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PLENARY SESSION – Diesel Efficiency and Emissions Policy

View From the Bridge

Chair: **John Fairbanks, U.S. Department of Energy**

Diesel Engines: What Role Can They Play in an Emission Constrained World?

Tom Cackette
California Air Resources Board

Diesel engines move the goods our society and economy depend on, but not without a cost. Emissions from Diesel engines cause serious public health effects, including premature death. Soon new heavy-duty on and off-road engines will be equipped with exhaust emission controls that will greatly reduce the health damage caused by the emissions from these Diesel. Programs to retrofit some of these technologies onto existing engines are underway, which will accelerate the reduction in harmful emissions.

While diesel passenger vehicles are widely available and popular in Europe, they are currently but a niche product in the United States. Urban emission requirements currently stand in the way of their expanded use. However the same exhaust emissions controls that will clean up heavy-duty engines offer the passenger diesel an opportunity to comply with stringent emission limits.

California is also moving ahead to establish the first emission limits for motor vehicle greenhouse gases this fall. Diesel engines have an advantage of lower greenhouse gases compared to current gasoline engines, but technologies to reduce greenhouse gases from gasoline engines are available and cost effective. The question remains whether passenger diesels will be able to turn their low greenhouse emissions into a larger market.

This presentation will review where the Diesel engine stands in the regulatory world of urban and global pollution control, and will explore what the future may hold.

Diesel-Cycle and Alternative Diesel Fuels are Key to California's Energy Economy A Policy Perspective

James D. Boyd, Commissioner California Energy Commission

The Energy Commission is the state's primary energy policy-making agency, responsible for addressing the energy challenges facing California. With a strong economy and rapidly growing population, California's energy providers are faced with the daunting task of ensuring reliable, clean and affordable energy and transportation fuels. The implications of future vehicle emission regulations can have a profound impact on our citizens' lifestyle. Balancing environmental and energy policies with the public's desire for affordable transportation must be done in a coordinated manner.

For over four decades environmental concerns have driven investments, however, on the not-too-distant horizon we see significant, growing energy concerns. There have been early warning signs that a storm is brewing on energy markets and this is especially evident by the higher prices and greater price volatility; statewide, nationwide and worldwide. Fundamental energy issues are poised to significantly impact California's economic stability. Some of these include:

- California's gasoline and diesel demand continues to grow, 1.6 percent annually for gasoline and 3.4 percent annually for diesel.
- California's fuel demand surpasses refinery capacity, requiring higher-priced imports to meet demand and augmented marine and pipeline infrastructure to handle these imports.
- Regulations on fuels and engines may adversely impact the production of fuels and increase fuel demand, thereby increasing the prospects of fuel supply shortages, which will drive prices even higher.

The Legislature has sought ways for California to head off future energy crises and the Energy Commission and California Air Resources Board (CARB) have responded with several assessments of California's future energy demand, in the Integrated Energy Policy Report and AB 2076 process. Through a rigorous analytical effort, the Energy Commission and CARB have recommended policies and strategies to ensure that energy and environmental objectives are balanced. One strategy to meet our near-term energy needs is through increased use of light and medium-duty diesel vehicles. Using Fischer-Tropsch Diesel as a nominal 33 percent blend is another significant strategy.

The Energy Commission is studying numerous conservation and petroleum displacement technologies. We are seeking ways that government can assist a variety of markets and remove barriers to the expanded use of cleaner, more efficient fuels and vehicle technologies.

Today, Europe sets a strong example for California and the nation to follow. Advanced clean diesel engines, which meet 2007 emission standards, are an example of a viable solution that could alleviate our growing energy appetite while maintaining environmental progress.

To curb California's unfettered appetite for transportation fuels, the Energy Commission and other agencies will need to move forward in a bold manner, "leaving no stone unturned." Expanding energy conservation efforts and increasing the use of alternative fuels now will minimize the potential energy disruptions that are, without a doubt, looming down the road.

Assessment of Future IC Engine and Fuels Cell Powered Vehicles, and Their Potential U.S. Impacts

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Laboratory for Energy and the Environment
MIT

A recent evaluation of the performance of various promising powertrains in light-duty vehicles will be reviewed. The various vehicles' operating characteristics were evaluated with a propulsion system in vehicle simulation. These tank-to-wheel assessments were combined with well-to-tank assessments to provide inputs for fleet impact calculations. Scenarios for development lead times, production capacity growth, and penetration into future in-use light-duty vehicle fleets were then prepared for United States fleet impact projections.

Boosted downsized gasoline engines, low emission Diesel engines, and gasoline/electric hybrids were judged to be about one development cycle away from market competitiveness. Fuel cells appear to be several cycles, at least 10-15 years, away from market competitiveness. The more varied the technology from current technology, the slower the production capacity growth and the in-use fleet penetration will be.

The future reduction of light-duty fuel consumption and greenhouse gas emissions are dependent upon new technology. Since the time scale for significant petroleum reduction with the emergence of hydrogen fuel-cell vehicles is some 50 years in the future, the importance of promoting and achieving nearer term improvements in mainstream technologies is clear. For example, to slow the growth of the in-use fleet's petroleum consumption and greenhouse gas emissions new technologies must continually be incorporated.

The impact of combining several fiscal and regulatory policies into an integrated strategy to promote such nearer term technology improvements will also be explored. Fleet-based analysis of several integrated strategies indicate their potential for providing both market "pull" and technology "push" in the nearer term, as well as creating conditions more conducive to introducing hydrogen and fuel cell technology.

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SESSION 1 – Emerging Diesel Technologies

Chair: **Carl Maronde, National Energy Technology Laboratory**

The Myth of Engine Maturity and the Reality of Engine Efficiency, Durability, Commercial Viability, and Potential Improvements

John W. Fairbanks
US Department of Energy

Miles Creasy
Energetics

The Diesel engine is viewed by some as mature technology. It is viewed as a transportation propulsion engine that has already maxed out its potential efficiency because of its age and current number of applications. Reviewing the chronological history of the current and future transportation propulsion engines shows this to by a myth. The Diesel engine was patented in 1893; 44 years after the invention of the fuel cell and nearly 20 years after the invention of the "Otto cycle" or the gasoline engine.

Diesel engine applications increased dramatically through the last century. Diesel powered locomotives began replacing steam powered locomotives in the 30's and today Diesel engines power about 99 percent of non-electrified trains. Diesel engines power almost all of the inland marine fleet such as the tow boats, tugs, ferries, and personal yachts and have systematically replaced steam turbines in deep water cargo and passenger ships. Virtually all heavy duty class 7 & 8 trucks, off-highway vehicles, most school and transit busses, and utility trucks are Diesel powered.

Improved efficiency and reliability over other propulsion engines has been the reason for its further increased usage. Thirty years ago, the Diesel engine was typically 20 to 30 percent more fuel efficient than competitive engines. Since then, the Diesel engine has had a 25 percent increase in fuel economy while engine life has been improved by a factor of 4. No heat engine or potential propulsion engine has shown this sustained rate of improvement. The Diesel engine has consistently become the cost effective surface transportation engine of choice for most applications except personal transportation in the United States.

Where can the Diesel go from here? In Europe, Diesel engine powered personal transportation sales are approaching 50 percent of the market with current technology. New technology has the potential to improve the current efficiency of 40 percent to approach an efficiency of 60 percent. This can theoretically be accomplished with advances in electric turbocompounding, high efficiency thermoelectrics, lightweight materials, low friction coatings, more efficient turbochargers, and advances in combustion (which could lead to reduced or no aftertreatment requirements for emission compliance).

Will the personal transportation market in the United States accept the Diesel in the near term to reduce oil consumption? What are the fuels of the future? Currently in the light truck industry, Diesels are about 50 percent more fuel efficient and emit 37 percent less carbon dioxide. Future vehicle propulsion selection will be primarily influenced by the availability and cost of the vehicle and fuel.

Future Potential of Hybrid and Diesel Powertrains in the U.S. Light Duty Vehicle Market

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K. G. Duleep
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Walter McManus
J.D. Power and Associates

Diesel and hybrid technologies each have the potential to increase light-duty vehicle fuel economy by a third or more without loss of performance, yet these technologies have typically been excluded from technical assessments of fuel economy potential on the grounds that hybrids are too expensive and diesels cannot meet Tier 2 emissions standards. Recently, hybrid costs have come down and the few hybrid makes available are selling well. Diesels have made great strides in reducing particulate and nitrogen oxide emissions, and are likely though not certain to meet future standards. In light of these developments, this study takes a detailed look at the market potential of these two powertrain technologies and their possible impacts on light-duty vehicle fuel economy. A nested multinomial logit model of vehicle choice was calibrated to 2002 model year sales of 930 makes, models and engine-transmission configurations. Based on an assessment of the status and outlook for the two technologies, market shares were predicted for 2008, 2012 and beyond, assuming no additional increase in fuel economy standards or other new policy initiatives. Current tax incentives for hybrids are assumed to be phased out by 2008. Given announced and likely introductions by 2008, hybrids could capture 4-7% and diesels 2-4% of the light-duty market. Based on our best guesses for further introductions, these shares could increase to 10-15% for hybrids and 4-7% for diesels by 2012. The resulting impacts on fleet average fuel economy would be about +2% in 2008 and +4% in 2012. If diesels and hybrids were widely available across vehicle classes, makes, and models, they could capture 40% or more of the light-duty vehicle market.

How Exhaust Emissions Drive Diesel Engine Fuel Efficiency

George Muntean
Pacific Northwest National Laboratory

A key defining attribute of Diesel engines is its ability to produce shaft power efficiently. This efficiency advantage has led to its widespread application in transport, construction, mining, and agriculture. Traditionally, Diesel engine efficiency was dominated by three key physical processes - 1) effective expansion ratio of the power cylinder, 2) transport of air into and exhaust out of the engine, and 3) parasitic losses. Over many years of development, these three processes were improved upon through the use of better materials, higher cylinder pressure capabilities, improved turbocharging, and more sophisticated fuel systems. However, in the last twenty (plus) years nothing has impacted the design of the Diesel engine more than exhaust emission constraints. This influence will only be increasing over the next ten years as future regulations cascade through the various Diesel markets. This presentation will give a simple tutorial on how Diesel engine efficiency has and will be influenced by new combustion strategies, nitrogen oxides aftertreatment devices, and particulate controls. The presentation will give easy "rules of thumb" that will describe how and why fuel penalties are incurred. And finally, a discussion of the "art of the possible" will be given.

Design & Development of e-Turbo™ for SUV and Light Truck Applications

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Honeywell Turbo Technologies

The purpose of the project is to develop e-Turbo™ technology for application to light truck class passenger vehicles. Earlier simulation work had shown the benefits of e-Turbo™ system on increasing low-end torque and improving fuel economy by possibly 6 to 17 percent over and above the advantage that turbo Diesel engines offer compared to conventional gasoline engines.

In order to fully demonstrate the benefits of e-Turbo a simultaneous development of five technology elements is being undertaken. These five technologies are being developed in parallel on independent platforms in order to speed up the development process and minimize the effect of uncertainty of one technology on another. At a suitable stage of demonstration these technologies will be integrated into a single system suitable for light truck class Diesel engines. The five technologies under development are.

- Development of base electrical machinery integrated into a turbocharger to meet rigorous design requirements of shaft stability at high speeds, temperature tolerance at realistic duty cycles, power electronics, and controls capable of handling required power level. This was done on a small turbocharger in order to minimize design and development issues by leveraging the large base of technology and experience available for smaller turbo-Diesel engines.

- Development of a control system for integrated control of VNT, EGR, electrical power, and battery charge management.

- Development of a variable geometry compressor to take full advantage of the flow capability provided by electric assist at low speeds.

- Development of an innovative design turbocharger of matched compressor and turbine wheel sizes in order to provide flow range and flow control and minimize inertia so that electrical power demands are reduced.

- Development of turbine wheels made of low inertia materials such as high ductility ceramics and Titanium Aluminide to minimize power demand from electric assist.

These five technologies are under various stages of development. The paper will report the status of each, preliminary results, future plans, and estimations of benefits of using it on light truck class turbo Diesel engines.

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SESSION 2 – Fuels and Lubrication, Part 1

Chair: **Kevin Stork, U.S. Department of Energy**

Plasmatron Fuel Reformer Development and Internal Combustion Engine Vehicle Applications

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Onboard generation of hydrogen-rich gas can be used in a number of applications to improve environmental quality and reduce petroleum consumption of internal combustion engine vehicles. Plasmatron fuel reformer technology is being developed at MIT as means of practical on-board production of hydrogen-rich gas from a variety of fuels. The device is based on the use of a special low current, low power volumetric discharge in very rich fuel/air mixtures. Although the process is slightly exothermic, system advantages overwhelm the slight inefficiency of the process. In this paper, recent progress on plasmatron fuel reformer and applications are described.

Diesel reformation: In 2003, a plasmatron fuel reformer was used by ArvinMeritor in a successful test on a bus of a two leg nitrogen oxides (NO_X) trap exhaust aftertreatment system regenerated with hydrogen-rich gas. The input Diesel fuel flow rate to the plasmatron fuel reformer was 0.8 g/s. In 2004 the input fuel flow rate of a Diesel plasmatron fuel reformer at MIT was operated with an increased Diesel fuel flow rate of 2 g/s, corresponding to 80 kW of fuel reformate. This reformer produced about 1.5 ^{l}/s of hydrogen without the use of a reforming catalyst for additional hydrogen generation. This type of higher flow rate operation can facilitate quick regeneration of single-leg NO_X trap systems aftertreatment.

Biofuels reformation: Reformation tests of renewable fuels have been carried out. Vegetable oils, including soy and canola oils, have been efficiently reformed, with no soot production at input rates of 0.5 g/s. Ethanol tests have been carried out. Results from both non-catalytic and catalytic (with a catalyst downstream from a homogeneous reforming zone) will be presented. Onboard conversion of biofuels into hydrogen rich gas opens up a range of opportunities for reducing petroleum consumption.

Rapid response: The plasmatron response has been determined using real time gas analysis techniques. For cold start, the response of a plasmatron fuel reformer using homogeneous reforming was faster than that from a plasmatron fuel reformer that included a catalyst. In addition, hydrogen production during warm start has also been studied. This mode of operation could be particularly relevant to some aftertreatment applications, where the hydrogen rich gas needs to be produced in short, frequent pulses.

Regeneration of Diesel Particulate Filters: Concepts have been developed for optimal regeneration of Diesel Particulate Filters, using hydrogen rich gas. The goal is the simplification of the aftertreatment system, the minimization of the fuel penalty, and minimization of fuel reformer system requirements.

Emissions and Operability Results from a Fleet Operating on GTL Fuel and Catalyzed Diesel Particle Filters

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This study examined the emissions and operability from a fleet of Class 6 delivery trucks over a 6-month period. Six vehicles participated in the study; three vehicles were “baseline”, operated on CARB specification Diesel and original equipment manufacturer mufflers, and three vehicles were fueled exclusively with gas-to-liquid (GTL) fuel and retrofit with Johnson Matthey CCRT™ filters. Chassis dynamometer emissions were collected at the start and the end of the project.

The filters performed as expected throughout the program, reducing hydrocarbons, carbon monoxide, and particulate matter to below detection limits over both the CSHVR and NYCB cycles. Nitrogen oxides (NO_X) emission reductions were also recorded over these same cycles, with reductions ranging from 8 percent over the CSHVR cycle to 14 percent on the NYCB cycle. NO_X emission reductions were only statistically significant over the low speed NYCB cycle.

The fleet operability was also monitored over the project. The switch to GTL fuel was overnight, with no modifications to the engines or vehicles. Qualitatively, no materials or operability issues have been identified, either with the switch to GTL fuel or the addition of the CCRT filters. A quantitative analysis on the maintenance data is underway. A slight fuel economy penalty was observed with the vehicles operated on GTL fuel and the CCRT filters.

Effect of GTL-Diesel Fuels on Emissions and Engine Performance

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In a detailed investigation, the effect of gas-to-liquid (GTL) Diesel fuel blends on emissions and engine performance has been studied. As reference and as a base stock a clean, sulfur-free European Diesel (EU Diesel) fuel was used. Dynamometer tests with a E220 CDI in the NEDC without any changes of the basic EU3 engine calibration revealed that GTL fuels may reduce emissions significantly even in a non-adapted engine. For neat GTL the carbon monoxide and hydrocarbon emissions were reduced by over 90 percent and particulate matter emissions by up to 30 percent. Slight improvements in the percentage range were observed for nitrogen oxides (NO_X) and carbon dioxide emissions. Blending GTL with EU Diesel revealed a strong non-linear characteristic: a 50 percent blend exhibited properties close to those of neat GTL. In order to explore the available potential for further emission reductions, stationary test bed runs were carried out for operating point's characteristic for the NEDC. Based on these data, the range of emission reductions was calculated by a design of experimental approach for a possible new soft-calibration with optimized exhaust gas recirculation rates and injection timings. For neat GTL a conservative prediction projects possible simultaneous reductions of 35 percent both in NO_X and in soot. The non-linear blending characteristic was corroborated for 2 blending ratios: for a 50 and a 20 percent GTL blend in EU Diesel, reductions in NO_X and soot were found to be 86 and 48 percent of the neat values, respectively. The heat release revealed an earlier start of pilot and main combustion for GTL fuels.

Certification of Shell GTL as an Alternative CARB Diesel Formulation

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Richard H. Clark, Shell Global Solutions (UK)

Roger R. Davies, Shell Gas & Power

Hot-start transient emission results were obtained from a 1991 Detroit Diesel Corporation (DDC) Series 60 heavy-duty diesel engine tested per Alternative 3, as specified in the California Air Resources Board (CARB) Procedure for Certification of Emissions Reductions for Alternative Fuels. Two formal testing protocols were conducted using (1) a reference fuel (Fuel R) and Shell gas-to-liquid (GTL) (Fuel C) and (2) a reference fuel (Fuel R) and a blend of 55 percent volume Shell GTL/45 percent volume reference fuel (Fuel C). For both of these testing protocols, the reference fuel (Fuel C) was a CARB ultra low sulfur Diesel (ULSD) obtained from the Shell Martinez Refinery.

Results include emissions of hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_X), particulate matter (PM), soluble organic fraction (SOF), SO_4, selected hydrocarbon species, aldehydes, and polynuclear aromatic hydrocarbons. In particular, reductions in NO_X, PM and SOF are substantial.

In addition, a modified testing protocol was conducted with the same reference fuel, Shell GTL, and volumetric blends of 20, 33, 55, and 75 percent Shell GTL in the reference fuel to establish a blend curve to determine emission reductions of HC, CO, NO_X, PM and SOF.

Be Advised: Results of this testing protocol have recently been reported to CARB by the testing laboratory (SwRI). We are actively pursuing formal CARB certification. The focus of this presentation will depend on the status of discussions/negotiations with CARB. In any case, we are prepared to present the emission benefits of the Shell GTL fuel, either neat, or in blends with CARB ULSD.

