest that diesel exhaust is likely to be carcinogenic when exposures are sufficiently high and protracted.

Past diesel regulations have been based on identification of the hazard without quantitative assessments of risk. The regulations have been technology-forcing. He posed the question "how low is low enough?" and noted that diesel is only one source of PM. Future assessment of hazard are unlikely to show diesel exhaust to be less hazardous. Future assessments based on an evaluation of health endpoints other than cancer may suggest that diesel exhaust is *more* hazardous than viewed previously. The use of qualitative estimates of cancer risk is unlikely to decrease the emphasis on control of diesel exhaust. Stringent standards for all PM will likely increase concern for diesel particulates. Absent clear "intelligible principles" for reaching decisions on "how low is low enough," the pressure will continue to reduce exposure to identified hazardous agents. He expects that pressure will continue to reduce emissions and personal exposure by improving diesel engine and fuel technology and exhaust treatment. To put diesel risk in the perspective of cigarette cancer risk, he noted that in the US, more than 100,000 people per year die from smoking-induced cancer. Some calculations have suggested that diesel exhaust exposures may add a few hundred cases.

Discussion

Quantitative risk assessment is potentially a good tool for "intelligible principles" but it must be coupled with uncertainties and costs. Expressions of uncertainty are needed to place bounds on numerical data and estimates. McClellan would argue that with $PM_{2.5}$ there is no clear line to aid in identifying an adequate "margin of safety," so the CAA approach to NAAQS is broken. There is a need to identify the most cost effective way to protect human health. He supports the use of goals rather than standards. A participant noted that this approach is used in Canada, where there has been less progress than in the US. It was also noted that the basis for emission standards isn't just cancer risk. There are enough other bases for concern about PM emitted near people to control to the level technically feasible. Some participants voiced concern about jumping to a cost-based approach. It assumes precision in the cost numbers, yet the range of uncertainty is almost as wide as the risk numbers. There is no precise formula. It is ultimately a political decision, and the public supports controlling diesel emissions. The question still remains for both diesel exhaust and particulate matter from all sources: "how low is low enough?".

A question was raised about the nature of PM coming from traps in 2007[9] (volatile material and H_2O_4) compared to gasoline engine emissions (metals, etc., from lubricating oil, wear, and the catalytic converter itself). It's not clear which is worse. The difference between diesel non-cancer health effects and those related to $PM_{2.5}$ was also raised. McClellan suggested that the effects are related, and differences depend on composition as well as particle size. Generally speaking, McClellan said that it's difficult to get scientists to work as a team to address policy issues such as these. People at risk typically have pre-existing conditions, and most of them are smokers or ex-smokers. The problem is that you can't buy time in biological systems, and therefore need to change the experimental strategy to put the emphasis on long-term studies in order to get the kind of data that are needed. There are some good retrospective studies but few prospective ones.

5.0 PANEL: HEALTH EFFECTS AND RISK ASSESSMENT *(Moderator: Dan Greenbaum, HEI)*

5.1 The EPA Assessment

Charles Ris, EPA

Introducing his talk, Charles Ris said that EPA has been assessing diesel health risk for 12 years. Diesel exhaust contains carbonaceous particles with some organics adhered, gaseous phase organics, and some metals. All of these have associated toxicological issues. Discussing diesel particles vs. ambient $PM_{2.5}$, he noted that diesel may constitute 6% of US ambient $PM_{2.5}$ inventory, but it can be as much as 30% locally. EPA is focusing its work on hazard identification and dose-response analysis. Having identified the hazards a dose-response analysis provides a tool to understand the hazard impact. A complete risk assessment would also include a full-blown exposure

[9] A variety of traps have been proposed for 2007 diesels. The three most likely are the continuously regenerating trap (CRT), the catalyzed wall flow trap, and the metal catalyzed wall flow trap (the current Peugeot system).

assessment and overall population characterization, but EPA's draft July 2000 Assessment is focusing on the first two aspects (it should be released by early August, and a review by the Clean Air Scientific Advisory Committee [CASAC] is planned). Some health hazards are clear, but others are less so.