A Life Cycle Assessment Comparing Select Gas-to-Liquid Fuels with Conventional Fuels in the Transportation Sector

Robert Abbott
ConocoPhillips

ConocoPhillips has completed a Life Cycle Assessment (LCA) of its proprietary gas-to-liquid (GTL) technology to convert natural gas to transportation fuels and petrochemical feedstock. GTL is one technological option for monetizing large reserves of natural gas around the world that are “stranded” due to their geographical location. This LCA compares energy efficiencies, greenhouse gas and criteria pollutant emissions among selected transportation fuels produced by GTL with those produced by conventional petroleum refining technologies. This LCA follows ISO 14040 guidelines, including an independent peer review. The Greenhouse Gases Regulated Emissions and Energy in Transportation (GREET) model provides a well-to-wheel comparison of selected fuel/vehicle pathways. One million British thermal units (for energy) and grams of emissions (for greenhouse gases and criteria pollutants, nitrogen oxides, sulfur oxides, particulate matter10, volatile organic compounds, etc.) are normalized against a functional unit chosen for the LCA. This functional unit is *light duty Diesel vehicle miles* driven in the United States. The GREET model was validated and run using efficiencies expected from ConocoPhillips GTL technology. An innovative LCA approach was developed to provide a more equitable life cycle comparison between conventional refining and GTL processes. This approach is referred to as the “Co-Product Function Expansion.” GTL fuels compare favorably with Ultra Low Sulfur Diesel (ULSD), being somewhat less energy efficient but having generally lower criteria pollutant emissions. Greenhouse gas emissions for these two fuels are equivalent. The Life Cycle Impact Assessment demonstrated GTL impact indicator values for acidification, eutrophication, photochemical smog, ecotoxicity, human health criteria, human health–cancer, and human health–non-cancer generally trending toward reductions in these parameters when compared to conventionally derived fuels.

Biodiesel Research Update

Robert L. McCormick
National Renewable Energy Laboratory

Biodiesel quality and stability have been major focus areas for research at the National Renewable Energy Laboratory over the past year. A survey of B100 quality and stability has been conducted, with collection of 27 B100 samples nationwide. Of these samples, 85 percent met the requirements of the B100 quality specification, ASTM D6751. Of the four samples that failed to meet the quality specification, one failed acid value and total glycerine (while meeting the free glycerine requirement), a second failed acid value only, a third failed total glycerine only (while meeting free glycerine), and the fourth failed phosphorus content. The fourth sample appeared to have been contaminated with lube oil because of high phosphorus and high sulfur (83 ppm). These samples were also examined for oxidation stability using several test methods. Using the European stability test (EN 14112), U.S. biodiesels exhibit a typical induction period of 1 hour or less. This is considerably below the European requirement of 6 hours, but it is not clear that this translates into actual stability problems in the field. Work to clarify the mechanism of biodiesel oxidation is ongoing in the summer of 2004 and results of this effort will be described. In a second major focus area; biodiesel produced from several different feedstocks has been tested in two different engines meeting the 2004 heavy-duty emission standards. This work has confirmed the trends observed in older engines: reduced emissions of particulate matter and carbon monoxide with increased emissions of nitrogen oxides. Ongoing studies are examining compatibility with elastomers and impact on fuel pump and injector wear. Additional studies are attempting to quantify the impact of B20 relative to conventional Diesel on vehicle maintenance costs during use by various fleets.

Fuel Impacts on Soot Nanostructure and Reactivity

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Diesel fuel production from alternative or renewable sources such as stranded natural gas, vegetable oils, and animal fats offers the potential of both reducing fossil carbon emissions and producing alternative ultra clean transportation fuels. It is well known that biodiesel, neat or in blends, can provide reductions in particulate matter mass emission through either oxygen content or enhanced air entrainment due to the higher boiling range of biodiesel. Fischer-Tropsch (F-T) Diesel fuel also can provide reductions in PM mass emissions, because F-T Diesel contains no aromatics. However, recent observations have indicated that biodiesel may provide other benefits with regard to particulate emissions. These observations have shown an oxidation reactivity variation with soots derived from different fuels. Identifying the dominant mechanism during oxidation, if any, may have practical implications for reducing the temperature required to regenerate catalyzed Diesel particulate filters. There exists evidence of correlation between reactivity and structure in the case of carbon blacks or coal chars that are synthesized from different hydrocarbons and at different temperature conditions. However, the manner in which crystallinity or pore structure affects soot oxidation rates has not been clarified for Diesel soot whether that soot is derived from conventional or alternative fuel sources.

This paper presents a comparison of soot nanostructures of particulates produced from different fuels in a commercial direct injection Diesel engine by means of high resolution electron microscopy imaging. This nanostructural information such as the graphene layer size and orientation is used to interpret the quantitative reactivity differences measured in an idealized thermo-gravimetric analysis/differential scanning calorimetry oxidation experiment. Together, these results show the potential impact of neat and blended alternative fuels on the low temperature oxidation characteristics of soot.

Alternate Fuels-DME Rheology and Materials Studies

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Penn State University

Dimethyl ether (DME) is a significant alternate fuel candidate for Diesel engines. It is environmentally benign and significantly reduces particulate emissions. However, DME is a gas at room temperature and requires modification of the system to maintain the fuel in the liquid state. Earlier studies at Penn State resulted in a 6-week test in a campus vehicle. The system was pressurized and maintained an approximate 1:5 ratio of DME to Diesel fuel.

Laboratory tests indicated that ideally a 1:4 ratio reduces particulate emissions by 25 percent or better. This study evaluated several properties of DME including viscosity, materials compatibility, and wear. One of the drawbacks of using DME is that its viscosity is an order of magnitude lower than the ASTM specification required for Diesel fuel. This paper reports on the development of a pressurized viscometer and a series of additives evaluated to increase the viscosity to achieve minimum requirements. Only three formulations of some two dozen formulations evaluated met this requirement at 25 percent DME in other fuels. The campus vehicle test also indicated the potential for material problems. Several seal materials were evaluated and the test results indicate most common seal materials are not adequate for extended use with DME. Wear of blends of DME in alternate and low sulfur fuels were evaluated in a modified Cameron Plint. As expected, the wear increased with increased DME concentration but was lower than some of the additive formulations. Although DME is a beneficial way to reduce engine out emissions, significant research is required to resolve material and rheological issues.

EVALUATING EXHAUST EMISSION PERFORMANCE OF URBAN BUSES USING TRANSIENT HEAVY-DUTY CHASSIS DYNAMOMETER

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Abstract

Engines for heavy-duty vehicles are emission certified by running standalone engines according to a specified load pattern. In the US, the US Heavy-Duty Transient cycle has been in use already for a number of years, and Europe is, according to the requirements of the Directive 1999/96/EC gradually switching to transient- type testing.

Evaluating the in-use emission performance of heavy-duty vehicles presents a problem. Taking engines out of vehicles for engine dynamometer testing is difficult and costly. It is also debatable, how well the standardized duty cycles reflect real-life driving patterns.

Testing a complete bus on a chassis dynamometer by driving representative urban bus cycles, like Braunschweig or Orange County Bus cycles will give results that represent accurately the desired real-life operation. In chassis dynamometer testing, all important vehicle-specific properties, for example weight of the vehicle, driving resistances and the performance of the whole power line have been taken into account.

VTT Processes has recently commissioned a new emission laboratory for heavy-duty vehicles. The facility comprises both an engine test stand and a fully transient heavy-duty chassis dynamometer. The roller diameter of the dynamometer is 2.5 meters. Regulated emissions are measured by using a full-flow CVS system.

A national program to generate emission data on buses has been set up for the years 2002-2004. Emission factors will be generated for about 35 different buses representing different degree of sophistication (Euro1 to Euro5/EEV, with and without exhaust gas aftertreatment), different fuel technologies (diesel, natural gas) and different ages (the effect of aging). The work is funded by the Metropolitan Council of Helsinki, Helsinki City Transport, The Ministry of Transport and Communications Finland, the gas company Gasum Oy and Swedish Road Administration (SRA).

The International Association for Natural Gas Vehicles (IANGV) has opted to buy into the project. For IANGV, VTT will deliver comprehensive emission data (including particle size distribution and chemical and biological characterization of particles) for diesel and natural gas vehicles. The main objective for the IANGV addition is to generate comprehensive emission data for the newest available diesel and natural gas vehicles.

Based on measurements, both NO_x and PM emissions have clear downward trend along with newer Euro emission standards. CRTs reduce particles effectively even on older Euro2 buses with high mileage. On other

hand, the CRTs seem to be vulnerable to poor maintenance or other failures. CNG buses have always extremely low particulate emissions and the NO_x follows generally the Euro levels hand by hand with diesels.

From the group of three different Euro5/EEV CNG buses, tested for the IANGV addition, the stoichiometric bus got the lowest NO_x and CO2 values. Engines operating on the lean burn principle seem to suffer from unfavorable interrelation of NO_x and CO2. Overall results for newer CNG buses were excellent, no signs of high aldehyde content, high number of small particulates or any other disadvantageous results were recorded.

Practically all CNG buses in Europe are catalyst equipped, which makes a difference between these results and the results of many North American studies.

The paper describes the methodology used for the measurements on buses, the test matrix and some emission data on both regulated and unregulated emissions.

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SESSION 3 – Fuels and Lubrication, Part 2

Chair: **Gary Yowell, California Energy Commission**

Robert McCormick, National Renewable Energy Laboratory

An Integrated Surface Modification Technique to Reduce Friction and Increase Durability

Stephen Hsu
National Institute of Standards and Technology

Surface texturing, thin film coatings, and coating specific lubricant chemistry can be integrated into a surface modification technology to dramatically alter material surface properties to achieve friction reduction and durability enhancement. This concept has been explored to see whether this technology can be applied to engine technology under various serving conditions for different components. The presentation will cover historical background, novel surface texture designs, fabrication techniques, and test results under elastohydrodynamic, mixed, and boundary lubricated conditions. It will be shown how these different surface textures, geometrical shapes, and design patterns impart different degrees of benefits.

Demonstrated Petroleum Reduction Using Oil By-Pass Technology on Heavy and Light Vehicles

J.E. Francfort, L.R. Zirker, and T.C. Murphy
Idaho National Laboratory

The Oil Bypass Filter Technology Evaluation is an ongoing fleet evaluation of an oil bypass filter technology by the Idaho National Engineering and Environmental Laboratory (INEEL) for the U.S. Department of Energy's FreedomCAR & Vehicle Technologies Program. Eight four-cycle Diesel-engine buses used to transport INEEL employees on various routes have been equipped with oil bypass filter systems from the puraDYN Corporation. The bypass filters are reported to have engine oil filtering capability of 1 micron and a built-in additive package to facilitate extended oil-drain intervals. As of March 2004, the eight buses have accumulated 400,000 test miles. This represents an avoidance of 33 oil changes, which equates to 1,165 quarts (290 gallons) of new oil conserved and therefore, 1,165 quarts of waste oil not generated. The test fleet has been expanded to include six INEEL Chevrolet Tahoe sport utility vehicles with gasoline engines and they have accumulated 68,000 miles in four months of testing, representing an additional 100 quarts (25 gallons) of oil not used or disposed of. To validate the extended oil-drain intervals, an oil-analysis regime is used to evaluate the fitness of the oil for continued service by monitoring the presence of necessary additives, undesirable contaminants, and engine-wear metals. The oil use and disposal saving rates are being extrapolated to the entire DOE complex as well as the entire Federal fleet of vehicles in order to identify the potential engine oil reduction throughout the nation. The INEEL evaluation progress, oil use reduction, and oil sampling results, as well as the potential to reduce engine oil use in all Federal fleets will all be presented.

X-Ray Characterization of Diesel Sprays and the Effect of Nozzle Geometry

Christopher F. Powell
Argonne National Laboratory

The development of accurate engine models is a key step toward producing Diesel engines with reduced in-cylinder emissions. One of the primary limitations of existing models is the simulation of the fuel spray itself. Since the mechanisms of spray atomization are not well-understood, it is very difficult to develop accurate models of the formation and structure of sprays. These uncertainties in the structure of the spray are very significant for emissions since the results of the spray models are used as the initial conditions for the combustion and pollutant formation models. The large uncertainties introduced by the spray sub-models limit the usefulness of overall engine models.

The x-ray absorption technique can make important contributions to solve this problem. This technique has the unique ability to make quantitative measurements of the spray core, even in the near-nozzle region which is inaccessible by other techniques. Such measurements allow modelers to test their simulations against measurements of fundamental spray properties such as mass distribution. This will lead to continual improvement of spray models and a better understanding of spray structure and dynamics.

In this talk, we will present some of our latest results of nozzle studies with different internal geometries which were given to us by DaimlerChrysler and Robert Bosch. This data will allow modelers to test their predictions of how the internal nozzle design affects the structure of the spray and will aid them in the development of newer, more accurate spray models. As spray models improve, engine models will gain more predictive power. More accurate engine models will allow quick and cost-effective design of fuel systems and engines with improved efficiency and reduced emissions.

Demonstration of the Low-Emission Potential for Urea Selective Catalytic Reduction and Diesel Particulate Filter Technologies

Magdi Khair and Chris Sharp
Southwest Research Institute

Ralph McGill
Oak Ridge National Laboratory

The objective of this project is to integrate several Diesel emission control technologies to demonstrate their capability to comply with the 2007-2010 heavy-duty Diesel engine emission requirements. Once the engine and control system were developed, several fuels having various sulfur content were evaluated to establish the sensitivity of the control system to sulfur. Two different emission control systems, both employing urea selective catalytic reduction catalysts and Diesel particulate filters, were calibrated and showed the potential for controlling nitrogen oxides and particulate matter to levels near the 2007-2010 requirements. Calibration of both systems has been completed and emissions with fuels of different sulfur levels have been measured. Additionally, a full suite of unregulated emissions has been measured using a low-sulfur refinery-type fuel. Both systems are undergoing the aging tests now with the target of achieving 6,000 hours of aging on a prescribed aging cycle. Both systems have completed over 2,000 hours of the aging, and emission tests of the systems at that point have been completed.

Phosphorous Exhaust Chemistry and Catalyst Poisoning

Bruce Bunting, Karren More, and Sam Lewis
Oak Ridge National Laboratory

Phosphorous in Diesel exhaust is derived from the zinc dialkyldithiophosphate (ZDDP) additive in lube oil used for wear control. Phosphorous emitted in the engine exhaust can react with an aftertreatment catalyst and cause loss of catalyst performance through masking or chemical reaction. It appears that there is a minimum level of ZDDP in lube oil needed for engine durability. One of the ways of reducing the effects of the resulting phosphorous on catalysts might be to alter the chemical state of the phosphorous to a less damaging form. One of the first requirements of altering the chemical state of phosphorous is to be able to measure its chemical state and compounds in Diesel exhaust.

In this study, lube oil containing ZDDP was added at an accelerated rate through a variety of engine pathways simulating various types of engine wear or oil disposal practices. In all cases, the phosphorous was found in an oxidized state as discrete particles on the exhaust particulate with the form and chemistry varying according to the method of introduction. Diesel oxidation catalysts run under these conditions of oil introduction showed phosphorous poisoning and masking effects as measured by light-off characteristics and material and chemical property changes. The analytical techniques and testing procedures have been related to field aging rates and can be used as a means to rapidly screen additives or catalysts for phosphorous poisoning behaviors.

Hydrocarbon Selective Catalytic Reduction Using a Silver-Alumina Catalyst with Light Alcohols and Other Reductants

John F. Thomas, Bruce G. Bunting, Samuel A. Lewis, Sr., John M. Storey, and Ron L. Graves, Oak Ridge National Laboratory Alexander G. Panov and Paul W. Park, Caterpillar, Inc.

Previous work with a full-scale ethanol-SCR (selective catalytic reduction) system featuring an $Ag\text{-}Al_2O_3$ catalyst demonstrated that this type of system has potential to reduce nitrogen oxides (NO_X) emissions by 80 to 90 percent. Increased emissions of hydrocarbons, acetaldehyde and ammonia were measured, but very little dinitrogen oxide was found. In this next increment of work, a number of light alcohols and other hydrocarbons were used in experiments to look at their potential with the same $Ag\text{-}Al_2O_3$ catalyst. A secondary goal was to "shed light" on the possible catalytic reaction mechanisms that make this system perform well. Experiments show that heavy-duty Diesel engine exhaust NO_X emissions can be reduced by more than 80 percent, utilizing ethanol as the reductant for a space velocity near 50,000/h and catalyst temperatures between 330 and 490°C. Similar results were achieved for other light alcohols, with a (desirable) shift to a lower temperature range. Heavier alcohols and other oxygenated organics were also tested as reductants, but with somewhat less successful results. Non-oxygenated hydrocarbons appear to be poor reductants for this system. Some speculative explanation is offered for the mechanisms governing the observed results.

APBF-DEC Heavy-Duty NO_x Adsorber/DPF Project: Catalyst Aging Study

Shawn D. Whitacre
National Renewable Energy Laboratory

This presentation summarizes the results of a 2,000 hour aging test conducted on an advanced test platform consisting of nitrogen oxides (NO_X) adsorber catalyst, a diesel particle filter and a heavy-duty engine.

The project that is discussed is one of several being conducted as part of the Department of Energy's Advanced Petroleum-Based Fuels – Diesel Emission Control (APBF-DEC) activity. This government/industry collaboration is examining how systems of advanced fuels, engines, and emission control systems can deliver significantly lower emissions while maintaining or improving vehicle fuel economy.

The potential for systems including NO_X adsorber catalysts and diesel particle filters to significantly reduce emissions from heavy-duty engines is well-documented. However, relatively few practical studies have been conducted which examine their performance over time. Sulfur poisoning and thermal degradation have been identified as potential mechanisms for performance loss.

In this study, a Cummins ISX EGR engine (15 L) has been modified with a secondary fuel injection system to enable NO_X adsorber catalyst regeneration and desulfation. Periodic performance evaluations were conducted during a 2,000 hour endurance test of the emission control system. Criteria pollutants as well as currently unregulated, but potentially toxic, emissions were evaluated over transient and steady-state operating cycles with a 15-ppm sulfur test fuel. Test results indicate that high system efficiency can be maintained when appropriate management strategies are employed.

Abstracts

SESSION 4 – Waste Heat Utilization

***Chair:* John Fairbanks, U.S. Department of Energy**

Aaron Yocum, National Energy Technology Laboratory

Challenges and Opportunities in Thermoelectric Energy Conversion

Arun Majumdar
University of California, Berkeley
Lawrence Berkeley National Lab

Thermoelectric devices are attractive for energy conversion because they are solid state containing no moving parts and, in particular for power generation, they are not fuel-specific, allowing them to be environmentally benign. Despite these advantages, a key drawback that has prevented them to be widely adopted is their performance – they generally operate below 10 percent of the Carnot limit, which makes them at least 2-3 times less efficient than macroscopic engines and refrigerators. At the heart of this issue is the lack of thermoelectric materials with sufficiently high figure-of-merit, ZT, which is defined as $ZT = S^2\sigma T/k$, where S is the thermopower or Seebeck coefficient, σ is the electrical conductivity, k is the thermal conductivity, and T is the absolute temperature. For the performance of thermoelectric devices to be about 30 percent of the Carnot limit, one must develop materials with $ZT > 3$. Five decades of research has increased room-temperature ZT of bulk semiconductors only marginally, from about 0.6 to 1. The challenge lies in the fact that S, σ, and k are interdependent – changing one alters the others, making optimization extremely difficult. The only way to reduce k without affecting S and σ in bulk materials is to use semiconductors of high atomic weight such as Bi_2Te_3 and its alloys with Sb, Sn and Pb. High atomic weight reduces the speed of sound in the material, and thereby decreases the thermal conductivity. Although it is possible in principle to develop bulk semiconductors with $ZT > 3$, there are no candidate materials in the horizon. Over the last few years, however, there has been a surge of interest in thermoelectricity driven primarily by discoveries of room-temperature $ZT > 1$, with claims even as high as 2.4. While there is debate over the exact values, producing materials with $ZT > 1$ can be considered a significant milestone. What has caused this sudden increase in ZT? The common feature in these studies is the use of nanostructures: the materials either contain superlattices or quantum dots. This talk will discuss the state of our understanding of how and why nanostructures increase ZT and if there is the possibility of developing materials with $ZT \approx 3$.