With respect to acute exposures, he said that qualitative observations of effects include eye, nasal, and respiratory irritation and allergenicity. However, there is a lack of quantitative exposure correlation or dose-response data, so there is no dose-response relationship available to translate effects to human population exposures. Therefore, it is not yet clear whether there is a short-term exposure problem apart from chronic exposure. As for chronic exposures, the human data are scanty for noncancer chronic toxicity effects, though suggestive of respiratory effects. Rodent data, on the other hand, show clear inflammation and resulting adverse effects on respiratory tissue. There is fairly good confidence in human hazard identification for the noncancer chronic respiratory effects. These effects are similar (but not identical) to $PM_{2.5}$ effects.[10] It is unknown whether diesel health effects are significantly different from $PM_{2.5}$. We need to know the role of carbon particles, the organics, the two together, and the importance of gaseous components. Since sufficient human data for dose-response are not available, animal data together with a dosimetry model can be used to transform rat exposure-responses to expected human exposure-response in order to establish protective levels for chronic human exposure. Another issue is whether diesel, like $PM_{2.5}$, exacerbates existing health problems.

Turning to cancer effects, he said that human data show an increase in lung cancer risk across 20-30 studies, but they lack precise quantitative measurement of risk. There are also questions about the role of smoking in study participants, and uncertainty with respect to historical exposures. As for animal data, rat inhalation data is supportive of hazard and mutagenic activity, however this is not the case for mice or hamsters. All told, there is good confidence in the evidence for a lung cancer hazard for humans, and EPA classifies diesel exhaust as a "probable" human carcinogen. EPA believes that the hazard applies to environmental levels and not just occupational levels.

The remaining questions include how to better characterize occupational risk and the role of the different components in the exhaust. Also, is micrograms per cubic meter the best measures of exposure? It is difficult to determine until we have a better sense of the health effect mechanisms. He noted that California EPA has worked on characterizing dose-response for cancer, and that there are currently really only two occupational studies that had some quantitative exposure information that could provide a starting point for quantitative dose-response based risk assessment. On the horizon is a big NIOSH (National Institute of Occupational Safety and Health) epidemiology study designed for risk assessment. Results are expected in 4-6 years.

5.2 The California Perspective

Shankar Prasad, CARB

Shankar Prasad began his presentation by noting the California definition of a "toxic air contaminant" (TAC), which is "an air pollutant which may cause or contribute to an increase in mortality or in serious illness, or which may pose a present or potential hazard to human health." The California Diesel Report, adopted in April of 1998, had findings that diesel exhaust contains 40 hazardous air pollutants (HAPS), with a cancer risk range of 130-2,400 per million. The California Air Resources Board (CARB) Board adopted a resolution in August of 1998 determining that diesel PM should be listed as a TAC, and directed the CARB staff to develop a Risk Reduction Plan (RRP). This was just released (July, 2000) in draft form. Key elements of the plan include new engine standards, retrofit requirements for existing engines, and significant reductions in the sulfur content of fuel.

He showed statewide cancer risks for TACs for diesel PM (540 per million excess cancers per million people in California) vs. benzene (428) and perchlorethylene (15) based on estimated ambient concentrations. He noted that control measures have been taken for substances with lower unit risk factors than diesel. They project the statewide average risk to drop from 540 per million to 400 by 2010 with federal heavy duty standard implementation, and to 100 per million with CARB measures. The next steps involve adopting and implementing the diesel RRP, characterizing exposures and short-term effects, and examining pollutant interactions.

[10] Cardiovascular effects seen with $PM_{2.5}$ exposure haven't been rigorously studied in relation to diesel exposures.

5.3 Industry's Perspective

William Bunn, NAVISTAR

William Bunn began by questioning the science used in the determination of diesel's health effects. He noted that 1989 animal data drove EPA's "probable" carcinogen rating, but since then it has been determined that animal studies are not particularly useful for human risk assessment. We can't ignore the inconsistencies between human and animal data. Only two of the human epidemiology studies really measure anything, and he critiqued these. In particular, he highlighted the confounding factors of smoking and nutrition patterns, which might explain the incremental risk assessed. Industrial hygiene studies show that the epidemiology studies were primarily studies of other types and sources of particles. He concluded that we need a good diesel epidemiology study that eliminates these other confounders.