Development of an Underarmor 10 Kilowatt Thermoelectric Generator Waste Heat Recovery System for Military Vehicles

John C. Bass, Daniel J. Krommenhoek, and Aleksandr S. Kushch
Hi-Z Technology, Inc.

Hi-Z Technology describes the preliminary design and development of a 10 kilowatt quantum well thermoelectric generator waste heat recovery system for military vehicles. This work is performed under the Armies Tank-automotive & Armaments Command funding and builds on quantum well materials and generator development supported by the Department of Energy (DOE) and a gasoline Automobile Exhaust Thermoelectric Generator (AETEG) supported by New York State Energy Research and Development Authority (Clarkson University prime), DOE, and Hi-Z. A preliminary design of a quantum well thermoelectric generator has been developed that can convert waste heat of a Caterpillar 3126 Diesel into electricity while an Army Stryker vehicle is underway, and can also act as auxiliary power unit (APU) to provide quiet fuel efficient operation while a Stryker vehicle is parked. When parked the thermoelectric generator will use a logistic fuel burner and control system.

Hi-Z presents the preliminary design for the thermoelectric generator to fit into the extremely compact space under the armor of an Army Stryker vehicle. This design is based on predictions showing how quantum well material properties and module configuration can augment the performance of current experimental thermoelectric generators tested in the exhaust of Diesel and gasoline engines. This quantum well waste heat recovery thermoelectric generator is predicted to provide four to five times higher electrical output than conventional thermoelectric materials in the same Stryker vehicle exhaust stream and its available space. Data is presented for current generators ranging from 200 W to 1 kW. Predictions show how this quantum well thermoelectric electrical generator performs under load and APU conditions; and its dependence on module design, quantum well material properties and thickness, and hot side vehicle exhaust and cold side heat transfer.

Progress Report for Scale-up of Multilayer Thin Film Thermoelectric Materials for Vehicle Applications

P. M. Martin and L. C. Olsen
Pacific Northwest National Laboratory, Richland, WA

Thermoelectric devices offer significant promise for utilization of waste heat from lean burn engines and industrial processes. While these devices can convert waste heat directly into electrical energy, the same device can also be used for cooling with application of a direct current (Peltier effect). Multilayer thin film thermoelectric junctions have recently demonstrated promise by way of high conversion efficiency (>10%), but large scale cost-effective fabrication, high efficiency in arrays of junctions, as well as engineering of modules remain to be demonstrated. This project was specifically undertaken to determine the feasibility of fabricating large area multilayer thin film thermoelectric material with the desired thermoelectric properties.

We will report on the development of and recent progress in scale up of Si/ $Si_{0.8}Ge_{0.2}$ and B_4C/B_9C thin film multilayer structures for thermoelectric generator applications, and particularly, fabrication of large quantities of these materials. The scale up of the magnetron sputtering process is proceeding on two fronts: (1) deposition on standard and ultra thin Si wafers and (2) deposition on noncrystalline substrates. Doping with Ge is essential to obtain high conductivity B_4C/B_9C material. Multilayer films with up to 1000 layers were deposited onto substrate areas as large as 0.5 m^2. Initial studies showed that the power factor of these films was ~ 0.06 - high enough to produce a ZT significantly greater than 1. Deposition of TE thin films on noncrystalline substrates is critical for use in functional devices and low cost TEG. Initial progress on noncrystalline substrates is encouraging and will be reported, but an order of magnitude improvement in power factors is required to make them viable for TEG applications. To date, we have deposited Fe-Si/ Fe-$Si_{0.8}Ge_{0.2}$ multilayers with power factors of ~ 0.005 on glass and aluminum oxide substrates. The estimated costs of large area films will also be discussed.

The Effects of an Exhaust Thermoelectric Generator on a GM Sierra Pick-up Truck

Aleksander Kushch
Hi-Z Technology Inc.

Madhav Karri, Brian Helenbrook, and Eric Thacher
Clarkson University

Clayton J. Richter
Delphi Corporation

A liquid-cooled, exhaust-driven thermoelectric generator (TEG) for use with a 1999 GM Sierra pick-up truck has been designed and built. The TEG consists of an exhaust gas heat exchanger that is surrounded on both sides by 8 HZ-20 thermoelectric modules (developed by Hi-Z Technology Inc.) and two coolant heat exchangers. The modules are connected in series and provide their output to a power-conditioning unit that is connected to the truck's electrical bus. The TEG system is designed to provide 330 Watts to the bus thus reducing the electrical load on the alternator and improving the fuel efficiency of the truck.

In cooperation with Delphi Corporation, extensive testing has been performed on the modified truck. The data from these tests will be presented at the conference. In the tests, data have been taken from both the baseline truck and the modified truck that allow the following to be assessed:

- the net increase in fuel efficiency provided by the TEG
- the additional power consumed in the coolant pumping loop
- the importance of insulating the exhaust to maintain exhaust temperatures
- the effect of coolant temperature on the TEG power
- the efficiency of the power conditioning unit
- back-pressure effects of the TEG on the truck
- the effect of the vehicle's electrical load
- the effect of ambient conditions
- the environment seen by the TEG during operation
- temperatures and pressures throughout the system

Using this information important factors will be discussed for improving the TEG system performance.

Status of the Application of Thermoelectric Technology in Vehicles

Lon E. Bell
Amerigon Incorporated

Over the last four years, Amerigon's climate control thermoelectric (TE) cooling/heating system has come into broad usage in the automobile and light truck markets. This is the first large-scale, consumer-driven, application of TE systems to the global vehicle market. Over 2,000,000 TE modules (4 per vehicle system) are installed in passenger cars and light trucks. The control climate system (CCS) system has proven to be reliable and durable in the field, and exhibits stable operation after exposure to the environments associated with use in cars and light trucks. Tests in both the laboratory and direct field experience confirm the capability of the CCS system to meet the requirements of the vehicle industry.

Focus group studies by vehicle manufacturers and Amerigon show that performance is superior to that of other competitive technologies, such as pure ventilation (without active cooling), heating alone (heated seat systems) or systems that duct air from the vehicle's HVAC system into the seat. Field experience to date also has been very favorable, with the installation take rate 50 to 100 percent higher than comparable seat heater installation rates. Consumers have determined that the added value of the cooling feature is both important as a benefit, and the cost increment over heated seats is worth the added cost of the combined cooling/heating system. The technology is becoming available on an increasing number of vehicle lines. The associated installation and demographic growth trends are presented.

Prospects for additional applications of advanced TE systems for cooling/heating, other temperature control usage, and waste power generation are discussed briefly in light of the present state of TE material technology and the impact of new developments in the field. Long-term societal needs for emission reduction and greater fuel efficiency, are opening opportunities for solid-state TE systems since they interface well with other advanced components including electronic fuel controls, power management systems, and electrical power storage systems. The trend toward further electrification of passenger vehicles offers additional opportunities for TE systems because of their ability to interface directly with other electronic subsystems. Thereby avoiding the energy conversion losses associated with the power conversion to mechanical work associated with subsystems that employ electric motors, actuators, or pumps for operation. Finally, the opportunity for use in newer vehicle types (such as hybrid, fuel cell, and electric powered vehicles) is discussed. These long-term trends match well with the properties of TE systems, and thus TE usage can be expected to continue to increase as larger numbers of advanced vehicles come to market.

Diesel Engine Waste Heat Recovery Utilizing Electric Turbocompound Technology

Ulrich Hopmann
Caterpillar Inc.

A cooperative program between the Department of Energy Office of Heavy Vehicle Technology and Caterpillar is aimed at demonstrating fuel consumption reduction using electric turbocompound (ETC) technology on a Class 8 truck engine. The goal is to demonstrate a 5 percent reduction in fuel consumption. Electric turbocompounding (ETC) is a way to recover exhaust heat energy and return it to the driveline. The system consists of a turbocharger with an incorporated electric motor/generator on the turbo shaft. The generator extracts the surplus power at the turbine and feeds it back to a crankshaft mounted electrical motor. The electric turbocompound system also provides more control flexibility in that the amount of power extracted can be varied. This allows for control of engine boost and thus air/fuel ratio.

This presentation will report progress to date on the technology demonstration program. Design and analysis of components, control system, and the ETC system will be reviewed. Design features and test results of the motor/generator will be shown. Results of turbocharger gas stand testing will be shown as well as test results of the complete ETC system on a heavy-duty Caterpillar on-highway truck engine.

Regulated 2-Stage (R2S™) Charging System for High Specific Power Engines

Dr. Frank Schmitt, Dr. Bertold Engels, and Patrick Sweetland
BorgWarner Turbosystems

The proportion of turbocharged engines is increasing from year to year. Passenger car Diesel engines are virtually all operated with an exhaust-gas turbocharger. While the boom in turbocharged engines is chiefly attributable to the lower pollutant emissions which must be complied with for current and future emission legislation, it is also attributable to the clear consumption advantages and thus, reduction in carbon dioxide emissions which the European auto industry has obligated itself to comply with. In addition, vehicles with modern turbocharged engines provide a great deal of driving enjoyment due to a very advantageous torque curve.

Now that the exhaust-gas turbocharger with variable turbine geometry (VTG) has become established as the state of the art for the Diesel engine, it is evident that certain limits to the charging system exist. Higher starting torques at lower engine speeds and, simultaneously, increasing rated power output lead to a more aggravated conflict of goals.

Regulated 2-stage turbocharging (R2S™) is an obvious choice for solving this conflict of goals. It offers the option of increasing both starting torque and rated power output. This article compares engines using VTG and R2S™ with respect to their performance potential. Along with the engine's rated power output and the starting torque, differences in transient engine operation will also be investigated.

Special importance is attached to the system design owing to the use of two turbochargers instead of one turbocharger with VTG. This article will also discuss control of the complex charging system with at least two anticipated bypasses.

Abstracts

SESSION 5 – Global Climate Change/Emission Measurement

Chair: **James Eberhardt, U.S. Department of Energy**

There is no Silver Bullet: Regionalization and Market Fragmentation in Greenhouse Gas Mitigation Strategies

Gerald M. Stokes
Director, Joint Global Change Research Institute
College Park, Maryland

Over the past decade investigations into the options available to nations for mitigating greenhouse gas emissions and stabilizing their concentrations in accordance with the UN Framework Convention on Climate Change have begun to paint an increasingly sophisticated picture of how the future might evolve. This picture is becoming richer, both in technological detail with regards to the differing portfolio demands of regions across the world, and in the nature and timing of the markets that may emerge in a carbon constrained world. From a regional perspective, availability of energy resources, land, and geologic sequestration capacity are beginning to be understood as key factors that will shape the evolution of national and regional energy systems as well as climate/energy policy for these regions. For example, regional insolation and competition for land with food production will create differing biofuel prices and opportunities. Markets too are beginning to exhibit interesting differences. For example, while gasoline, Diesel, and jet fuel serve different end-uses in the current economy, the fact that they are petroleum distillates hides some of the differences in the associated markets. As we examine these markets and the future energy demands it appears for example that multiple "advanced conventional transportation technologies" (e.g., hybrids, bioethanol, Diesel, biodiesel) can and likely will persist in the market for many decades. Near term penetration of these technologies depends on the availability of compatible vehicles. In the long run, these technologies will be controlled by resource availability, for example, biofuels dependence on land availability.

Pollutants Emissions, Global Warming Potential Effect, First Comparison using External Costs on Urban Buses

Gabriel Plassat
French Agency for Environment and Energy Management (ADEME)

In 1999, ADEME started a national program relating to a comprehensive study on urban transports. Several technical solutions were evaluated to quantify on a real driving condition for buses, on one hand pollutant emissions and fuel consumption and on the other hand reliability and cost in a real existing fleet.

There are two different action types:

- The pollution caused by the existing fleet can be reduced by using fuel modifications, Diesel particulate filters (DPF) and/or nitrogen oxides (NO_X) reduction systems. The following technologies were evaluated: Diesel with low sulfur content, Diesel with water emulsion, Diesel with biofuel content, five different DPF's, and an exhaust gas recirculation system were tested (an estimation of NO_X reduction was done).
- When renovating a fleet and opting for vehicles whose emissions are lower than Diesel, new measures can be adopted. By using natural gas vehicles (stoechiometric and lean combustion solutions with Euro II engines), liquid petroleum gas, hybrid buses, or of electric buses.

First, representative driving cycles for buses were established by ADEME and industrial partners. Using these cycles, pollutants were measured as well as fuel consumption, at the beginning of the program and one year after to quantify reliability and measure the increase/decrease of pollutant emissions. Coincidently, under real conditions, each technology was tested on bus fleets in city use. Information (such as fuel consumption, lubricant analysis, problems with the technology) was followed during the one year program.

This paper presents results obtained from testing these urban buses. For these vehicles, the same test procedure was used, to set up clear comparison between these technologies. An external cost comparison was done using European Cleaner Drive methodology and results are presented.

Impact of Clean Diesel Technology on Climate Change

Robert McGraw and James Wegrzyn
Brookhaven National Laboratory

The lifetime and radiative properties of black carbon (BC) in the atmosphere are thought to depend strongly on the extent of the mixing of these particles with sulfate. Such mixing controls the transformation rate between hydrophobic and hydrophilic BC, hence atmospheric lifetime, and the extent to which BC aerosols become coated by sulfate, hence BC optical (radiative) properties. In this talk we will summarize progress and plans to carry out atmospheric simulations using regional-to-hemispheric scale chemical transport models. These models now fully include atmospheric sulfate processes and will soon include the latest inventories for Diesel BC emissions, including the projected emissions reduction achievable through clean Diesel technology. These inventories will be used to evaluate the relative importance of Diesel as a BC source in comparison with other sources (biomass burning, etc.). The mixing state of the aerosol will be represented using a multivariate aerosol module developed at Brookhaven for simulating the microphysical properties and dynamics of generally-mixed aerosols. Here we focus on the mixing state of BC plus sulfate taking into account both sulfate emissions (e.g. from powerplants) and BC emissions and determine if this mixing is important to aerosol optical properties and climate. When complete, the new calculations will provide an independent assessment of the importance of the Jacobson effect.

Mass Correlation of Engine Emissions with Spectral Instruments

David Kittelson, Tim Hands, Chris Nickolaus, Nick Collings, Ville Niemelä, and Martyn Twigg

This paper presents results from a study comparing three spectral aerosol instruments (DMS500, SMPS, DMM230) that were used to make dilute Diesel emission measurements from a light duty DI engine capable of running legislated drive cycles. Transient spectral data is presented and also used to estimate particulate mass emissions. These results are compared to filter paper measurements. The correlation for untreated dilute measurements is compared to that for an aerosol sample with a catalytic stripper applied. Transient mass emissions are presented for the instruments capable of real-time measurements.

Bifunctional Catalysts for the Selective Catalytic Reduction of NO By Hydrocarbons

Christopher Marshall, Michael Neylon, Mario Castagnola, and Jeremy Kropf
Chemical Engineering Division, Argonne National Laboratory

Novel bifunctional catalysts combining two active phases, typically Cu-ZSM-5 and a cerium oxide modifier were prepared and tested for the selective catalytic reduction of nitrogen oxides using hydrocarbons in order to overcome the hindering effects of water typically seen for single phase catalysts such as Cu-ZSM-5. Chemical characterization by temperature programmed reactions, DRIFTS and x-ray absorption spectroscopy indicated strong interaction between the two phases, primarily producing materials that exhibited lower reduction temperatures. Two improvements in NO_X reduction activity were seen for these catalysts compared with Cu-ZSM-5: a lower temperature of maximum NO_X conversion activity (as low at 250°C), and an enhancement of activity when water was present in the system. The use of the modifier phase provides a way to further tune the properties of the catalyst in order to achieve mechanistic conditions necessary to maximize NO_X remediation. The catalyst works best for olefin reductants but shows highly promising activity and selectivity at 350°C when JP-8 is used as a reductant. Effects on feed conditions will be discussed.

Making Mobile Measurements Using an EEPS^{TM} Spectrometer

Tim Johnson and Rob Caldow
TSI Incorporated

Laboratory measurements of engine exhaust provide meaningful information about engine emissions, but the sampling and conditioning of the emissions affect the size distribution of the particle emissions. Roadside measurements, and increasingly on-road measurements, provide an important link to what the emissions are in the real world. On-road measurements are transient and various methods such as sampling bags have been used to obtain size distribution measurements of on road particles. The TSI Engine Exhaust Particle Sizer^{TM} (EEPS^{TM}) spectrometer was designed primarily to measure engine exhaust emission transients in a laboratory setting. A study was done to see if the EEPS could be used in a mobile lab environment.

Vibration is a problem for many instruments in a mobile measurement environment, but is a particularly difficult one for an instrument such as the EEPS that uses electrometers that are sensitive to vibration. The electrometers are rings that surround a central high voltage rod. Vibrations in the electrometer rings or in the central rod produce currents that increase the noise in the signal. The vibration from road noise leads to increased noise in the baseline signal of the instrument. Therefore, using the EEPS in a vehicle to measure on-road exhaust emissions presents a challenge.

To determine the usefulness of the instrument for this application, a test vehicle was assembled using a Toyota Sienna minivan as a platform for on-highway chase tests. A conductive probe was mounted on the roof of the van and conductive flexible tubing brought the air sample to a flow splitter and from there to a TSI 3090 EEPS and a TSI 3022A CPC. The instruments were strapped down to the floor of the vehicle for stability during vehicle motion. No additional vibration isolation was employed. A video and still camera were used to record for correlation purposes and a laptop was used to collect data. An inverter was used to provide AC power to the instrumentation during the tests.

Baseline noise levels were measured by collecting data with a high efficiency filter in the sampling line while operating the vehicle over a bumpy road. Results showed that although the baseline RMS noise for bumpy road conditions was about 3 times higher than the bench top levels, the signal is sufficient to clearly show particle burst events from most diesel sources such as trucks, buses, and semi-trailers. The EEPS total concentration also closely matched the CPC concentrations and correlated very well with particle bursts. Therefore, based on the test results, the EEPS should prove to be a valuable tool for mobile on-road chase experiments.

Abstracts

SESSION 6 – Environmentally Concerned Public Sector Organization Panel

Chair: **Michael Block, Northeast States for Coordinated Air Use Management (NESCAUM)**

Abstracts

SESSION 7 – Combustion and Homogeneous Charge Compression Ignition Regimes

Chair: **Gurpreet Singh, U.S. Department of Energy**

Are There Practical Approaches For Achieving the Theoretical Maximum Engine Efficiency?