Next, he said we need to sort out the diesel PM/$PM_{2.5}$ issue. If the health effects of diesel exhaust is a particle effect, why separate the risk assessments, he asked. If it's not a particle effect, then health effects researchers need to sort out what it is. His opinion is that quantitative risk assessment is not appropriate, and that there's a danger in presenting to the public numbers like California's.

Finally, he detailed some ongoing science studies, including the HEI series. Future studies needed include prospective and retrospective approaches that look at morbidity as well as mortality, and that reconcile PM vs. diesel exhaust health effects. Qualitative risk assessment is still difficult to carry out. However, he believes that advanced technologies will be applied regardless or risk assessment outcomes. New technologies must proactively consider health risks as well as engine performance.

5.4 The Environmental View

Rich Kassel, NRDC

Rich Kassel first explained why environmentalists want to dump dirty diesels. The key word, he said, is "dirty." Ten million trucks drive a significant number of miles (VMT, or vehicle-miles-traveled), and this is growing at a faster rate than passenger car VMT. There is a growing awareness of environmental and health impacts. Discussing the ramifications of the current understanding of diesel health risks, he said that the precautionary principle is not being applied in regulating diesel toxics. He called for doing what we can to reduce exposures. Causality is important, but we need to act on what we do know. EPA could act broadly to address ambient toxic levels, but has chosen a limited source-specific view instead.

His second point was that non-cancer health effects are not being addressed sufficiently. The fundamental debate is whether diesel causes cancer, but this masks other important issues including asthma, premature death, recent Japanese findings about endocrine disrupters, and the general question of what is it about particles that matters to health.

Third, he commented on the growing practice that industry (rather than regulatory agencies) defines "clean diesel." New Jersey Transit calls its new buses "clean diesel" whereas their engines merely meet EPA's current emission standards. In addition, diesel companies challenge CNG on emission comparisons, but leave toxics out of the equation.

Finally, he said that there hasn't been enough community involvement in the issue. Health researchers need to address community concerns. Regulators need to get beyond grams per brake-horsepower-hour emissions to determinations of what people are actually exposed to.

5.5 Assessing the Toxicity of Diesel Exhaust

Diane Mundt, HEI

Diane Mundt reviewed information about HEI's involvement in understanding the health effects of diesel exhaust. In 1998 HEI began the Diesel Epidemiology Project, which included three main components. In March 1999, they conducted a workshop called Strategies to Improve Information for Diesel Risk Assessment[11] They also assembled an expert panel to evaluate the two quantitative epidemiological studies. The conclusion from this effort was that there were several limitations with the railroad workers data, and the Teamsters study might benefit from additional work to reconstruct past exposures.[12] HEI also funded a series of feasibility studies to evaluate new possible cohorts and new methods to obtain exposure data. The final reports from the feasibility studies are being peer reviewed and will inform research planning efforts at HEI regarding whether to fund another long-term study. They are also going to focus on acute effects of diesel exhaust and how it relates to other PM, mechanisms, and exacerbation of existing conditions

5.6 Health Effects and Risk Assessment Discussion

There was some discussion of Kassel's point about the importance of acting on what we know. Bunn's perspective is that it's important to do the right thing at the right time. Any change involves competing risks. We can do the right thing technically without setting a specific numerical reduction requirement. However, NRDC's position is that what we know changes over time, so we have to act on the best available information at decision points. For example, EPA's approach to PM locks in a mass-based measurement for four years.

There was a caution that diesel exhaust is a changing entity over time, and emerging toxicity studies need to account for this. There is a lot of uncertainty in the health data, but we can draw some conclusions based on trends. Nevertheless, it's still difficult to determining whether new information supports an increasing or decreasing diesel risk. Asthma rates are increasing but we really don't know why. It was noted that it may be a disservice to tell communities that diesel is the culprit. We would need to follow up on any decrease in diesel emissions by looking for any associated decrease in asthma. There is an interest in these communities, however, in identifying the variables that government can address to reduce an asthma trigger. (It was pointed out that there is a distinction between the incidence and cause of asthma and triggers which set off an attack.)

Other areas of research were discussed. There may be some efforts to look at diesel exposure data in Asia, where personal motorization is low but diesel vehicles are old and dirty. The World Bank has conducted some PM studies in some of these countries. A California report has an analysis of what happens to exposures over a 20 year horizon with regulations implemented. Finally, it was noted that HEI will issue a Request for Applications too begin the process of looking more systematically at distinctions between diesel engines, exhaust treatment, and fuel content.

6.0 PANEL: VIEWS OF THE FUTURE: WHERE WILL DIESEL FIT IN?

Moderator: Richard John, Volpe National Transportation System Center, DOT

Pat Flynn, Cummins
Allen Schaeffer, Diesel Technology Forum
Alan Lloyd, CARB
Klaus-Peter Schindler, VW
Jason Grumet, NESCAUM
Rich Kassel, NRDC

Richard John began by focusing the discussion on three issues: (1) what forces over the next 10-20 years would cause an increased penetration of diesel into the light duty arena? (2) Are climate change concerns sufficient to bring back CAFE (Corporate Average Fuel Economy) standards or fuel taxes? (3) Looking ahead, how much more stringent might diesel emission requirements get?

---

[11] The document is available from HEI.
[12] This report as well as related information and documents are available on the HEI website, http://www.healtheffects.org.

Pat Flynn spoke first. He said that looking at the "Big Three" diesel manufacturers, each company has a different relationship with and present commitment to light duty diesel. Chrysler doesn't have these engines and seems hesitant to introduce them given current uncertainty. General Motors has a pre-existing relationship with Isuzu, so it's a low-risk path. After 2007, it will depend on when emissions become equivalent to gasoline vehicles. Generally speaking, if the technology evolves with respect to emissions and relative fuel prices change, diesels may eventually have a place in the light duty sector. He is confident that the particulate emission problem will be solved, but the NOx issue is more challenging. With respect to future regulations, he said his company prefers performance standards that are fuel neutral so the decision can be made based on economics and technical capability. The climate change issue is really a matter of political will, he said. Asked about other advanced technologies not yet in the marketplace that might be a substitute for 18-wheel long-haul diesel trucks, he reviewed a few technologies. CNG is used for buses, which is a small market and not an economically viable business for Cummins. But for a long-distance, heavy load vehicle, the space needs of CNG's heavy tanks wouldn't work. As for hybrids and fuel cells, they would need to look at applicable duty cycles. Hybrid doesn't make sense unless the average power demand is significantly lower than the peak power demand. It also must have a demand cycle where there can be energy recovery on a short (minutes) time scale -- possibly for urban buses and pick-up and delivery trucks. He noted that these are small niches, though. There is anxiety over fuel cells' potential for market penetration. It largely depends on reformer technology; because gaseous fuel is only viable for a captive fleet with short range, liquid fuel is needed. However there are questions concerning well-to wheel efficiency. There may be initial niches, but he's not sure about beyond that. Asked about the problem of lubricant composition, he said that they have a model with the best oil consumption in the market, but it is still at a level that would harm an adsorber. With respect to in-use certification, he said that it is the manufacturer's responsibility to certify the controls for their full useful life. They will need to examine the economics of this and determine how to make such a requirement work.