David E. Foster
University of Wisconsin – Madison

It is generally understood that the maximum theoretical work that can be obtained from an internal combustion engine is equal to the Gibbs free energy of the fuel being used as the energy carrier. For typical hydrocarbon fuels, like gasoline or Diesel, the Gibbs free energy is approximately equal to the heating value of the fuel. Therefore, the maximum theoretical efficiency of an internal combustion engine burning typical hydrocarbon fuels is 100 percent. This is the same theoretical limit as the fuel cell. Considering that the efficiencies of current internal combustion engines are no where near 100 percent, the question naturally arises as to where the losses occur and what can be done to reduce them?

The losses fall into many categories, which can be referred to as irreversibilities. Examples of the irreversibilites include, but are not limited to, heat transfer between the engine cylinder and the coolant and engine compartment, available energy contained within the exhaust which is thrown away during the exhaust process, and friction. Thermodynamic analysis of the combustion process within the engine indicates that typically 20 percent of the fuel availability is lost during combustion. The question being addressed in this presentation is can the energy release of combustion be affected in a different way such that this availability destruction can be reduced? And, if methods of reducing the irreversibility of combustion can be developed, can they be accomplished without undo loss in power density?

The mechanisms of loss of useful work during combustion (availability destruction) can be determined through second law analysis and explained in general as follows:

1. The availability destruction is directly proportional to the rate at which the chemical reactions are taking place.
2. The availability destruction is directly related to the affinity of the reactions that are occurring.
3. The availability destruction is inversely related to the temperature at which the reactions are taking place.

The analysis also allows one to postulate possible avenues by which irreversibilities of combustion can be reduced. The availability destruction within the combustion process potentially could be reduced by:

1. Slowing down the chemical reactions
2. Choosing fuels or establishing stoichiometries such that the chemical reactions have lower affinity
3. Raising the temperature at which the reactions occur.

Unfortunately some of these approaches conflict with one another, or the desire to obtain maximum power. For example, if one raises the temperature at which the reaction occurs two things will happen. The increased temperature will reduce the impact of the affinity on the availability destruction, which will tend to decrease the availability destruction rate. However, the chemical reaction rate is also a function of temperature, and typically an increase in temperature results in an exponential increase in reaction rate. The increased reaction rate will tend to increase the availability destruction rate. So, it is apparent that the approach of raising the temperature, which is motivated by heat engine thinking, results in conflicting drivers in terms of availability destruction.

In this presentation the fundamentals of combustion irreversibilities will be reviewed and cast in a form which highlights the processes responsible for the availability destruction during combustion. Then a philosophy will be postulated for carrying our combustion processes that will reduce availability destruction in combustion. Questions will then be raised as to whether this combustion philosophy can be carried out without loss in power density and what the critical issues will be of such an approach to energy transformation.

Factors Affecting HCCI Combustion Phasing for Fuels with Single- and Dual-Stage Chemistry

John E. Dec and Magnus Sjöberg
Sandia National Laboratories

Controlling combustion phasing is an important issue that must be addressed for the successful implementation of Homogeneous Charge Compression Ignition (HCCI) engines. As the engine load (fueling rate) is varied, the combustion phasing will shift unless some compensation is applied. Adjusting the intake temperature is a straightforward method for compensating so that the charge mixture auto-ignites at the desired crank angle. For a variety of fuels, including those with both single and dual-stage auto-ignition chemistry, the intake temperature must be reduced to maintain combustion phasing as the fueling rate is increased. This can give the appearance that for all fuels, richer fuel/air equivalence ratios (ϕ), auto-ignite more easily (*i.e.*, at lower temperatures) under HCCI conditions. However, more careful examination reveals that changes in ϕ affect several factors, each of which contributes to the change in required intake temperature. These factors include: combustion duration, wall temperatures, residuals, heat/cooling during induction, and fuel auto-ignition chemistry and thermodynamic properties (referred to as fuel chemistry). In order to understand the relative importance of these factors and to isolate the effects of fuel chemistry, a systematic study has been conducted. In this study, the experiment was altered in a series of steps to remove changes due to each of these factors, leaving only the changes due to fuel chemistry. This approach allowed the relative magnitude of these factors to be determined and the isolated fuel-chemistry effect to be evaluated for various fuels.

Heating/cooling during induction is a particularly important factor, and it can be affected by heat-transfer during induction, dynamic flow effects (whose magnitude depends on the engine speed and port configuration), and cooling by fuel vaporization if direct injection is used. As a result, the effective temperature of the fresh gases in the cylinder at the end of the intake stroke can be quite different from the temperature measured in the runner. These fresh gases then mix with residuals, further changing the in-cylinder temperature. A straightforward procedure is presented for estimating the charge mixture temperature at the end of the intake stroke. This procedure accounts for both heating/cooling during induction and for the effect of residuals.

The experiments were conducted in a single-cylinder HCCI engine (0.98 liters/cylinder). Three fuels were examined: iso-octane and gasoline, which are single-stage ignition fuels, and PRF80, which has significant two-stage ignition chemistry at the conditions studied. The results showed that iso-octane exhibits only a small change in auto-ignition chemistry with fueling rate (ϕ), and that gasoline had a change just slightly larger than iso-octane. In contrast, PRF80 had a large change, due to its significant cool-flame chemistry. As a result, sudden changes in fueling are shown to have little effect on combustion phasing for single-stage ignition fuels (iso-octane and gasoline), whereas two-stage ignition fuels (PRF80, or by inference Diesel fuel) can require significant compensation immediately with changes in fueling rate. However, because ignition is sensitive to ϕ for two-stage fuels, they offer the potential for controlling combustion phasing with stratification of the charge mixture. This was investigated, and the data showed that stratification can significantly and rapidly shift combustion phasing with PRF80, but not with iso-octane.

HCCI Fuel Selection: An Engine Heat Release Based Approach

Tom Ryan
Southwest Research Institute

A study was performed to examine the effects of engine operating parameters on Homogenous Charge Compression Ignition (HCCI) combustion using multiple fuels. The parameters studied include compression ratio, inlet air temperature and pressure, and EGR level. Extensive experiments were performed using Diesel fuel, gasoline, blends of gasoline and Diesel fuel, and Fischer Tropsch Naphtha. Experiments were performed on a single-cylinder variable compression ratio research engine. The independent variables included compression ratio, exhaust gas recirculation level, intake manifold conditions, and the fuel composition.

A detailed heat release rate analysis was used to examine the effects of various characteristics of the heat release process on the engine efficiency. The results of the heat release rate analysis and cycle simulation modeling results were used to develop simple regression models and rules for controlling the heat release rate to produce the maximum efficiency. These results are used to suggest an optimum fuel formulation using a blend of gasoline and Fischer-Tropsch Naphtha.

Heavy Duty HCCI Development Activities

Kevin Duffy
Caterpillar, Inc.

Implementing a practical homogeneous charge compression ignition (HCCI) engine has numerous technical challenges. Among these are ensuring a proper mixture preparation, controlling combustion phasing and cylinder pressure rise rates, and expanding the operating range both to higher loads and idle/light loads. Methods to control combustion phasing include inlet manifold temperature and pressure, injection timing, valve timing, and fuel properties. Caterpillar and a major oil company are working together to understand HCCI using advanced engines, fuel combustion chemistry, and combustion models. Recent progress on part load HCCI operation in both single and multi-cylinder engines using Diesel fuels will be presented. Results from a single-cylinder engine have shown that HCCI technology can achieve very low particulate matter and nitrogen oxides emissions at light-medium load with a range of distillate fuel properties including U.S. market fuel. Three quarter load has been achieved using Diesel fuel with an in-cylinder injection strategy. Results from a multi-cylinder engine will also be reviewed.

Advanced Air Handling, Combustion, and Fuel Efficiency in Gasoline Engines

Bruce Bunting
Oak Ridge National Laboratory

Gasoline engines are likely to continue to be the power plant of choice for passenger cars in the U.S. market for the next decade. Improved fuel efficiency for these engines could result in significant energy savings. Techniques for improved part load efficiency include reducing pumping losses through variable valve timing strategies, increased or variable compression ratio, and homogeneous compression combustion ignition (HCCI) combustion.

Data showing efficiency benefits of these operating strategies and showing how these tools can be used to transition between conventional and HCCI combustion will be presented. HCCI combustion produces about 12 percent better fuel efficiency compared to conventional spark ignited combustion while reducing nitrogen oxides emissions by about 95 percent. The transition from conventional to HCCI combustion is made possible with a spark assist, which can then remain on or be shut off in HCCI mode. Reduced pumping losses through late intake valve closing and internal exhaust gas recirculation when combined with variable compression ratio also improve part load engine efficiency.

Fuel composition and chemistry also affects the transition to HCCI and HCCI combustion characteristics. Fuels with lower octane appear to enhance HCCI ignitability and ease the transition from conventional to HCCI combustion. Fuel properties such as octane, composition, and pre-flame chemistry correlate to the heat release characteristics in HCCI combustion.

Mixed-Mode Diesel HCCI/DI with External Mixture Preparation

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Center for Automotive Research
Columbus, OH – USA

Diesel HCCI (Homogenous Charge Compression Injection) is a combustion technology showing great promise for the reduction of oxides of nitrogen and particulate matter from Diesel engines. Our implementation is a mixed-mode concept which relies on the use of an essentially unmodified common-rail CIDI (Compression Ignition Direct Injection) engine, coupled with a highly effective atomizer (patent pending) for external mixture formation. With this concept, the engine can operate in HCCI mode, HCCI/DI mixed mode, or DI (Direct Injection) mode depending on the load and with seamless, progressive mode transition.

The external mixture preparation for the HCCI mode offers a number of advantages over techniques that utilize only the DI system to perform HCCI mixture preparation. External mixture formation, with the additional residence time and very active mixing through the intake stroke, allows for better HCCI operation due to the very effective mixing and charge homogeneity when compared to direct injection HCCI. The traditional problems of external mixture formation (wall wetting, poor cold start, etc.) are eliminated by a novel fuel atomizer capable of ultra-fine, sub-micron atomization. Furthermore, when used in a mixed combustion mode or in pure DI mode at higher loads, the DI injectors can be optimized strictly for DI operation with respect to number, orientation, or size of injector holes without compromise for HCCI operation.

This mixed-mode operation has been recently demonstrated on a single cylinder engine (1/4 of a recent production 2 L engine, CR = 18) in collaboration between Ohio State University and the University of Stuttgart, Germany. The concept has demonstrated extremely low levels of nitrogen oxides (below 3 ppm) and negligible smoke (FSN < 0.01) in pure HCCI operation up to an Indicated Mean Effective Pressure (IMEP) of 4.7 bar. Operation at various conditions (engine speeds, loads, boost pressures, intake temperature, exhaust gas recirculation rates from 0 - 60 percent, etc.) have shown that this technique enables HCCI operation over a wide range of engine conditions with relative insensitivity of the combustion phasing process to operating conditions. This is probably due to the high level of charge homogeneity achieved by this technique. Furthermore, experiments in mixed mode (*i.e.*, part of the fuel supplied externally in homogeneous mixture plus fuel directly injected internally) demonstrated that the transition from HCCI to mixed HCCI/DI to DI combustion mode is seamless (superposable within a sizable finite region of overlap), significantly enabling the controllability of such a combustion system over the entire engine operating map.

Finally, recent experiments with the same technology for external mixture formation in a 2.4 L, 4-cylinder engine have confirmed the results obtained for HCCI operation in terms of load limits and emissions. Furthermore, the elevated levels of hydrocarbons and carbon monoxide in HCCI operation can be easily reduced through a simple Diesel oxidation catalyst despite the lower exhaust temperatures to their respective post-catalyst levels in DI operation at the same load points.

Achieving High Efficiency Clean Combustion in Diesel Engines

Robert M. Wagner, C. Scott Sluder, John M. Storey, and Sam A. Lewis
Oak Ridge National Laboratory

We have been exploring the potential of Diesel combustion regimes that exhibit simultaneous low engine-out nitrogen oxides (NO_X) and particulate matter (PM) emissions. Through proper combustion management, we have achieved significant reductions in NO_X (90 percent) and PM (30 percent) emissions without the decrease in efficiency typically associated with operating in these regimes. This type of operation is commonly referred to as High Efficiency Clean Combustion (HECC) and was achieved on a multi-cylinder engine using only production-like hardware. The combustion process was characterized using in-cylinder pressure transducers as well as by applying powerful analytical methods to the exhaust constituents. The combination of thermodynamic and exhaust chemistry information results in a more complete description of the combustion process than is usually available. Another important aspect of operating Diesel engines in advanced combustion modes is the ability to transition in and out of these modes with minimal adverse effects on emissions or performance. We were able to demonstrate seamless transitions in and out of Diesel HECC operation with no significant emission spikes or effects on performance.

New Methodologies for Analysis of Premixed Charge Compression Ignition Engines

Salvador M. Aceves, Daniel L. Flowers
Lawrence Livermore National Laboratory

Temperature gradients present in an engine cylinder due to heat transfer to the cylinder walls have a great deal of impact on the combustion process in the Homogeneous Charge Compression Ignition (HCCI) class of engines. Numerical models have been able to accurately capture these temperature effects on the combustion process for homogeneous mixtures. However, to facilitate control and higher power density, some researchers have deviated from truly homogeneous mixtures and looked to more elaborate ways of mixture formation, such as Variable Valve Actuation (VVA) or Direct Injection. These techniques introduce composition stratification in addition to temperature stratification in these engines, which we will call Premixed Charge Compression Ignition (PCCI) to differentiate from HCCI engines. Modeling of this process becomes much more complicated because both mixing and chemistry must be handled in a computationally efficient way.

We have developed a multiple modeling approach that fully integrates a computational fluid dynamics code (KIVA-3V) with a multi-zone model with detailed chemical kinetics. These methodologies are an extension of the authors' previous work in that they can now account for both temperature and equivalence ratio (composition) gradients in the cylinder. In this direction, a method of tracking down the equivalence ratio in each cell during combustion is introduced. One important consideration is how to actually define equivalence ratio to adequately capture the spatial composition field throughout the cycle.

Validation cases were developed by solving the detailed chemistry in every cell of a KIVA-3V grid. This allowed the validation of the chemistry model alone, isolating the chemistry model from depending on other KIVA-3V sub-models. The methodology was tested for several cases with varying initial temperature and equivalence ratio distributions, showing good agreement with the detailed solutions, while providing further insight into the effect of equivalence ratio distribution on ignition, burn duration and emissions in a PCCI engine.

High-Energy, Pulsed-Laser Diagnostics for the Measurement of Diesel Particulate Matter

Peter O. Witze
Combustion Research Facility
Sandia National Laboratories

With stricter particulate matter (PM) emission regulations looming ahead in 2007, there is a need for new instrumentation capable of real-time measurements with high sensitivity. We foresee applications for both extractive sampling and *in situ* measurements, where the former is the simplest approach to implement, and the latter is needed to characterize engine-out/aftertreatment-in conditions for design optimization and life-cycle simulation. High-energy, pulsed-laser diagnostics are well suited for these tasks, and offer a wide range of measurement capabilities that include the following:

LII: Laser-Induced Incandescence directly measures soot volume fraction (elemental carbon only) and the diameter of the primary particles that make up soot aggregates. Primary particle size is important because it represents the smallest size of carbonaceous particles in the exhaust, and because it can be used to estimate aggregate particle surface area, which has significant health implications.

ELS: Elastic Laser Scattering measures particle size. The most simple application, Rayleigh scattering, yields an estimate of the mean equivalent-sphere diameter of polydisperse aerosols. A more complex application, Rayleigh-Debye-Gans polydisperse aggregate (RDG/PDA) analysis, provides additional information such as the radius of gyration and fractal dimension of aggregates. While it is possible to estimate a size distribution based on an assumed shape (i.e., log-normal), ELS cannot measure size distributions directly.

LIDELS: Laser-Induced Desorption with Elastic Laser Scattering measures the volatile organic fraction (VOF) of PM. Measurements at low laser energy give the mean equivalent-sphere diameter of the total PM; measurements at high laser energy vaporize the VOF, yielding the mean equivalent-sphere diameter of the remaining soot.

LIBS: Laser-Induced Breakdown Spectroscopy identifies elemental species and measures their concentration, and is well-suited to investigate the metallic ash in Diesel PM. These include sulphates; phosphates; oxides of calcium, zinc, magnesium, and other metals that are formed from fuel and lubricant additives; metal oxides of iron, copper, chromium and aluminum that result from engine wear; and iron oxides that result from corrosion of exhaust system components.

3D-Combustion Simulation Strategy Status, Future Potentials and Applications Issues

Ruediger Steiner
DaimlerChrysler AG, Stuttgart, D

Concerning the development of future internal combustion engines, the automotive industry is searching for new approaches to shorten the classical procedure of trail and error. The rapid increase of computing power enables the 3D simulation of reactive in-cylinder flow dynamics as an increasingly valuable tool for combustion designers. In this paper, a computational fluid dynamics concept for the simulation of direct injection - Diesel engine combustion is introduced, complying with industrial requirements, such as a high degree of predictability and economical computational costs. The proposed approach allows the incorporation of complex chemistry into a detailed turbulent flow prediction.

In order to overcome the well-known drawbacks of conventional stochastic spray models in the near nozzle region, an Eulerian approach in combination with orifice resolving meshes is applied to improve predictability. For the numerical simulation of the Diesel combustion process, a limited number of appropriate progress variables are defined to describe the reactive phases of self-ignition, premixed, and diffusion combustion. For each progress variable, a transport equation is solved in the CFD code. The mixture field in physical space is characterized by the mixture fraction and its variance. By weighting the chemical solution in mixture fraction space with a presumed probability density function, the transport equations for each progress variable in physical space are closed. The introduced progress variable approach offers a way of separating the numerical effort associated with the solution of the turbulent flow field from that of solving the chemistry. Thereby, arbitrarily complex chemistry can be used to simulate the reactive processes.

In order to evaluate the models developed in this study, various Diesel engines were simulated, including a passenger car, heavy-duty truck, and marine engine. Both, the passenger car and the marine engine are equipped with a Common-Rail injection system, whereas the heavy-duty truck engine is set up with a Pump-Line-Nozzle system. Several operating conditions have been investigated. For the validation of the combustion models, the measured cylinder pressures are used. The pressure data were obtained with single-cylinder engines. Additionally, heat release curves are compared which results from zero-dimensional heat release calculations based on the pressure traces. For the spatial characterization of mixture formation and combustion of the heavy-duty truck engine, at DaimlerChrysler a single cylinder optical engine has been set up, allowing full optical access to the combustion chamber, for e.g. high speed photography. Photographic sequences of combustion processes are used to compare the flame front propagation between simulation and experiment. The results show good agreement. The computational costs fulfill industrial demands.

New Developments of the NADI™ Concept to Improve Operating Range, Exhaust Emissions, and Noise

Bertrand Gatellier, Alain Rannini, Sébastien Potteau
Institut Français du Pétrole

Due to their high thermal efficiency coupled with low carbon dioxide (CO_2) emissions, Diesel engines are promised to be an increasing part of the transportation market if their oxides of nitrogen (NO_X) and particulate (PM) emissions are reduced. Today, Diesel PM traps seem to be the industrial solution for reducing PM emissions. On the other side, adequate deNO_X after-treatments are underdevelopment with concerns about fuel economy, robustness, sensitivity to sulfur fuel content, and cost because of their complex and sophisticated strategies.