Allen Schaeffer of the Diesel Technology Forum[13] was the next panelist. The message of the Diesel Technology Forum is that "Diesel powers the world." It is a vital, efficient source of power, and we have made significant progress reducing emissions. Modeling has huge uncertainties but we rely on it heavily for regulatory decisions. Health concerns exist, but there are many uncertainties. We've learned that there are many tradeoffs, e.g. criteria pollutants vs. GHGs, which involve political determinations based on values. There are differing domestic and international policies and priorities for diesel. Energy efficiency is often overlooked. He heard a strong theme from the auto manufacturers with respect to the potential for light duty diesel. The market forces that could push the use of diesel in the light duty sector are reliability and durability, towing needs, and public policy including Corporate Average Fuel Economy (CAFE) standards. The US system fosters a disjointed and fragmented view of diesel power, and he cited the focus on risks rather than benefits, and the focus on new engines and standards rather than vehicle operation. Furthermore, he said that taxation and marketplace approaches are opportunities overlooked. He said that EPA's system approach for standards (engine, after-treatment, fuel) was long in coming. He has heard resounding concurrence over the need for improvements despite arguments over specific numbers. As for the future, he feels that the focus will shift more from new engine standards to existing equipment, including I/M and retrofit programs. There is still a need to fix existing smoking engines. Some states have begun smoke testing programs, but many states don't do anything at all. They'd like more states to adopt these programs, which help combat the negative image from visible puffs of black smoke. There are opportunities for retrofits, and current efforts include California school buses and US Navy ships stationed in Norfolk, Virginia. His organization is working with EPA on a challenge to retrofit 10,000 engines. His conclusion is that there are significant challenges in technology, policy, and communications. There is a commitment to address these problems and take diesel to the next level. He cautioned people not to underestimate the importance of diesel power to our quality of life and economic well being. In the future, he thinks diesel will fit in everywhere.

Alan Lloyd spoke from California's perspective. He said that diesel's future will depend on our ability to clean up the existing fleet and get new technologies into the marketplace. California regulators are trying to do a lot of health studies and field studies, and they are moving with aggressive but sensible regulations that have translated to improvements in air quality. Diesel concern is moving into communities. People are becoming aware of exposures and are requesting monitoring. With respect to climate change, he said that it is an important factor, and diesel's energy efficiency/CO_2 attributes are important. Higher atmospheric temperatures will lead to increased ozone

[13] http://www.dieselforum.org

formation, so there is an indirect link between global warming and urban air pollution. With respect to the existing fleet, he said that both on- and off-road emissions need to be addressed. California is planning to retrofit 1.25 million engines, mostly mobile and some stationary, starting immediately. This represents both a challenge and an opportunity in the form of job creation. He noted that the state's plan is supported by the California trucking industry. If the retrofitting efforts fail, the future of diesel will look very different. He noted that CARB is disappointed that EPA didn't push for the same sulfur reduction in off-road fuel. Finally, he discussed California's fuel cell project (which has the participation of numerous automobile manufacturers and oil companies, DOT, DOE, and others) and some of the technical issues related to fuel cells. In response to questions, he said that more attention on in-use testing is needed.

Klaus-Peter Schindler showed the growth in mobility by mode since 1800. The challenge is the need for individual mobility in light of requirements to protect the environment from emissions and to reduce noise and fuel consumption. Conservative vehicle powertrains include diesel engines, gasoline engines, and transmissions. Alternative powertrains include gasoline reformers (for fuel cells), hydrogen fuel engine, electric vehicles (including fuel cell), and natural gas fuel vehicles. Comparing the conservative systems in terms of fuel consumption, he said that gasoline spark-ignition uses more than direct injection gasoline, which uses more than compression ignition, which uses more than turbo direct injection diesel. Fuel consumption and CO_2 emissions are coupled. But, he said, CO_2 is only half of the global warming problem, and we need to take into consideration other greenhouse gases, including emissions from fuel production. Comparing gasoline, diesel, methanol fuel cell, and hydrogen fuel cell, diesel is the most energy efficient. (With renewable energy, the potential for hydrogen fuel cell vehicles greatly improves.) Over the next 20-30 years, gasoline and diesel will remain the most advanced vehicle systems. He said that the modern diesel engine is powerful, economic, and ecological, and Volkswagen's priority is to reduce primary emissions first. Concluding, he said that the failure to meet NOx limits poses the biggest threat to the future of diesel technology, and that to enable new exhaust gas aftertreatment technologies, further fuel quality improvements are needed.

Jason Grumet began by noting that the Northeast is characterized by a lack of light duty diesel vehicles and a higher rate of vehicle turnover due to salted highways. He said that he isn't eager to see an increase in light duty diesel vehicles; we need to address present and past diesel before embracing future diesel. He advocated a fuel-neutral approach, with the benchmark being what's possible with gasoline vehicles. Performance standards are key. With respect to climate change, he said that it will probably be several years before the US seriously grapples with the problem. (He stated that advocating diesel for addressing the climate change problem is like taking up smoking to lose weight.) However, he conceded that with EPA's proposed rules, "clean" and "diesel" might eventually belong together in the same sentence. He is generally enthusiastic about efforts to address existing stock with retrofits by taking advantage of the opportunity in "coerced voluntarism." We need to focus collectively on in-use emissions. Finally, he addressed the integration of academic and regulatory advisory committees. These processes move forward without a deserved deliberative process, and have become very polarized. He contested the presumption that it is possible for any panel to be independent and unbiased. He doesn't think that these so-called independent panels are working as intended, and there is a danger that the public will start to mistrust them. It is more useful to have a more process-oriented discussion, including public disclosure, access, etc., and he cited the example of the Clean Air Scientific Advisory Committee (CASAC) coming under fire for holding public meetings that the public was never made aware of.

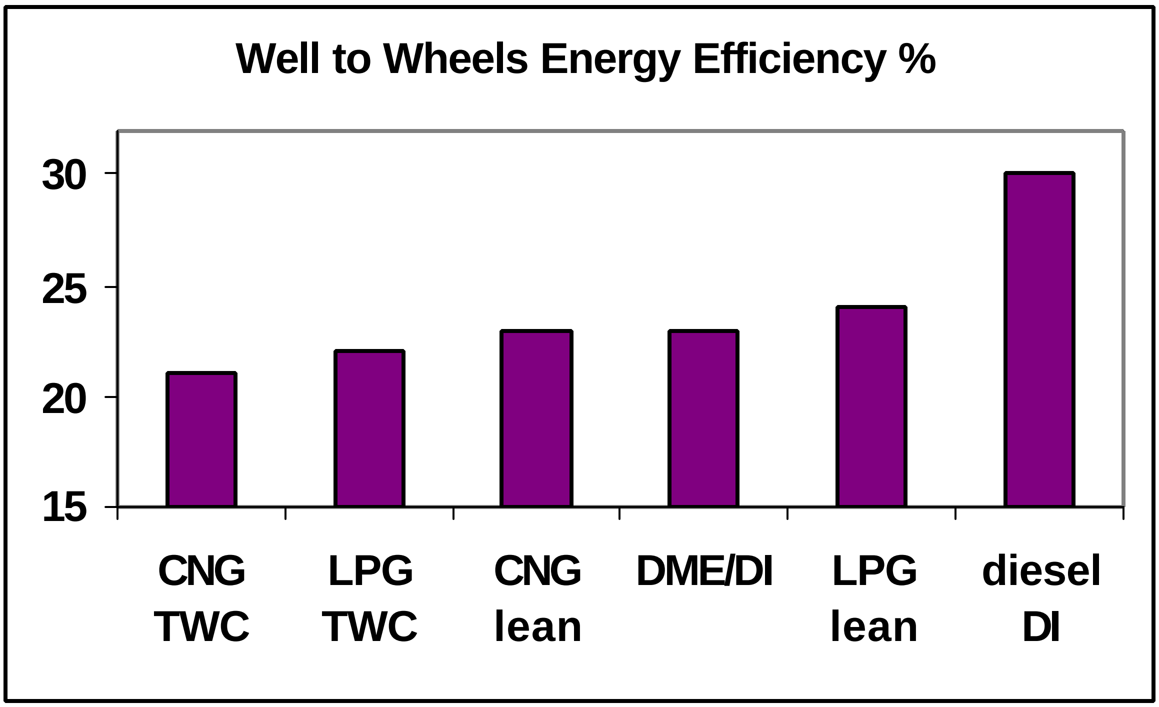
Speaking last, Rich Kassel addressed the issue of light duty diesel. He thinks that public health concerns about diesel will increase, and the manner in which these issues are addressed will largely define the future role of diesel in the light duty fleet. Public concern about greenhouse gases will also increase, he said, but so long as fuel prices are low compared to worldwide levels, the US is not likely to see a switch to diesel for fuel efficiency purposes. With respect to climate change as a catalyst for CAFE standards and fuel taxes, he suggested that the issue of sport utility vehicles (SUVs) being "free riders" will become the catalyst for fuel economy requirements. Movement on CAFE requirements will happen as soon as the first company says that their SUVs will perform at the level of passenger cars. Fuel taxes are a different issue, however, and will be a difficult policy to impose given the future orientation of the climate change issue. In the future, he predicted there will be no single fuel or technology that will be "winner-take-all" as it was in the 20th century. Likely, CNG, hybrid electric, and fuel cells in transit buses or other urban fleets will all have a place. Long distance trucks might still be diesel-fueled, but with low-sulfur fuel and aftertreatment. At some point, fuel prices might become a factor to increase penetration of light duty diesel vehicles in the fleet. Non-road diesel engines will increase in environmental importance, as they are big, they are dirty, and they last a long time. Summing up, he said that to create cleaner diesel vehicles for the future, EPA must finish the Diesel Health Risk Assessment; require 15 ppm sulfur by 2006 and 0.2 g/bhp-hr NOx and 0.01 g/bhp-hr PM by 2006; and implement an in-use compliance and enforcement program that works.