New combustion processes, such as Homogeneous Charge Compression Ignition (HCCI) or heavy premixed combustion, are being investigated for their potential to achieve near zero PM and NO_X emissions. Their main drawbacks are high hydrocarbon (HC) and carbon monoxide (CO) emissions and combustion control (timing and noise) at high load as a consequence of the limited operating range and power output.

As a result of the challenges facing the Diesel engine, the Institut Français du Pétrole has developed a combustion system able to achieve near zero PM and NO_X emissions while maintaining performance standards of the direct injection Diesel engine. This "dual mode" engine application called NADI™ (Narrow Angle Direct Injection) applies HCCI at part load and switches to conventional Diesel combustion to reach high and full load requirements.

This presentation will cover the latest development regarding power density, operating range, CO and HC emissions, and combustion noise for this concept obtained on a single cylinder engine. At full load, the NADI™ system is consistent with the future Diesel engine power density standard (60 kW/l has been reached). In HCCI combustion mode, above 1500 RPM, 9 bar of Brake Mean Effective Pressure (BMEP) has been achieved with NO_X emissions under 0.05 g/kWh, which is 100 times lower than a conventional Diesel engine. CO and HC emissions have been deeply improved, especially at low engine load. To be fully compatible with the future stringent standard levels and thanks to an appropriate multiple staged injections strategy, a large reduction of combustion noise was reached at high load. Except for the highest load, these results have been obtained without any fuel penalty when compared to a conventional Diesel engine.

This presentation will also cover the preliminary results obtained on a 2.2L multi-cylinder engine. The associated new technologies in fuel injection system, air loop control, supercharging, exhaust after-treatment, and engine management system fields are covered and discussed. The results show a large potential to reach the future Euro V emissions standard proposed by the UBA (German EPA), 0.08 g/km of NO_X, on an 1810 kg class vehicle.

Abstracts

SESSION 8 – Diesel Engine Emissions, Parts 1 and 2

Chair: **Roland Gravel, U.S. Department of Energy**

Development of an Active Regeneration Diesel Particulate Filter System

Mike Anderson, Z. Jason Hou, Ed Steinbrueck, Wenzhong Zhang
Mike Protas, Wayne Wagner, Paul Way and Ted Angelo
Donaldson Company, Inc.

Due to increasingly strict Diesel engine emission regulations, exhaust aftertreatment devices are widely used to reduce harmful emissions. Particulate matter (PM) emissions have been typically reduced through the use of Diesel particulate filters (DPF). Unless the filter is cleaned, or regenerated, it will eventually fill with soot and become plugged. The two most common forms of regeneration include: 1) passive regeneration where the filter relies on catalytic treatment and sufficient exhaust gas characteristics and 2) active regeneration where controlled heat is added to burn the soot from the filter. In general, the strict requirements for reliable passive filter operation have precluded their use in many applications. Active regeneration is one way to overcome the limitations of passive systems.

A new active filter regeneration system was developed for both retrofit and 2007 original equipment manufacturer aftertreatment applications. The current system is intended for retrofit market release by first quarter 2005. Several active regeneration technologies were evaluated including electric heating, fuel burners, and aerodynamic pulsing. Fuel Injection (FI) based active technology was selected based on preferred regeneration characteristics and less complex system design. General system development and details of key subsystems will be discussed. Extensive lab and field test results will be shown.

Two critical success factors are transient control of fuel injection and a robust regeneration strategy. To allow for use on a wide variety of vehicle applications and duty cycles, a model-based feed-forward adaptive control algorithm was developed. Transient control was refined to ensure rapid regeneration while avoiding thermal degradation of the catalyst system. A regeneration strategy that addresses the issues of fuel penalty and catalyst durability was developed.

To provide for the widest operating range and design flexibility, a unique fuel delivery system has been developed. The effects of the fuel system design parameters such as atomizer design, spray pattern, and fuel/air pressure on regeneration performance will be discussed.

The catalyst system design has significant effect on the operation, efficiency, and durability of the active system. To provide for high hydrocarbon conversion efficiency, low light-off temperature, low tailpipe NO_2/NO_X ratio, and desired durability, a number of catalyst formulations for the Diesel oxidation catalyst (DOC) were evaluated. In addition, the effects of DPF catalyst formulation on regeneration duration and temperature profile were evaluated. Lastly, combinations of the DOC and DPF were evaluated to characterize system-level performance synergies.

Finally, other system parameters including flow distribution, backpressure, outer surface temperature, exhaust leaks, and filter maintenance have been investigated.

Excellent Fuel Efficiency while achieving 2007 Emissions Goals

Chris Nelson
Cummins, Inc.

Since 2001, the Department of Energy has challenged Cummins Inc. to pursue increased levels of Brake Thermal Efficiency amidst the onslaught of ever more stringent emission goals for Heavy-Duty (HD) Trucks. In response to this, Cummins has responded by first achieving 45 percent Brake Thermal Efficiency in January of 2002 while meeting 2002 Legislated Emissions for HD Trucks and then, most recently, by achieving 44 percent Brake Thermal Efficiency in February of 2004 while meeting 2007 Legislated Emissions for HD Trucks. This most recent achievement was accomplished by incorporating advanced, in-cylinder combustion techniques with increased levels of cooled exhaust gas recirculation to reach the very low levels of brake specific nitrogen oxides called for and regenerative particulate filtering to address brake specific Diesel particulate matter goals. Optimized parasitic loads were also studied to benefit the Brake Thermal Efficiency goal. The base engine system was demonstrated to achieve emissions and efficiency performance goals in a calibrated engine test cell. Concurrently, an in-vehicle demonstration was made to prove the realistic feasibility of this technology solution.

Rypos Trap-Field Demonstrations and Recent Developments

Frank DePetrillo and Osama Ibrahim
Rypos, Inc.

The Rypos Trap is an actively regenerated Diesel exhaust particulate trap in which the filter media and the heating element are one and the same. The filter material is made of sintered metal fibers and has high porosity, high soot holding capacity, and low thermal mass. The trap is self cleaning by an electrical current and very tolerant of fuel sulfur levels. It can be combined with a Diesel oxidation catalyst to further reduce Diesel emissions. The Rypos Trap is currently installed on a prime power generator, accumulating operating hours towards durability testing. Recent developments include scaling up the design to larger applications, such as up to 2 MW electrical generators. The Rypos Trap regenerates during normal operation and does not require being taken off line to regenerate. Fuel penalty for regeneration is about 1 percent. Regeneration is controlled by monitoring back pressure and exhaust temperature. Soot particle reduction is 85-95 percent, depending on design.

Transient Simulation of a 2007 Prototype Heavy-Duty Engine

W. Kent Rutan
Caterpillar, Inc.

Caterpillar ACERT™ (Advanced Combustion Emission Reduction) technology is a unique systems approach to delivering an engine with low emissions and excellent customer value. Simulation played a critical part in the identification and development of the ACERT technology solution. The order of magnitude reduction in emissions required by future regulations requires even more emphasis on simulation for performance, emissions, and controls development. To support this need, a detailed transient simulation model of a prototype 2007 heavy-duty Diesel engine and aftertreatment system has been built in the Caterpillar Dynasty simulation software. The details in the engine model have a one-to-one correspondence to the real engine and the model is hardware and software reconfigurable like the real engine to match different application needs. Results from a transient emissions test cell model containing the engine system are compared to measured data. Results are also shown for the engine system in a detailed on-highway truck model.

Aftertreatment Modeling Status, Future Potential and Application Issues

Brian Bolton, Detroit Diesel Corp

The presentation will cover the status of aftertreatment model performance. The stringent emissions standards of 2007 and beyond require complex engine, aftertreatment and vehicle systems with a high degree of sub-system interaction and flexible control solutions. This necessitates a system-based approach to technology development, in addition to individual sub-system optimization. Analytical tools can provide an effective means to evaluate and develop such complex technology interaction as well as understand phenomena that are either too expensive or impossible to study with conventional experimental means. The analytical effort can also guide experimental development and thus lead to efficient utilization of available experimental resources.

A suite of analytical models has been developed to represent particulate matter and nitrogen oxides aftertreatment sub-systems. These models range from computationally inexpensive zero dimensional models for real-time control applications to computational fluid dynamics (CFD) based multi-dimensional models with detailed temporal and spatial resolution. Such models in conjunction with well established engine modeling tools such as engine cycle simulation, engine controls modeling, CFD models of non-combusting and combusting flow and vehicle models provide a comprehensive analytical tool-box for complete engine, aftertreatment and vehicle sub-systems development and system integration applications. However, the fidelity of aftertreatment models and application going forward is limited by several factors, including for example the lack of fundamental kinetic data.

Advanced Diesel Common Rail Injection System for Future Emission Legislation

Dr.-Ing. Juergen Hammer and Dr.-Ing. Roger Busch
Robert Bosch GmbH, Germany

Dipl.-Ing. Karsten Hummel
Robert Bosch GmbH, USA

Future emission legislation will define a challenging goal for Diesel engines and an intense competition with alternative concepts e.g. advanced gasoline engines. Lowest emissions with the highest engine performance, namely high specific power output, gasoline like noise levels, benchmarking low fuel consumption, and attractive costs are defining the goals of future development activities. The key for success will be a highly sophisticated Fuel Injection System which supports all of these goals.

To cover all segments of Diesel market demands BOSCH started two parallel development paths; an evolutionary way based on the piezo-inline injectors and a revolutionary way to define the requirements for future injection systems regarding mixture preparation, maximum injection pressure, rate shaping capability, and multiple injections. Based on studies with state-of-the-art piezo systems and several versatile prototype injection systems a comprehensive engine investigation was accomplished to determine the optimum system configuration for the above mentioned Diesel engine goals.

Applying the criteria function performance, manufacturing robustness, durability over lifetime, and costs, the number of technical solutions has been reduced down to four concepts which were selected for the future product development process.

With all four concepts, the “Piezo Vario Coaxial Nozzle Injector”, “Hydraulically Amplified Diesel Injector”, both stages of the “Piezo-Inline Injectors” (Vario Coaxial Nozzle and 2000bar injector), and the “Hydraulically Amplified Diesel Injector” BOSCH will support the engine manufacturers to achieve challenging future emission goals in a wide spectrum of engine applications for cars and trucks. To maintaining the highest fuel metering accuracy, intelligent closed loop functions will drive the hydraulic system. In addition for the “Piezo Vario Coaxial Nozzle Injector”, and “Hydraulically Amplified Diesel Injector” concepts, the innovative high pressure platform, the so-called CP4, will be introduced in regard to the hydraulic system.

Performance and Durability Evaluation of an Integrated NO_X Adsorber Aftertreatment Subsystem

Jim Li, Sriram Popuri, Jason Chen, Arvind Suresh, Brad Stroia, and Lisa Prentiss
Cummins, Inc.

Ken Howden
U.S. Department of Energy

Howard Hess
Johnson-Matthey

In order to assess the capability of an integrated nitrogen oxides (NO_X) and particulate matter (PM) aftertreatment system to meet expected 2007 emission levels, several durability tests were conducted. These durability tests included: (1) a 500 hour accelerated test focusing on thermal deactivation, (2) a 500 hour accelerated test focusing on both thermal deactivation and sulfur poisoning, (3) a 1250 non-accelerated test focusing on thermal deactivation and sulfur poisoning, and (4) a vehicle test to assess the cold-operation capability of the aftertreatment system. First, the main catalyst deactivation factors for integrated NO_X and PM aftertreatment systems were described. Then each durability test scope and procedure was described. Results for each durability test for NO_X, PM and other conversion functions were presented. The results included steady state NO_X conversion, NO_X capacity, sulfur capacity, NO_X conversion over transient cycle, and PM regeneration. Based on the results, several improvements to the architecture of the integrated aftertreatment system were suggested to improve overall performance.

Long-Term Aging of NO_X Sensors in Heavy-Duty Engine Exhaust

John Orban
Battelle Memorial Institute

The Advanced Petroleum Based Fuels – Diesel Emissions Control (APBF-DEC) program has sponsored an ongoing project at Southwest Research Institute to assess the low emissions potential of an emission control system consisting of urea selective catalytic reduction (SCR), exhaust gas recirculation, and diesel particulate filters. This project includes an aging phase in which the emission control systems are exposed to exhaust from a heavy-duty engine operating over a cycle for a total of 6,000 hours. During this phase of the work, 25 nitrogen oxides (NO_X) sensors, generously supplied by NGK, are also being exposed to the engine exhaust for the 6,000 hours. The sensors are located in three different locations along the exhaust stream – two locations upstream of the SCR catalyst and one after the cleanup catalyst at the end of the system. Sensors of two different NO_X ranges are included – 1-1500 ppm and 0-500 ppm.

Performance of the sensors is being monitored continuously along with the emission control systems' performance. This paper summarizes the NO_X sensors' performance for the first 2,000 hours of the aging test. The analysis of data examines how well the NO_X sensors correlate with the NO_X analyzer data, whether there are systematic changes in sensor performance, how often the sensors need recalibrations, and what might be their expected life.

NO_X Sensor and NO_X Removal Technologies at Ceramatec, Inc.

Balakrishnan G. Nair, Jesse Nachlas, Sai Bhavaraju and James Steppan
Ceramatec, Inc.

Ceramatec, Inc. is developing a nitrogen oxides (NO_X) sensor and NO_X removal technologies. The sensor work is funded by the Environmental Protection Agency (EPA) and the NO_X removal work is internally funded.

In the EPA funded program, Ceramatec has demonstrated a mixed potential type sensor system which offers the advantages of high-temperature operation and very good sensitivity to low NO_X concentrations due to the logarithmic response to NO_X concentration. Previously, mixed-potential type NO_X sensor technologies have been limited by problems of cross sensitivity with other gas constituents commonly found in diesel exhaust, as well as an inability to provide a meaningful signal in varying NO/NO_2 mixtures. A novel proprietary catalyst system developed at Ceramatec has overcome many of the problems previously associated with such NO_X sensors. Sensors have been fabricated and tested that have the following characteristics: (1) Operation temperature of 500-600^{o}C; (2) excellent sensitivity in NO_X levels of 1-1200 ppm; (3) response times as fast as 1-3 seconds; (4) insensitivity to various NO/NO_2 ratios in the exhaust stream; (5) very low cross-sensitivity to carbon monoxide, carbon dioxide, water, and low levels of sulfur dioxide; (6) ability to operate in oxygen-containing environments with no requirement for a pumping cell. The primary application targeted for the new sensor technology is heavy-duty diesel trucks. Other potential applications include advanced turbines, light-duty trucks, automobiles, heavy farm and construction machinery, off-road vehicles, and power generation as well as applications that utilize natural gas as the combustion fuel.

Through internally funded work, Ceramatec has developed a proprietary ceramic catalyst system, with no noble metal content, that can oxidize >85% of nitric oxide (NO) to nitrogen dioxide (NO_2) at 275^{o}C. In combination with a conventional NO_2 adsorber, which intrinsically is a very poor absorber of NO, it has been demonstrated that the catalyst can remove greater than 95% of NO from a gas mixture. Ceramatec is actively seeking partners to develop this technology for engine emissions reduction systems.

Abstracts

SESSION 9 – Diesel Engine Development and Durability

Chair: **Ken Howden, U.S. Department of Energy**

The Diesel Engine Powering Passenger Cars – Today and Tomorrow

Klaus-Peter Schindler
Volkswagen AG

In Europe Diesel passenger cars have long been accepted. The need for reduced carbon dioxide emission and for increased energy supply are two reasons for this acceptance. In Europe Diesel engines are held to different emission standards than gasoline engines. Diesel vehicles have lower carbon monoxide standards but are allowed higher oxides of nitrogen. There are continually steps being taken to ensure that the new Diesel engines will comply with future emission standards (i.e. need for aftertreatment). In Europe, Diesel vehicles are already highly competitive with gasoline engines and future Diesel technology will ensure this competitiveness continues.

In the U.S. Diesel vehicles are not common for passenger cars and light-duty trucks. What is stopping the Diesel engine from flourishing in the U.S.? Will new carbon dioxide emission regulations, or energy supply problems help promote the Diesel engine? There is the known challenge of reaching the future Environmental Protection Agency Tier II emission standards. This and other concerns will be explored.

Lowest Engine Out Emissions as the Key to the Future of the Heavy-Duty Diesel Engine – New Development Results

Franz X. Moser, Rolf Dreisbach, Theodor Sams
AVL List GmhH, Graz

Latest development results on heavy-duty Diesel engines show that it is possible to achieve the United States emission limits for 2010 with exhaust gas aftertreatement. Exhaust gas aftertreatment systems with $deNO_X$ and filter efficiencies of at least 90 percent will be mandatory in order to achieve the future nitrogen oxides (NO_X) and particulate matter (PM) levels. Achieving these levels will require engine concepts with a peak firing pressure capability of at least 200 bar, cooled exhaust gas recirculation (EGR) with EGR rates of 25 percent at full load, injection systems with a pressure potential of 2,400 bar, and two-stage turbocharging. Turbocharger efficiencies of more than 50 percent are required to keep the fuel penalty within acceptable limits. The same will apply for Europe in case it adopts the United States limits. If NO_X limits were set to approximately 1.0 instead of 0.27 g/kWh, then the reduced requirements on the engine would allow significantly better fuel economy.

Cummins/DOE Light Truck Diesel Engine Progress Report -- 2004

John Stang, David Koeberlein, and Michael Ruth
Cummins, Inc.

Cummins continues the design and development of the V-family engine system with the Department of Energy's (DOE) partnership. Requirements of the Light-Truck Automotive market in the United States have been studied and the proposed V-family of engines is believed to meet those needs. The engine system combines the requirements of a very fuel-efficient commercial Diesel and the performance and sociability requirements of a gasoline engine. Results show that the full Environmental Protection Agencies (EPA) Tier II Bin 5 Emission results are achieved, while also meeting the fuel economy targets established by the DOE. Ongoing system developments for improved overall robustness are shown including air-handling system, noise, and overall vehicle performance. General aftertreatment system design and direction is discussed.

An European Perspective of US 07 / EURO 5 HD Engines and Chassis Technologies

Jean-Paul Fayolle
Volvo PWT Engine Research
Renault Division

First emission regulations were introduced more than thirty years ago. At the beginning, visible emissions drove regulation philosophy: smoke was regulated first. Nitrogen oxides (NO_X) came later as acid rain effects became evident. Particulate emissions were restricted as their detrimental health consequences were discovered.

Several different test procedures emerged in relation with local situations. To improve big cities air cleanliness, step transients were enforced to reduce gear shifting black clouds, later U.S. Federal Test Procedure was the first non steady state cycle to be introduced. At the end all countries are merging to the same philosophy: steady state and transient cycles, NTE (not to exceed) figures, and random check of steady points.

But in practice different test procedures can lead to favor different emission control technologies. This is true in exhaust aftertreatment systems selection as they are efficiency sensitive to gas temperatures. Efforts to develop harmonized procedures are underway. Fuel quality, sulfur content, is coming to converge, as well.

Nevertheless, Europe and U.S. will not introduce the same technologies for U.S. 07 and EURO 5 regulation steps. Out of the panel of potential technologies Europe has selected selective catalytic reduction, and U.S. exhaust gas recirculation to control NO_X while a Diesel particulate filter has been chosen as a common way to control particulates. Everybody knows the infrastructure concern of urea distribution played an important role in not selecting SCR to be introduced in the US market.

Within the Volvo group future products development is progressing enough to propose a fair comparison of U.S. and European ways. First is regulation compliance that both technologies will meet. Second are customer demands: high fuel economy, high reliability, and durability. Third is original equipment manufacturer request that enough margin for the satisfaction of shareholders.

The comparison given includes all factors an OEM operating on both sides of the Atlantic can control. A brief approach of carbon dioxide emission aspect is proposed.

Beyond U.S. 07 and EURO 5, next steps of regulations will come. Expectation is to better serve simultaneously the environment, our customers, and our shareholders.

Light Duty Diesel Engine Technology to Meet Future Emissions and Performance Requirements of the US Market

Adrian Greaney
Ricardo Inc.

For Diesel powertrains to establish a significant role in the U.S. light-duty vehicle market numerous technical and commercial challenges must be overcome. Nitrogen oxides (NO_X) emission reduction to meet the stringent requirements of the Environmental Protection Agency Tier II Bin 5 is widely recognized as the most significant technical challenge. Major research efforts within the industry have been focused on this problem and have successfully demonstrated the feasibility of achieving the required levels through a combination of engine and aftertreatment technologies. As 2007 approaches, more emphasis is being placed on ensuring robust emissions control over vehicle life and balancing low emission with other cost, performance, and fuel economy attributes to deliver viable products to the U.S. market. Analysis has shown that engine development to improve emission control in-cylinder can provide significant NO_X reduction at lower cost than an exhaust aftertreatment based approach. Furthermore, minimizing the aftertreatment NO_X reduction requirement mitigates the risk of emission compliance over life.

This paper provides an interim report on an approach to meet the technical and commercial demands of future U.S. light-duty Diesel products, with particular emphasis on the light-duty truck sector. The ACTION (Advanced Combustion Technology for Improved engine-Out NO_X) strategy described applies incremental developments in combustion, air handling, and control technologies to conventional Diesel engines. Reduced emissions are enabled through highly pre-mixed and lower temperature combustion. Current results from single and multi-cylinder engines are tabled and applied to potential U.S. applications by vehicle simulation.

Abstracts

SESSION 10 – Environmental Science and Health Impacts

Chair: **James Eberhardt, U.S. Department of Energy**

History of the FreedomCAR Environmental Science & Health Impacts R&D Activity

Dr. James J. Eberhardt
Energy Efficiency and Renewable Energy
U.S. Department of Energy

The Alternative Motor Fuels Act (AMFA) sought to lessen the dependence of the U.S. transport sector on imported oil by encouraging the use of other fuels including gaseous fuels, especially those that can be produced domestically, such as natural gas and ethanol from biomass. Less is known about the emission characteristics of alternative fueled vehicles compared to those from gasoline- and Diesel-fueled vehicles. In order to ensure that large scale utilization of these alternative fuels would not cause negative environmental and health impacts, the Department of Energy, Office of Transportation Technologies initiated shortly after the passage of AMFA a research program to investigate the “Atmospheric Reactions” which emissions from these fuels would undergo. In 1996 with the emphasis on “Dieselization” and the creation of the Office of Heavy Vehicle Technologies, work was directed at the investigation of the health impacts of Diesel particulate emissions. This work has sought to put the health impacts of Diesel emissions into context with emissions from other sources, especially automotive gasoline. Emissions from the latter often have been assumed to be benign due to the installation of the automotive catalytic converter in 1975.

Presently, the FreedomCAR and Vehicle Technologies (FCVT) Program conducts an Environmental Science and Health Impacts (ES&HI) activity that seeks to provide a rational basis for determining and comparing vehicle emissions, the relative contribution to the ecosystem of both petroleum and alternative fuel vehicle emissions, and their impact on human health. The aim is to provide a basis for minimizing the environmental and health impacts of vehicle emissions, especially emissions from new technologies being developed by FCVT so as to avoid unanticipated negative impacts from large-scale use of these fuels and vehicles.

A brief history of the DOE/FCVT ES&HI activity will be presented from the years following the passage of AMFA in 1988 to the present. The discussion will address the evolving nature of Diesel emissions, the focus of the DEER Conferences, in the context of motor vehicle emissions in general.

DOE's Gasoline/Diesel PM Split Study

Douglas R. Lawson,
National Renewable Energy Laboratory

Eric M. Fujita, David E. Campbell, Barbara Zielinska, William P. Arnott, and Judith C. Chow
Desert Research Institute

James Schauer and Charles Christensen
University of Wisconsin-Madison, Environmental Chemistry and Technology Program

Nigel Clark
West Virginia University, Dept. of Mechanical & Aerospace Engineering

Peter Gabele (retired)
US EPA, Office of Research and Development, NREL

The Department of Energy's (DOE) Gasoline/Diesel particulate matter (PM) Split Study was conducted to quantify the relative contributions of tailpipe emissions from gasoline-powered motor vehicles and Diesel-powered motor vehicles to the ambient concentrations of fine particulate matter ($PM_{2.5}$) in the urbanized region of Southern California using an organic compound-based chemical mass balance model (CMB). This study involved several groups working cooperatively on sample collection and quality assurance aspects of the study, but working independently, at least initially, on chemical analysis and data analysis. Groups participating in the Study include California's Bureau of Automotive Repair, South Coast Air Quality Management District, U.S. Environmental Protection Agency, Ralph's Groceries, Clean Air Vehicle Technology Center, West Virginia University, the University of Wisconsin at Madison (UWM), and the Desert Research Institute (DRI). Source testing of 59 light-duty vehicles (including 2 Diesel vehicles) was completed in June 2001; ambient measurements were performed in July 2001, and the testing of 34 heavy-duty vehicles was completed in September 2001. DRI used sample collection and chemical analysis methods consistent with those employed during the 1996/97 Northern Front Range Air Quality Study. Parallel samples were collected by UWM using methods consistent with previous PM studies in Los Angeles. This paper describes the chemical compositions and apportionments of gasoline- and Diesel-powered vehicles that were obtained by DRI.

Twenty-four hour ambient samples were collected on Teflon and quartz filters and Teflon-impregnated glass fiber (TIGF) filters followed by polyurethane foam (PUF) plugs and XAD-4 resin cartridges for twenty-eight consecutive days at air monitoring stations in downtown Los Angeles and Azusa. Teflon filters were analyzed for gravimetric mass, elements, and ions, and quartz filters were analyzed for organic and elemental carbon by Thermal Optical Reflectance (TOR) and Thermal Optical Transmittance (TOT) using both IMPROVE and NIOSH protocols. The TIGF/PUF/XAD samples were combined and extracted together by day of week, and analyzed for polycyclic aromatic hydrocarbons, hopanes, steranes, alkanes, methoxyphenols, lactones, sterols, and polar organic compounds. A third set of ambient samples was collected from a mobile sampling van at several regionally representative sites and at locations with expected higher proportions of PM emissions from Diesel trucks (e.g., Terminal Island, truck stop, highway truck routes) and from gasoline vehicles (e.g., congested freeway during commuter rush hour, surface streets during weekends, a parking lot at major sporting events). Black carbon and total particulate matter were monitored continuously by photoacoustic and DustTrak instruments. As a prelude to the chemical mass balance analysis, we examined the variations in relative abundances of key marker compounds in the source-dominated ambient samples relative to corresponding variations in the samples from regional air quality monitoring sites by day of week. The ambient source apportionments are placed in context with previous ambient source apportionment studies and emission inventory trends. This work was supported by the DOE's Office of FreedomCAR & Vehicle Technologies through the National Renewable Energy Laboratory.

2007 Diesel Particle Measurement Research Project

Imad A. Khalek
Southwest Research Institute

In 2007, on-highway heavy-duty Diesel engines will be required to meet a particulate matter (PM) emission level of 0.01 g/hp-hr, a 90 percent reduction from the current emission level. In addition, exhaust PM composition is expected to change because of new catalyzed exhaust traps/filters implemented to help meet the new standards. These traps/filters will stop most PM except a small mass of particles, mainly consisting of volatile and semi-volatile hydrocarbon and sulfate species derived from unburned and partially burned fuel and lubricating oil. This low level of remaining volatile PM mass poses a technical challenge for its accurate measurement using the 2007 prescribed filter-based sampling protocol. Not only is there concern for sampling a very low quantity of PM mass to be deposited on the sample filter, but also for several factors including filter handling, filter media, negative or positive artifact, sampling system conditioning, and control of the dilution parameters that can significantly affect quantifying PM mass emission.

Most concerns relative to PM measurement from future Diesel engines are to be addressed in Project E-66, sponsored by the Coordinating Research Council, Department of Energy/National Renewable Energy Laboratory, Engine Manufactures Association, Environmental Protection Agency, and the California Air Resource Board. The effect of filter media, filter face velocity and temperature on PM measurement will be investigated in Phase 1 of the project. This phase also includes comparing the performance of alternative real time particle measuring instruments to that of the filter-based method. Other phases will examine the effect of primary and secondary dilution parameters on PM measurement and the potential use of partial flow sampling systems as an alternative to constant volume sampling under transient engine testing.

The proposed presentation will cover the progress made during Phase 1 of Project E-66 with information on other phases of the project.

On-Road Exposure and Emission Measurements

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The University of Minnesota's mobile emission laboratory (MEL) has been used to characterize on-road particle exposures and to determine engine emission factors under real world conditions. Particles emitted by modern Diesel and spark ignition engines do not all form during combustion. Many particles, particularly those in the 3 to 30 nm diameter (nuclei mode) range, form from volatile materials as the exhaust dilutes and cools in the atmosphere. These particles may constitute 90 percent or more of the nanoparticle (< 50 nm) number emissions. Unfortunately, the formation of these particles is a nonlinear, gas-to-particle nucleation process that is extremely dependent upon dilution conditions. These conditions are difficult to simulate in the laboratory, especially in animal exposure facilities. Using the MEL as an exposure platform avoids this difficulty by using the actual on-road atmosphere to provide dilution. Two types of experiments have been performed. In the first, the MEL was driven on an urban and rural route and, to the extent possible, on-road plumes from Diesel powered heavy-duty trucks were used to provide the exposures. In the second, a new sampling system was installed on the MEL that made it possible to sample the MEL's diluted exhaust plume. A 2000 model year engine that provides a particle signature, which is characteristic of modern engines, powers the MEL. We describe the characteristics of the exposures achieved by the two test conditions along with the instrument array, calibration, particle losses, sampling artifacts, ambient conditions, traffic conditions, and sampling locations or routes. As an added benefit of this study, real world particle emission factors for heavy-duty Diesel engines have been determined. The instrument suite includes an Scanning Mobile Particle Sizer to size particles in 9 to 300 nm size range; a Ultrafine Condensation Particle Counter with a lower limit 50 percent counting efficiency at 3 nm; instruments to measure total submicron particle surface area; a Photoelectric Aerosol Sensor to measure aerosol photoemission response; carbon dioxide, carbon monoxide, and nitrogen oxides analyzers; and a thermal denuder to distinguish between solid and volatile particles.

Relationship Between Toxicity and Composition of Inhaled Diesel Exhaust

Jacob D. McDonald, Kevin S. Harrod, JeanClare Seagrave, and Joe L. Mauderly
Lovelace Respiratory Research Institute

Diesel engine emissions change in composition with variations in fuel, engine configuration, engine operation, and emission reduction technologies such as catalyzed particle traps. While previous studies have shown that Diesel exhaust can cause inflammation in rodents and humans and decreased resistance to respiratory infection in mice, there is little information on the impact of changes in exhaust composition (resulting from changes in fuel, engine operation, and after-treatment technology) on these effects. To address this, identical inflammation and respiratory infection assessments were conducted after exposure of mice to Diesel exhaust generated from a single cylinder Diesel engine generator under four steady-state conditions: 1) high-load operation, number 2 certification fuel (371 ppm sulfur, 29 percent aromatics), emissions diluted to 200 $\mu g/m^3$ particulate matter (PM); 2) high-load operation, certification fuel, non-catalyzed ceramic trap, same dilution rate as condition one; 3) low-load operation, certification fuel, diluted to 200 $\mu g/m^3$ PM; and 4) high-load operation, 15 ppm sulfur fuel, catalyzed ceramic trap, same dilution rate as condition one. Changing the operation (load) of the engine resulted in an approximately 4 times change in particle organic content. Lower load operation yielded increased vapor phase organics and PM primarily composed of condensates that were smaller in size than produced during high load. Resistance to infection was decreased and lung inflammation was increased when the non-volatile (black carbon) portion of the exhaust was highest (high load condition). All health effects were decreased with higher organic carbon (low load) and with the use of a catalyzed emissions trap/low sulfur fuel combination.

Assessment of Health Hazards of Repeated Inhalation of Diesel Emissions, with Comparisons to Other Source Emissions

Joe L. Mauderly, Edward B. Barr, Edward G. Barret, Steven A. Belinsky, Matthew J. Campen, Kevin K. Devine, Andrew A. Gigliotti, Kevin S. Harrod, JeanClare Seagrave, Jacob D. McDonald, and Matthew D. Reed,
Lovelace Respiratory Research Institute

Judith Chow and Barbara Zielinska
Desert Research Institute

Eric Grosjean
Daniel Grosjean & Associates

James J. Schauer
University of Wisconsin, Madison

Steven K. Seilkop
SKS Consulting Services

James A. Swenberg
University of North Carolina, Chapel Hill

It continues to be difficult to place the potential health hazards of Diesel emissions into proper context in regard to hazards from competing technologies of other mobile and stationary source emissions and the potential health benefits of emission reductions. Among the factors contributing to the difficulties is the lack of information on: 1) exposure-response relationships for exposures down to environmental levels and 2) comparative hazards of Diesel and other source emissions. Identically-designed studies of the health effects of subchronic, repeated inhalation exposures to several source emissions are being conducted under the auspices of the National Environmental Respiratory Center program, with support from multiple federal, state, and corporate sponsors, including the Department of Energy and several engine manufacturers. Not only will the study of each source emission provide contemporary assessments of hazard, but the results also allow direct comparisons of hazard among sources and multivariate analyses of the combined data from all studies to determine the physical-chemical components associated with different health effects. Exposures to Diesel emissions and hardwood smoke are completed and most data have been analyzed. An exposure to gasoline emissions is underway, and exposures to urban street dust and coal emissions are planned.

Rodents of different species, strains, genders, and ages, specific to the different health outcomes, were exposed 6 hr/day, 7 days/wk for up to 6 months to clean air or emissions from 2000 Model Cummins ISB 5.9L engines burning certification fuel (350 ppm sulfur, 30 percent aromatics), using Shell Rotella-T 15-40w crankcase oil, connected to eddy current dynamometers, and operated on engine stands on continuously repeating heavy-duty certification test cycles. Whole exhaust was diluted to particle mass concentrations of 1000, 300, 100, and 30 $\mu g/m^3$. The physical-chemical composition of the exposure atmospheres were characterized in detail. Health evaluations included general indicators of toxicity, serum chemistry, hematology, bronchoalveolar lavage, electrocardiograms, development and exacerbation of respiratory allergic responses, resistance to respiratory infection with bacteria and virus, and indicators of cancer hazard including micronuclei in circulating cells, lung adenomas in A/J mice, and lung DNA methylation and oxidative injury. In an identically-designed study, rodents were exposed to smoke generated from burning oak in a non-certified heating stove over a 3-phase, 6-hr daily cycle. Results from the Diesel study will be reviewed, and the health effects of exposure to Diesel emissions and hardwood smoke will be compared.

The California Demonstration Program for Control of PM from Diesel Backup Generators (BUGs)

Wayne Miller, David R. Cocker III, Kent Johnson, Sandip Shah, and Bill Welch (University of California, Riverside); Marla Mueller (California Energy Commission); and Bonnie Soriano and John Lee (California Air Resources Board)

Diesel backup generators (BUGs) are an important source of electricity in many critical areas, such as hospitals, municipal services, and bank clearing houses. Emission factors from uncontrolled BUGs are listed in the Environmental protection Agency's (EPA) AP-42 factors but actual in-use measurements indicate that the emissions are much less than the values in the EPA tables. Furthermore, no emission factors existed for controlled Diesel engines used in BUGs.

The report will present emission results from a number of BUGs ranging in size from 300 kW to 2,000 kW and for units built between 1985 and 2002. There were some surprising results. For example, emission factors did not always vary with size; some of the largest units had the lowest emission factors. For controlled BUGs, results show that the particulate matter (PM) emissions can be controlled to low levels with technology borrowed from the mobile source applications. Taken in total, the results indicate that the emissions from BUGs are lower than reported in AP-42 and that PM emissions can be controlled with various technologies so as to reduce the personal exposure to a toxic air contaminant.

Diesel Exhaust: Phsical, Chemical and Celluar Response Characterization

Jim Cowin, Alex Laskin, Alla Zelenyuk, Gary Holom, Brian Thrall, Mike Alexander, John Sorey, Doug Worsnop
Fundamental Science Directorate, Pacific Northwest Laboratory

Diesel exhaust particulates vary in their detailed composition and morphology depending upon engine conditions, oil additives, and other factors. The potential health effects should also depend on these parameters, but few approaches have the potential to link specific cause and effects in sufficient detail and speedily enough to guide optimization of engine technology. Insensitive detailed inline and offline analytical methods are used to probe how engine running conditions change the output particulates. Using well controlled cellular systems permitting rapid throughput, the biological responses to air-delivered particulates are identified be profiling the global genomic responses. Particle characterization was via Single Particle Laser Ablation Time of Flight Mass Spectrometer (SPLAT-ms), the Aerodyne Aerosol mass spectrometer, and automated particle scanning electron microscopy/elemental analysis. Preliminary results are presented, along with updates on cellular response mechanisms, on-cell nanoparticle imaging, and new instruments (SPLAT II).

Abstracts

SESSION 11 – Emission Control/NO_x Reduction

Chair: **Ron Graves, Oak Ridge National Laboratory**

Diesel Emission Control Technology in Review

Tim Johnson
Corning Incorporated

This presentation will review the field of Diesel emission control with the intent of highlighting representative studies that illustrate the state-of-the-art. First, the author reviews general technology approaches for heavy- and light-duty applications. The presentation reviews: filter technology, covering regeneration strategies, filter properties, durability, and maintenance; nitrogen oxides (NO_X) control by SCR (selective catalytic reduction), LNT (lean NO_X traps), and lean NO_X catalysts; and particulate matter (PM) and NO_X system integration.

In general, progress is impressive and studies demonstrate that high-efficiency systems are within reach in all highway vehicle sectors. Engines are making impressive gains and will increase the options for emission control. Filter technology is focusing on optimization with work being done on better ways to regenerate the filter and improve system back pressure and durability. Mixed mode engine operation provides significant flexibility in this regard, and better control of hydrocarbon species going into the system is a major advancement. SCR NO_X control is focusing on low-temperature performance and system control. LNTs are continuing the rapid evolution of past years with much better sulfur management and new configurations. System integration of filters and NO_X control is currently being road tested for heavy-duty applications using SCR. DPF plus LNTs help prototype light-duty Diesels approach U.S. Tier II Bin 5 standards.

New Diesel Emission Control Strategy for US Tier II and Post Euro IV

Jeffrey A. Leet, Shizuo Sasaki, PhD., Gary D. Neely, and Yiqun Huang, PhD.
Southwest Research Institute

This presentation discusses a new Diesel emission control concept, not only to meet U.S. Tier II and post Euro IV emissions regulations, but also to minimize the fuel consumption (carbon dioxide) penalty.