APPENDIX I: LIST OF SPONSORING ORGANIZATIONS

American Petroleum Institute
California Air Resources Board (CARB)
Chevron Products
Cummins Engine Co.
Engine Manufacturers Association
ExxonMobil
General Motors Corp.
The Health Effects Institute (HEI)
MIT Center for Environmental Initiatives
MIT Energy Laboratory
Northeast States for Coordinated Air Use Management (NESCAUM)
Pennsylvania Power & Light Company
Sun Oil Company
Volkswagen America
US DOT Volpe National Transportation Systems Center
US EPA/MIT Center on Airborne Organics
US EPA Office of Research & Development

APPENDIX II: WELL-TO-WHEELS ENERGY EFFICIENCY DATA PRESENTED BY DAVE RICKEARD

Diesel provides energy- efficient means of transport—but with penalty of high NOx/PM



APPENDIX III: ACRONYMS

CAFE	Corporate Average Fuel Economy
CARB	California Air Resources Board
CASAC	Clean Air Scientific Advisory Committee
CNG	compressed natural gas
CO_2	carbon dioxide
COPD	chronic obstructive pulmonary disease
DOE	Department of Energy
DOT	Department of Transportation
DPF	diesel particulate filter
DRI	Desert Research Institute
EER	effective expansion ratio
EGR	Exhaust Gas Recirculation
EMA	Engine Manufacturers Association
EMFAC	Emissions Factor (Model)
EPA	Environmental Protection Agency
EU	European Union
FHWA	Federal Highway Administration
g/b-hp-hr	grams per brake-horsepower-hour
HAPS	hazardous air pollutants
HC	hydrocarbons
HDDV	heavy duty diesel vehicles
HEI	Health Effects Institute
HP	horsepower
I/M	inspection & maintenance
LPG	liquid petroleum gas
MBPD	million barrels per day
mpg	miles per gallon
MVEI7G	Motor Vehicle Emissions Inventory (California model)
NAAQS	National Ambient Air Quality Standards
NESCAUM	Northeast States for Coordinated Air Use Management
NIOSH	National Institute of Occupational Safety and Health
nm	nanometers
NOx	nitrogen dioxides
NRDC	Natural Resources Defense Council
OECD	Organization for Economic Cooperation and Development
PAH	polycyclic aromatic hydrocarbons
PNGV	Program for a New Generation of Vehicle
PM	particulate matter
$PM_{2.5}$	particulate matter smaller than 2.5 microns
ppm	parts per million

RRP	Risk Reduction Plan
SCR	selective catalytic reduction
SI	spark ignition
SIP	State Implementation Plan (under Clean Air Act)
SUV	sport utility vehicle
TAC	toxic air contaminant
VMEP	Voluntary Measures Retrofit Program
VMT	vehicle miles traveled