This system consists of a new combustion control technology and a 4-way catalyst system based on a Diesel particulate filter and lean nitrogen oxides (NO_X) trap. No exhaust port injection system or other special devices are required to realize rich operation with this concept. There is a possibility that today's Diesel engine can transform itself into a 4-way catalyst system with applying only mature gasoline engine technology.

In this work, five representative points of the FTP-75 emissions test cycle were chosen and the emissions and fuel consumption were evaluated using a PSA DW10 2L passenger Diesel engine.

Utilizing Low Temperature Combustion (LTC) and Premixed Controlled Compression Ignition (PCCI) with no post injection, NO_X conversion efficiencies greater than 90 percent were achieved with a minor fuel penalty at every representative point where the break mean effective pressure ranged from 0.8 bar to 8.3 bar. Use of LTC resulted in catalyst bed temperatures above the light-off temperature for the lowest load; and rich, stabilized LTC enabled high NO_X conversion efficiencies at light load. PCCI provided NO_X reductions at high load points. It was confirmed that rich operation, with or without minimal post injection, provided high NO_X conversion efficiencies with only minor fuel penalties.

Urea SCR and DPF System for Diesel LDT/SUV Meeting Tier 2 Bin 5

Jennifer Fischer, Robert Hammerle, David Kubinski, Paul Laing, Christine Lambert, Mike Levin, Cliff Montreuil, Rick Soltis, Devesh Upadhyay, Michiel van Nieuwstadt, James Warner, Scott Williams
Ford Research & Advanced Engineering

Joan Axelrod, Rich Grosser, Marcus Moore, Mike Noorman
ExxonMobil Research & Engineering Company

Erik Koehler, Dean Tomazic
FEV Engine Technology, Inc.

Ford Motor Company, with ExxonMobil and FEV, is participating in the Department of Energy's (DOE) Ultra-Clean Transportation Fuels Program with the goal to develop an innovative emission control system for Diesel sport utility vehicles. The focus on Diesel engine emissions is a direct result of the improved volumetric fuel economy (up to 50 percent) and lower carbon dioxide emissions (up to 25 percent) over comparable gasoline engines shown in Europe. Selective Catalytic Reduction (SCR) with aqueous urea as the nitrogen oxides (NO_X) reductant and a catalyzed Diesel Particulate Filter (DPF) were chosen as the primary emission control system components. The program expects to demonstrate more than 90 percent reduction in particulate matter (PM) and NO_X emissions on a light-duty truck/SUV application. Very low sulfur Diesel fuel (~15 ppm) will enable lower PM emissions, reduced fuel economy penalty due to the emission control system, and improved long-term system durability. The end result will allow vehicles with Diesel engines to be Tier II emissions certified at a minimized cost to the consumer.

Third year results showed a 40 percent reduction in engine-out NO_X emissions of a mid-size prototype Diesel engine through engine recalibration and increased exhaust gas recirculation. Use of a rapid warm-up strategy and urea-SCR provided over 90 percent further NO_X reduction, while a catalyzed DPF reduced tailpipe PM levels almost to gasoline vehicle levels. Development work continued to separately improve urea-SCR and DPF system durability. Improvements in exhaust gas NO_X and ammonia sensors were also made for more accurate reductant injection control and on-board diagnostics. Durable hardware was developed, with the help of nozzle and dispenser manufacturers, for delivery of Diesel fuel and aqueous urea simultaneously to the vehicle.

SCR Potential and Issues for HD Applications in the USA

Kuno Flathmann, Detroit Diesel Corp

Stringent emissions standards require complex engine, aftertreatment, and vehicle systems with a high degree of sub-system interaction and flexible control solutions. Among currently foreseeable nitrogen oxides (NO_X) reduction aftertreatment solutions selective catalytic reduction (SCR) is the most mature technology capable of supporting a powertrain to demonstrate near zero NO_X emissions. SCR is being pursued for heavy-duty fleet transportation in Europe and most recently in Japan. This presentation will review the SCR technology and required infrastructure being proposed for customer applications in these markets. The presentation will also review the infrastructure proposed for the U.S. to support this technology for 2007 as well as comment on how the situation changes considering potential implementation for 2010.

A Fast Start-up On-Board Diesel Fuel Reformer for NO_X Trap Regeneration and Desulfation

Rudy Smaling
ArvinMeritor Inc.

The presentation will describe recent progress in our program to develop an emissions technology allowing Diesel engines to meet the upcoming 2007/2010 regulations for nitrogen oxides. At the heart of this technology is the ArvinMeritor Diesel Fuel Reformer that reforms the fuel, on-demand, on-board a vehicle. The fuel reformer uses plasma to partially oxidize a mixture of Diesel fuel and air creating a highly reducing mixture of hydrogen (H_2) and carbon-monoxide (CO). In a previous publication, we have demonstrated that using a reformate rich in H_2 and CO to regenerate a NO_X trap is highly advantageous compared to vaporized Diesel fuel used conventionally. In this presentation we present results and a strategy for performing desulfation of the traps using the fuel reformer. In contrast to vaporized Diesel, which requires very high temperatures that fall outside the normal exhaust operating temperatures for Diesel engines, desulfation was achieved at temperatures around 350°C using the Plasma Fuel Reformer. This is likely to provide substantial durability benefits for the NO_X traps, a major hurdle remaining in the commercialization of that technology. A lower temperature that falls within the normal engine operating range also provides an effective desulfation strategy including the possibility of some desulfation occurring simultaneously with NO_X regeneration. In this presentation, experimental results will also be presented on the fuel reformer including hydrogen yield, soot production, start-up time, and durability. The fuel reformer is capable of reaching up to 90 percent of the theoretically possible hydrogen yield at a range of fuel flow rates when used in conjunction with a downstream catalyst. The soot production is minimal both upstream (<20 mg/m^3) and downstream ($<$ 5 mg/m^3) of the catalyst, while the start-up time required to reach 90 percent of the maximum hydrogen output is around 5 seconds. The system has been operated for more than 5000 cycles without any noticeable performance degradation.

Impact of SO_2 on Lean NO_X Trap Catalysts

Sonia Hammache; University of New Mexico (Department of Chemistry) and Lindsey Evans, Ronald S. Sandoval, Eric N. Coker, and James E. Miller; Sandia National Laboratories (Advanced Materials Laboratory)

The use of Lean NO_X Trap (LNT) catalysts to reduce greenhouse gas and nitrogen oxides (NO_X) emissions from lean-burn gasoline and Diesel engines is an appealing idea due to the low impact of infrastructure deployment compared to competing technologies. However, performance issues and (particularly) durability of catalysts are key barriers to the commercial acceptance of LNT catalysis for Diesel aftertreatment. Pt-BaO/γ-Al_2O_3 is a promising LNT formulation. However, deactivation of this benchmark material by sulfur oxides is severe, hence the need to improve durability. We have chosen to study the effect of copper on Pt-BaO/γ-Al_2O_3 based on its demonstrated ability to impart sulfur tolerance to related catalyst systems. The resistance of Pt-BaO/γ-Al_2O_3 (1 wt.% Pt, 20 wt.% BaO) and Pt-Cu-BaO/γ-Al_2O_3 (1 wt.% Pt, 2 wt.% Cu, 20 wt.% BaO) to deactivation by sulfur dioxide (SO_2) addition was investigated during both lean and rich cycles at 380°C. Our results showed that addition of copper to the benchmark catalyst decreased the initial storage capacity of NO_X on the catalyst; however, it also slowed its deactivation by SO_2. Additional characterization of the materials suggests that the improved sulfur tolerance results from the formation of bimetallic Cu-Pt phases.

Use of a Diesel Fuel Processor for Rapid and Efficient Regeneration of Single Leg NO_X Adsorber Systems

R. Dalla Betta, J. Cizeron, D. Sheridan, S. Vilayanur
Catalytica Energy Systems, Inc.

Nitrogen oxides (NO_X) adsorber or NO_X trap systems must be regenerated frequently to convert the adsorbed NO_X to nitrogen and to regenerate the NO_X adsorption capacity of the NO_X trap. This regeneration requires a reducing environment and the presence of a reductant capable of reacting with the NO_X trap components. Numerous reports have shown that "reactive" reductants such as hydrogen, carbon monoxide, and oxygenated species can regenerate NO_X traps more rapidly and at lower temperatures than with direct Diesel injection. While this offers a clear NO_X reduction advantage, providing such a reductant in a cost effective manner can be problematic.

A cost effective Diesel fuel processor has been developed that can operate from low loads to full load. The fuel processor can produce periodic high concentrations of a "reactive" reductant as required during the regeneration cycle. Full-scale engine tests with several different origioinal equipment manufacturers have shown that the fuel processor produces a "reactive" reductant over a wide exhaust temperature range and with good control of reductant mass flux. The benefits of a reactive reductant were demonstrated by tests in which the NO_X trap was regenerated with reductant pulses as short as 1 second. Steady state tests have shown fuel penalties of less than 3 percent for a single leg system with greater than 90 percent NO_X conversion. The operating characteristics and performance of the Diesel fuel processor will be presented.

High Throughput Program for the Discovery of NO_X Reduction Catalysts

Richard J. Blint
General Motors R and D Center
Chemical and Environmental Sciences Laboratory

Gerald Koermer
Engelhard Corporation

George Fitzgerald
Accelrys Corporation

This project for the discovery of new lean nitrogen oxides (NO_X) catalysts is now into its second year and, using high throughput techniques, is searching through many materials very rapidly to find new catalyst prospects. The Engelhard discovery system has been modified and has been active since May of 2003. Material scale up techniques to evaluate promising candidates in the GM reactor have been developed and implemented. The GM reactor has been modified and has been used in validation studies. Validation shows that the discovery reactors and the GM reactor are good techniques for describing the response of a catalyst to Diesel engine conditions. A secure network for database population is operational and the database is being populated. Over 2,000 materials have been evaluated and approximately 10 percent of those materials have been identified for detailed analysis in the GM reactor. Informatics software for data import, a database, search and query tools and trend analysis has been developed. Trend analysis and design of experiment are being used to refine the search for high activity NO_X reduction catalysts. This presentation will be a report on the progress of the program.

Economic Comparison of LNT versus Urea SCR for Light Duty Diesel Vehicles in US Market

John Hoard, Robert Hammerle, Christine Lambert, George Wu
Ford Motor Company

Lean NO_X trap (LNT) and urea selective catalyst reduction (urea-SCR) catalysts are under development for nitrogen oxides (NO_X) reduction. In this paper, we compare the total cost effects of choosing LNT versus urea-SCR for NO_X reduction. The input data used for this analysis is developed from publicly available sources.

To estimate the costs, we first describe typical systems in terms of catalyst size and loading, and added required equipment such as additive dosing systems and control sensors. From these descriptions we develop cost estimates. The high precious metal loading and volume typical of LNT catalysts makes those systems significantly more expensive than urea-SCR, even after including a urea dosing system.

Further, LNT strategies involve periodic rich regeneration, causing degradation in fuel efficiency. Since manufacturers must meet Corporate Average Fuel Economy (CAFÉ) standards, any degradation in vehicle fuel efficiency for some vehicles must be offset by improvements in the fuel efficiency of other vehicles. Using estimates of Diesel vehicle market penetration along with the cost to improve fuel efficiency, we can estimate the expenditure required to offset the LNT fuel economy penalty.

The cost of vehicle ownership is affected by fuel consumption and, in the case of urea-SCR, urea purchase costs. The cost of added fuel consumption for LNT more than offsets a likely urea cost.

Of course, urea-SCR system function requires the vehicle to have urea available onboard. Estimates of the cost of a urea co-fuelling infrastructure are made.

The total cost to provide urea co-fuelling infrastructure is roughly equivalent to about three years' cost increase for LNT over urea-SCR. That is, total cost to society is lower after three years when urea-SCR systems are used, even choosing the most expensive urea infrastructure option.

Use of urea-SCR offers better fuel efficiency and lower greenhouse gas emissions, higher and more robust NO_X conversion, much lower aftertreatment system cost, and lower cost of ownership. Business, consumers, and government should work together to enable urea-SCR technology.

Development of a Durable Low-Temperature Urea-SCR Catalyst for CIDI Engines

Donovan A. Peña, Eric N. Coker, Ronald S. Sandoval, and James E. Miller
Chemical Synthesis and Nanomaterials, Sandia National Laboratories

In the quest for effective emission control devices for compression ignition direct injection (Diesel) engines, Selective Catalytic Reduction (SCR) using urea lies ahead of most other technologies due to its high nitrogen oxides (NO_X) reduction efficiency. It is well documented, however, that the performance of SCR catalysts drops precipitously at low temperatures (typically <250°C), leaving emissions control for light-duty (LD) Diesels unsolved. We have embarked upon the development of an active and durable low temperature urea-SCR catalyst that could enable regulatory acceptance of LD Diesel vehicles (*e.g.*, SUVs, light-duty trucks). Active component development has deliberately steered away from the use of vanadium, a highly active yet toxic metal. Our catalyst formulations are based on transition metals supported on hydrous metal oxide substrates. Activities screening utilized granulated powder catalysts, while promising formulations were transferred to monolith platforms in house for further evaluation. Comparison of powder and monolith data verified that, under the experimental protocols employed, monolith performance could be accurately predicted from data collected using powders. Some successful candidates that meet all of the performance requirements of original equipment manufacturer collaborators have been developed and subjected to a number of durability tests. Fresh, degreened performance was evaluated using simulated LD-Diesel exhaust, with ammonia as the reductant, across a range of temperatures (125 – 450°C), $NO:NO_2$ ratios, and space velocities. Durability tests were conducted on the best-performing candidates, and included evaluating catalytic activity after high-temperature hydrothermal treatment, exposure to hydrocarbons, and exposure to sulfur dioxide. The results show that the addition of a promoter to specific formulations results in catalysts that meet all activity and durability targets.

Review of SCR technology for Diesel Emission Control:
European experience and perspectives for 2010

Emmanuel Joubert
Aaqius & Aaqius

Selective catalytic reduction (SCR) technology has been used to control emissions from stationary sources for more than 20 years. More recently, it has been applied to selected mobile sources, including heavy duty-trucks, marine vessels, and locomotives. In October 2005, SCR is expected to be introduced in Europe targeting on-road Diesel heavy-duty vehicles (HDV) to help meet the Euro 4 emission standards.

This presentation describes the current roadmap of SCR in Europe in the HDV segment and reviews all key elements of this technology. A European market overview will be presented describing the implementation of the SCR in terms of infrastructure, cost, efficiency, architecture, and vehicle integration for HDV. Some forecasts will be developed for light-duty vehicles in order to comply with future standard regulations, Euro V/VI and US10.

Decomposition and Storage Phenomena of Urea in SCR Systems

John M. E. Storey, C. Scott Sluder, Samuel A. Lewis, Linda A. Lewis
Oak Ridge National Laboratory

Continued interest in the benefits of high efficiency lean burn engines for light-duty and some heavy-duty applications has challenged exhaust aftertreatment with operation at low temperature. Concerns over durability of nitrogen oxides (NO_X) adsorber catalysts have re-invigorated interest in urea-SCR (selective catalytic reduction) for light-duty Diesel applications. In several studies of SCR systems on light-duty and heavy-duty Diesels, urea decomposition and SCR performance has been investigated. Experiments were carried out using a 1.7L four-cylinder common rail injected Diesel engine as well as a 5.9L medium-duty Diesel to generate exhaust for the SCR devices. Urea injections at stoichiometric levels and below were used. Measurements of NO_X performance, urea hydrolysis, and unregulated emissions such as dinitrogen oxide, nitrates, nitrites, and ammonia, were made. Additionally, instrumentation and sample collection challenges are described. Long duration exposures and burn-off studies revealed the long time scale storage of ammonia and ammonia precursors at low temperatures. Results indicated that there was very significant storage of ammonia in the form of ammonium nitrate and isocyanic acid at temperatures below 180°C. These storage and release phenomena have important implications for model-based control of the urea-SCR process. Higher temperature operation and over-spray led to formation of several identifiable urea decomposition products.

Diesel Aftertreatment Systems Development

J. Josh Driscoll and Maarten Verkiel
Caterpillar, Inc.

The use of aftertreatment will be required to meet future heavy-duty exhaust emission regulations. A systems-level development approach will be necessary to fully evaluate both the potential benefits of aftertreatment as well as the technical challenges that require additional focus. Catalyst bench test facilities, engine testing capability, and a combination of device- and system-level modeling tools have been developed. These capabilities have been applied to evaluate the integration of advanced aftertreatment devices with Advanced Combustion Emission Reduction (ACERT) technology.

Abstracts

SESSION 12 – Emission Control/PM Reduction

Chair: **Mike Bogdanoff, South Coast Air Quality Management District (SCAQMD)**

Particle Sensor for Diesel Combustion Monitoring

David Kittelson and Hongbin Ma, University of Minnesota
Michael Rhodes and Brian Krafthefer, Honeywell International

The goal of this research program has been to develop a particle sensor for use in Diesel engine applications that is low cost, robust to harsh environments, and manufacturable in high volume. The sensor would be used for engine control applications as opposed to highly accurate laboratory measurements. The current sensor concept is based on image charge monitoring for reasons of probe (electrode) complexity, probe ruggedness, electronics complexity, speed of response, and background effects. The sensor has demonstrated good response with well-defined and reproducible signals and is applicable across multiple engine sizes and types. The sensor response is proportional to the soot or elemental carbon concentration in the exhaust. The time response of the sensor is sufficient to monitor emissions from individual cylinders and its sensitivity is sufficient to detect particle emissions from modern low emission engines such as a Euro IV VW TDI and a Caterpillar C12. The sensor's unique design makes it resistant to carbon fouling. The sensor works best near the exhaust ports because the strength of the signal decreases downstream, although flow through the turbocharger has no significant effect on sensor response. Tests on the VW TDI which was equipped with a catalytic converter showed a 30 percent reduction in sensor response on passing through the catalyst, while tests on the Caterpillar C12 which was equipped with a Diesel particulate filter (DPF) showed nearly 100 percent reduction of the sensor signal (and soot) downstream of the DPF. These results suggest that sensors installed upstream of aftertreatment could be useful for engine control and determination of when filter regeneration is necessary, while sensors downstream of aftertreatment could be useful in on-board diagnostic applications.

Reliability and Design Strength Limit Calculations in DPF's

James E. Webb
Corning Incorporated

Diesel particulate filters, particularly those for heavy duty applications, have stringent requirements for reliability and lifetime. From these requirements, estimates of design strength limits can be calculated. The design strength limits presented here are based on parameters including shape of the strength distribution, DPF size, and time dependent strength or what is commonly known as fatigue behavior in ceramics. Some sample calculations will be presented with typical mechanical properties. However, the main focus will be a normalized strength approach, where the impact of the various inputs on the design strength limits can be compared to each other, similar to a sensitivity analysis. From these design strength limit estimates, implications for confidence intervals and design of test plans will also be discussed.

A New CFD Model for Understanding and Managing Diesel Particulate Filter Regeneration

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One of the key challenges to Diesel Particulate Filter (DPF) technology is regeneration. How well regeneration is understood and managed will have a significant impact on the success of this technology. A good regeneration can be defined as fast, complete, safe, and causing minimal fuel penalty. To achieve this goal, the impact of exhaust gas flow rate, gas temperature, oxygen content, filter material, and soot loading, to name just a few, on regeneration performance must be studied and understood.

DPF regeneration involves a complex variety of physical and chemical processes, encompassing fluid flow, heat transfer, chemical reaction, and catalysis. Modeling can be an effective method to study the complex activities encountered during regeneration. However, most models in the literature are two-dimensional and based on assumptions that the flow field in DPF channels can be treated as such, even though the flow in DPF is fundamentally three-dimensional. There is also a lack of sophistication in the way the filter wall (substrate) and the soot cake layer are modeled.

A new computational fluid dynamics model was developed to predict fluid flow, heat transfer, and soot reaction during DPF regeneration. The underlying physics was solved in one inlet/outlet channel set based on a three-dimensional, unsteady framework. The filter wall and the soot cake layer was modeled as porous media, for which the full Navier-Stokes equation is solved. Specific permeability and thermal properties were assigned for the wall layer and the soot layer, which vary as regeneration proceeds and as a function of temperature. Soot combustion was tracked with a modified Arrhenius equation, which includes the effect of the catalyst applied on the filter.

The model was validated by comparisons with results of DPF heat-up tests and regeneration tests. The validated model was then used to study the effects of exhaust gas flow rate, exhaust gas temperature, oxygen content, filter design, and soot loading on regeneration performance. Spatially and temporally resolved distributions of velocity, temperature, oxygen, reaction rate, and soot layer thickness, etc. will be presented. The model was also used for “what-if” studies, such as the runaway regeneration scenario study. Excellent agreement between measurement and prediction was achieved. The model is being used in the design and development of DPF systems.

Diesel Particulate Filter Technology for Low Temperature and Low NO_X/PM Applications

Sougato Chatterjee, Ray Conway, Satish Viswanathan, Todd Jacobs
Johnson Matthey Catalysts
Environmental Catalysts & Technologies

Diesel Particulate Filter Technology is being widely accepted as a retrofit or first fit technology that can provide significant reductions in hydrocarbon (HC), carbon monoxide (CO) and particulate matter (PM) emissions. Numerous tests and fleet demonstration programs have shown that the technology can be installed and operated for a reasonable cost and that the technology is durable. As a result many legislators are requiring the retrofit of captive Diesel fleets with this technology. Before Diesel particulate filter (DPF) technology can be fit into an application, the vehicle has to be evaluated to ensure that its operating characteristics will allow for the proper operation of a passive device. For the Johnson Matthey CRT® (Continuously Regenerating Technology) to work properly the exhaust temperature profile and the engine out NO_X to PM ratio must be above specific levels. If these criteria are not met, there will be insufficient soot combustion in the filter resulting in high back pressure that will hamper engine operation. In our experience we have found primarily two types of applications that will not work well with the CRT; vehicles with operating cycles that have very low temperature profiles and vehicles with engines that have low NO_X/PM ratios under the real world operating cycle.

This paper will discuss technologies that Johnson Matthey has developed to address applications that have low exhaust temperature profiles, low NO_X/PM ratios, or both. One is a passive system that is a combination oxidation catalyst and catalyzed soot filter and the second is an active system that increases the engine out exhaust temperature by throttling the engine inlet air.

The CCRT® (Catalyzed –CRT) is similar in function to the CRT in that it consists of an oxidation catalyst up stream of a wall flow filter. However, in the CCRT, the wall flow filter has a catalytic coating. Similar to the CRT, nitrogen oxide (NO) is oxidized to nitrogen dioxide (NO_2) in the catalyst section of the CCRT and the NO_2 oxidizes soot trapped in the filter. Within the catalyzed filter of the CCRT, the NO that is formed from the reaction of soot with NO_2, can again be converted to NO_2 and can thus be reutilized for further soot combustion. Because of this mechanism, the CCRT can be used in applications with low NO_X/PM ratios. The additional NO_2 availability also appears to allow the CCRT to operate at a much lower temperature than the standard CRT.

Studies have shown that restriction of the air flow into or out of the engine will increase the exhaust temperature, but careful control is necessary so that such a system will not affect engine power or emissions. The active system developed by Johnson Matthey involves throttling the engine inlet air at the air inlet manifold. The system monitors the engine speed and load and only applies throttling at conditions that have low exhaust temperatures. The maximum amount of throttling that can be applied at each load and speed was determined through an engine mapping process. The maximum amount of throttling that can be applied is limited by the effect on power, inlet manifold temp, increase in exhaust temperature, and engine out emissions. This throttle based active regeneration device can increase the on-road exhaust temperature profile by up to 60°C thus enabling CRT operation in cold exhaust applications.

This presentation will show development test data for both of the above products as well as on-road durability data.

Advanced Ceramic Filter for Diesel Emission Control

Cheng G. Li, Frank Mao, Ravi Ramanathan
Dow Automotive

A new advanced ceramic (ACM) filter for both Diesel particulate matter and exhaust gas emission control has been developed by Dow Chemical Company through a catalyst reaction process. With the ability to modify the filter wall porosity and pore size distribution, the ACM filter provides deep filtration and performance benefits such as little pressure drop, fast regeneration, and multiple emission catalyst function. This technology can also be applied to fine particulate filtration. The testing results from laboratory and an engine dynamometer have demonstrated ACM's advantage as expected and also indicated that there is a high possibility of a 4-way system development by using ACM.

A New Active DPF System for Duty Cycle Vehicles: Durability and Improvements

Jean-Claude Fayard, COMELA
Thierry Seguelong, Aaqius & Aaqius

Diesel urban buses as well as refuse trucks are part of the particulate emission sources that affect the city air quality. So, several Diesel particulate filter (DPF) systems were proposed to reduce such emissions. But the reliability and the durability of the current DPF systems remain an issue, due to the lack of the filter regeneration control during the duty cycles.

To fit particular duty cycle requirements, a new active DPF system was developed with a new regeneration strategy in order to overcome the durability and reliability issues. The DPF system consists of particulate filter units, an oxidation catalyst placed in front of the filters, valves and actuators allowing thermal insulation of the filter units, temperature and pressure sensors, and an electronic control unit to control the positions of the insulation valves.

The principle strategy is based on an adjustable volume of filtration in combination with the global thermal management allowing the filters to regenerate in all driving conditions. Furthermore, in order to fully control the filters regeneration, an additional heat injection strategy is needed. Diesel fuel injected over the oxidation catalyst, heats up the filters individually depending on the position of the insulation valves.

The DPF System was evaluated by the ADEME (French Agency for Environment and Energy Management) on refuse truck (EURO2) applications for more than 12 months, using standard European Diesel fuel (350ppm of Sulphur). The DPF system demonstrated high efficiency and durability and reduced particulates by more than 89 percent (in mass per kilometre) over the duty driving cycle reference. This result confirms the previous evaluations carried out on EURO½ urban buses and EURO3 original equipment manufacturer refuse trucks.

In parallel, in order to extend the field of applications, further improvements have been developed, using a fuel-borne catalyst (FBC) to control the filters regeneration and limit the maintenance. The experiments have demonstrated the positive effects of FBC in the trap loading as well as the filter regeneration. In addition, the combination of the basic process and the FBC leads to a limitation in FBC dosing rate. Details of experiments and results will be presented in the paper.

DPF Systems Comparison – Fuel Borne Catalyst or Catalyzed Particulate Filter for Diesel Passenger Cars

J. Michelin, S. Schürholz, A. Lang, and F. Terres
Tenneco Automotive

The German Automobile industry has announced to fit at least a part of their Diesel models with particulate filters by the beginning of this year (2004). In contrast to the PSA concept, which is dependent on fuel additives to support the regeneration, most of the German car manufacturers want to launch a system that operates without additives. The innovative system they rely on needs a catalyzed soot filter.

The content of this presentation is the technical comparison of both concepts with regard to exhaust backpressure, regeneration behavior, packaging and related issues, fuel consumption, and operating cost. In this comparison the fuel borne catalyst has clear technical advantages. A severe disadvantage is the additional ash from the fuel-bourne catalyst clogging the filter leading to an increased maintenance schedule. This issue can be solved using a bigger filter or using new filter geometry.

Using P-CAT, a calculation tool developed by Tenneco Automotive, it is possible to show that the back pressure targets for 250,000 km (useful life) set by the car manufacturers can be met with both systems. On one hand, the fuel additives have been optimized, which permitted a reduction in the dosage and thereby reduced ash production. On the other hand, a new generation of filters has been developed with optimized ash storage capacity.

Improvement and Simplification of DPF System Using a Ceria-based Fuel-borne Catalyst for Diesel Particulate Filter Regeneration in Serial Applications

Pierre Macaudiere
Rhodia Electronics & Catalysis

Since the market introduction of the Diesel Particulate Filter (DPF) system in serial applications in May 2000, more than 500,000 vehicles have been DPF-equipped. Tracking the current situation, several themes for improvement have been identified, including system simplification to limit its total cost as well as proposition to optimize maintenance. The paper presents those upgrades that will be proposed in serial applications.

Based on DPF regeneration assisted by engine management systems in combination with the use of a Ceria-based fuel-borne catalyst, the first improvement is to limit the ash build up phenomenon of fuel-borne catalyst and then to limit the DPF clogging effect.

In the first stage, catalytic activity of Ceria-based fuel-borne catalyst has been improved, by introducing Iron as a catalytic promoter. Targeting the “fit for life” DPF application (and thus "zero maintenance" on the DPF), it is necessary to find a compromise between the catalytic activity (reduction in the temperature of soot burn-off and kinetics of DPF regeneration), the temperature peak generated during the DPF regeneration (exotherms of regeneration), and the density of the inorganic ash arising from the fuel-borne catalyst (ash build-up speed). A good compromise is proposed in this way, based on the use of the Iron-doped Ceria nanoparticules as the active catalytic ingredient.

In parallel, a dosing strategy of a fuel-borne catalyst is being developed to match with the proposed evolution in the Ceria-based fuel-borne catalyst for serial applications. New designs of the automatic on-board dosing system have been developed to ensure the global accuracy in the Diesel fuel treatment. On the other hand, the maintenance operation for fuel-borne catalyst tank refilling is integrated in the design of the dosing systems, which is adapted to the platform of the vehicle and the car makers’ specifications. In the paper, the following approaches are developed, and the data obtained on a demonstrator are proposed.

Retrofit Program on EURO 1 and EURO 2 Bus Fleet in La Rochelle using a Ceria Based Fuel Borne Catalyst for Diesel Particulate Filter Regeneration - Status after one Year Experience.

Laurent Rocher
Rhodia

Diesel emission control is becoming a priority particularly in urban areas and specific efforts are made to reduce emissions from urban buses. In September 2003 the CDA La Rochelle has started a voluntary retrofit program to equip their EURO 1 & 2 urban bus fleet. The selected technology was the combination of a Silicon Carbide Diesel Particulate filter and a Ceria based fuel borne catalyst used to ensure a fast and complete Diesel particulate filter (DPF) regeneration. This paper describes the preliminary technical assessment phase which was done to implement the system followed by the extension of the equipment to the whole bus fleet.

In the first phase a preliminary study was carried out on a EURO 2 Diesel engine bench test to check the regeneration behavior and thus the efficiency of the DPF technology. In the second phase the system was fitted on 4 buses and has proven its efficiency after 4 months of field evaluation even with fuel containing 250 ppm sulfur. In parallel a stationary automatic dosing system was used to add the ceria based fuel borne catalyst to the fuel by a co-filling process.

After this field evaluation, the CDA La Rochelle decided to extend the DPF system to the whole EURO 1 and EURO 2 bus fleet. Different parameters were measured (back pressure, exhaust temperature and efficiency of DPF regeneration). A specific maintenance procedure was also set up and the filter could be washed successfully by using a mobile DPF washing machine.

The paper relates more than 10 months of a large scale experience showing the reliability of a diesel emission control technology based on a Particulate Filter and a ceria based fuel borne catalyst. Details of experiments, results, and approaches will be described in the paper.

Diesel Particulate Filters Market Introduction in Europe: Review and Status

Thierry Seguelong
Aaqius & Aaqius

The challenge for Diesel particulate filters (DPF) in serial applications is real, multiple, and complex. Taking into account different and sometimes conflicting aspects such as: **technical** (DPF efficiency, reliability, durability, and compatibility with engine performance); **economical** (system cost compatibility and maintenance); **environmental** (regulated and non-regulated emissions, such as nitrogen dioxide, ozone, furans, dioxins, and solid particulate); **geographical** (flexibility regarding Diesel fuel qualities and sulfur content); and finally, **customer acceptance** (extra cost, vehicle drivability, acoustic performance and maintenance constraints).

Since May 2000, PSA Peugeot Citroën has marketed the “FAP™” DPF System as a world first. It is based on the sequential DPF regeneration that uses a specific engine management, a silicon carbide-based DPF, pressure and temperature sensors, adapted DPF canning, the Eolys™ Ceria-based fuel-borne catalyst, and an automatic on-board dosing system. Since its market introduction, more than 1million vehicles have been sold over Europe, without recall or failure, and with constant improvement in the global DPF System approach.

With EURO IV deadline approaching, European car manufacturers have accelerated their development effort and the Diesel Particulate Filter was the most presented emission control technology during the 2003 edition of the prestigious Frankfurt Auto Show. The principle of a Diesel soot filter was largely announced and appears to have gained automotive industry acceptance as the preferred technology for Diesel particulate emission control. This move from industry is also a response to the current pressure of environmental organizations and public opinion in some countries. As main conclusions on the Frankfurt Auto Show, it can be said:

- The important number of announcements confirms that DPF is now accepted by the Automotive Industry.
- Uncertainties remain as to when significant series introduction will truly begin.
- Maturity of the different technological options is diverse and work remains to be done.

The paper will present the present situation and the main issues to address such as the global cost function and evolution, the maintenance and recycling, and the compatibility in the next challenge of particulate matter, nitrogen oxides, and carbon dioxide standards.

Soot Nanostructure: Definition, Quantification and Implications

Dr. Randy L. Vander Wal and Aaron J. Tomasek
The NCMR c/o the NASA-Glen Research Center

Soot is ordinarily considered as a carbonaceous material with environmental and health consequences highly dependent upon particle size. Though to-date unexplored, the nanostructure of the soot, i.e. the degree of atomic level order in carbon lamella comprising the soot primary particle can have profound consequences for soot reactivity and associated environmental and health effects. The talk will define soon nanostructure, describe its quantification by image analysis of high resolution transmission electron microscopy images and illustrate its impact on oxidation rate.

Differences in soot nanostructure based upon formation and growth conditions will be presented first. Fuel structure effects can be masked or accentuated depending upon both temperature and rate of increase. Low temperature yields different results depending upon the rate of increase. A rapid increase as realized by a high flow rate, emphasizes pyrolysis kinetics that favor polyaromatic hydrocarbons (PAHs) with 5-membered rings leading to soots with many shells capsules; a highly curved nanostructure. Slower rates result in a different pyrolysis chemistry leading to graphitic soot, as characterized y long graphite segments, o riented p arallel to e ach o ther. Reflecting h igh t hermodynamic stability, P AHs may resist decomposition and yield a less graphitic soon nanostructure using either a fast or slow temperature increase. In contrast, ethanol produces a highly curved nanostructure using wither temperature increase rate.

To quantify these differences in nanostructure, a lattice fringe analysis program has been developed to quantify the data conveyed by H RTEM images. By providing a direct measure if the molecular level of graphitic structure, it is expected that its application could provide predictive capabilities for carbon reactivity, particularly towards oxidation. The robustness of this program is demonstrated by using a series of carbon blacks possessing different levels of graphitic structure, prepared at different heat treatment temperatures. Its credibility is benchmarked against a traditional measure if graphitic structure as provided by Roman analysis. Lattice fringe length is found to be monotonic with the level of graphitic structure as provided by the ration of the integrated intensities of the G/D spectral peaks in the Raman spectra. Reciprocally, for production purposes, the G/D band intensity ratio can serve as a direct measure of the lattice fringe reactivity.

We further explore the relationship between soot nanostructure and reactivity towards oxidation b y m easuring t he o xidation r ates o f l aboratory sy nthesized s oots w ith Ò modelÓ identity. Structural variations in the graphene layer plane dimensions necessarily alter the ratio of basal plane versus edge site carbon atoms. A corresponding variation on the overall reactivity, reflecting an average of the different relativities associated with these specific atomic sites arises. This variation is illustrated here between a disordered soot derived from benzene and a graphitic soot derived from acetylene. Their oxidation rates differ by nearly 5-fold. Curvature of layer planes, as observed for an ethanol derived soot, is found to substantially increase oxidative reactivity. Relative to fringe length as a manifestation of graphitic structure, curvature more effectively increases reactivity towards oxidation. Larger variations in oxidation behavior may be expected, depending upon the soot synthesis conditions. Other physical properties may similarly be affected. Related implications due to differences in nanostructure will be discussed.

Emission Control Systems and Components for Retrofit, and First-Fit Applications

Bradley L. Edgar, Ph.D.
Cleaire Advanced Emission Control

Cleaire has developed a set of core components that serve as "building blocks" of integrated emission control systems for retrofit and first fit applications. The key components include the following: a modular "gasketless" packaging design, a hydrocarbon dosing system, a control module with datalogging and I/O capability, an active lean NO_X (HC-SCR) catalyst, and a catalyzed silicon carbide particulate filter. These components can be assembled in total as an integrated "turnkey" system for retrofit applications, or can be used individually to support optimized catalyst/engine platforms for First-Fit applications.

An example of an integrated "turnkey" system is Cleaire's Longview; the first CARB verified NO_X and PM control system for retrofit applications. The system, called Longview, is verified to reduce NO_X by 25% and PM by 85% on the majority of heavy-duty diesels built between 1994 and 2002. To date, over 500 systems have been installed in a variety of applications. As a result, these systems and components have logged millions of miles and thousands of hours of "real world" experience, which has proved their durability and robustness.

This presentation will discuss the design, testing, and application of these systems and components.

Catalyzed Particulate Filter: Development and Application for Diesel Engine Emission Control

Yinyan Huang, Zhongyuan Dang, Yongtaek ChoiAmiram Bar-Ilan
Süd-Chemie Protot ech, Inc.

A catalyzed Diesel particulate filter (CDPF) was developed with the use of Corning cordierite wall flow filter substrate. A new precious metal/base metal catalyst on high surface area support was developed. The deposition of catalyst/washcoat leads to negligible back pressure increase to blank filter substrate. Lab bench testing shows that the CDPF is very active for the oxidation of carbon monoxide (CO) and hydrocarbon (HC). Supporting the catalyst on high surface area material enhances the activity for CO, HC oxidation. The catalyst also shows high thermal stability.

The CDPF was tested on 8HP LPA2 stationary Diesel engine at 1800 rpm with the use of federal Diesel fuel. The balance point temperature of the CPDF is 350^{o}C. As the CDPF was tested on Caterpillar C12 Diesel engine with ultra low sulfur Diesel fuel, high removal efficiency of CO, HC and PM was achieved. The measure balance point temperature is 300^{o}C.

Full verification of the CDPF for back-up generators (BUG) at Ce-Cert is in progress. Under ISO8178 five model test cycles with the use of regular CARB fuel resulted in the CDPF having a high removal efficiency of CO (99%), THC (86%) and PM (90%) for Caterpillar 3406 Diesel Genset.