Advanced Petroleum-Based Fuels—Diesel Emissions Control Project (APBF-DEC)

Annual Progress Report
FY 2002

April 2003

A government/industry partnership studying the effects of fuel & lubricant compositions in engine systems to reduce diesel emissions

APBF-DEC Reports

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This is the first Annual Progress report issued by the APBF-DEC project. Other information about APBF-DEC is available on the World Wide Web at http://www.ott.doe.gov/apbf.shtml

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APBF-DEC Quarterly Updates

The Quarterly Update is produced four times a year to provide current information about the progress and preliminary results from the five APBF-DEC projects. Seven Quarterly Updates have been distributed to date, via e-mail and USPS. The updates and a background fact sheet are posted on the Web at
http://www.ott.doe.gov/apbf.shtml.

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Acronyms

ACC	American Chemistry Council (ACC)
APBF-DEC	Advanced Petroleum-Based Fuels—Diesel Emissions Control project
API	American Petroleum Institute
ATL	Automotive Testing Laboratory
B	boron
BP15	ULS Refinery fuel-15ppm
BPT	balance point temperature
Ca	calcium
CARB	California Air Resources Board
CCV	closed crankcase ventilation
CDPF	catalyzed diesel particle filter
Cl	chlorine
CO	carbon monoxide
CO_2	carbon dioxide
CR-DPF	continuously regenerating diesel particulate filter
CVS	constant volume sampling
DECSE	Diesel Emission Control—Sulfur Effects Program
DOC	diesel oxidation catalyst
DOE	U.S. Department of Energy
DPF	diesel particle filter
ECS	emission control systems
EGR	exhaust gas recirculation
EMA	Engine Manufacturers Association
EO	engine-out
EPA	U.S. Environmental Protection Agency
FEV	FEV Engine Technology
FTP	Federal Test Procedure
g/bhp-hr	grams/brake horsepower-hour
GVWR	gross vehicle weight rating
HC	hydrocarbon(s)
HT	high-temperature
KW	kilowatt
L	liter
LT	low-temperature
MECA	Manufacturers of Emission Controls Association
Mg	magnesium
Mo	molybdenum
N_2 (or N)	nitrogen
NH_3	anhydrous ammonia
NO	nitric oxide
NO_2	nitrogen dioxide
NO_3	nitrate
NO_x	nitrogen oxide
N_2O	nitrous oxide
NPRA	National Petrochemical and Refiners Association
OICA	Organisation Internationale des Constructeurs d'Automobiles
ORNL	Oak Ridge National Laboratory
P	phosphorus
PAH/NPAH	polycyclic aromatic hydrocarbons/nitrated polycyclic aromatic hydrocarbons
PM	particulate matter
ppm	parts per million
S	Sulfur
SCAQMD	South Coast Air Quality Management District
SCR	Selective catalytic reduction
SO_2	sulfur dioxide
SO_3	sulfite
SO_4	sulfate
SOF	soluble organic fraction
SUV	sport utility vehicle
SwRI	Southwest Research Institute
THC	total hydrocarbons
TPM	total particulate matter
ZDDP	zinc dialkyl-dithiophosphate

Background

Five test projects have been under way since the spring of 2001 at laboratories across the country to determine the best combinations of low-sulfur (S) diesel fuels, lubricants, diesel engines, and emission control systems to meet projected emission standards for the 2000 to 2010 time period. The laboratories are also studying properties of fuels and vehicle systems that could lead to even lower emissions beyond 2010.

The tests are part of the Advanced Petroleum-Based Fuels—Diesel Emissions Control (APBF-DEC) project. The five test projects are evaluating:

- Selective catalytic reduction/diesel particle filter (SCR/DPF) technologies, fuels, and engines
- Nitrogen oxides (NO_x) adsorber catalyst/DPF technologies, fuels, and engines for passenger cars, light-duty trucks/SUVs, and heavy-duty applications (3 projects)
- Lubricant formulations that may affect the performance and durability of advanced diesel emission control systems.

Initial tasks for the SCR and NO_x adsorber projects developed the test cells and installed test engines, optimized the systems to reduce emissions, determined the effects of various S levels in diesel fuel on regulated and unregulated emissions, and conducted emission control system durability tests. The lubricants project began by measuring engine-out emissions using a variety of oil formulations. Table 1 gives an overview of the five test projects.

The project responds to the need for both light- and heavy-duty vehicles to meet stricter emission control standards. Between 2004 and 2009, lower emissions standards will be phased in for passenger cars and light-duty trucks up to 10,000 pounds gross vehicle weight rating (GVWR). These are "fuel neutral" standards, and for diesel-powered vehicles to comply, catalytic emission control systems will probably be required. The U.S. Environmental Protection Agency (EPA) has also set new emission standards for heavy-duty engines, which will be phased in between 2007 and 2010, and has mandated drastic reductions in the S content of on-highway diesel fuel by 2006. These standards (for emissions of both particulate matter [PM] and NO_x) will, for the first time, require catalytic emission control systems on heavy-duty vehicles.

APBF-DEC's mission is to identify optimal combinations of fuels, lubricants, diesel engines, and emission control systems to:

- Meet projected emission standards during the 2000 to 2010 period while maintaining continuous improvement in engine efficiency and durability
- Maintain customer satisfaction with vehicle performance
- Provide the basis for economical transport of people and goods
- Meet additional potential constraints (e.g., emissions of presently unregulated substances, including ultra-fine pm and greenhouse gases).

Funding for APBF-DEC has been budgeted at $33 million for the four years of testing and is being provided by federal and state government agencies, trade associations, and private industry. The $33 million includes $19.3 million in cash ($12 million from the federal government) and $14 million in in-kind contributions. Major funding is being provided by the U.S. Department of Energy (DOE), the Engine Manufacturers Association (EMA), the American Petroleum Institute (API), the Manufacturers of Emission Controls Association (MECA), the American Chemistry Council (ACC), the California Air Resources Board (CARB), and the South Coast Air Quality Management District (SCAQMD). EPA and the National Petrochemical and Refiners Association (NPRA) are providing technical assistance. Representatives from these and other agencies, trade and professional associations, national laboratories, and private sector companies serve on the 20-member APBF-DEC Steering Committee and its working groups.

The APBF-DEC projects have been designed to provide timely information to both government and industry as new technologies are being developed and deployed throughout this decade. Fuels tested will include the base fuel (less than 1-part per million [ppm] S content), special test fuels (containing 8-, 15-, and 30-ppm S content), and a 15-ppm refinery fuel refered to as BP15. As the tests proceed, APBF-DEC is providing interim data and preliminary findings on the effects of differing fuel and lubricant properties on the emissions and performance of advanced automotive and heavy-duty vehicle systems.

Phase I, consisting of five projects studying the effects of fuel and lubricant sulfur on different engine/system technologies, is expected to be completed in fiscal year 2004. Phase II, which has not yet been defined, could begin in 2004. The APBF-DEC Steering Committee is considering possible recommendations for Phase II tasks, such as extending durability testing, investigating the impacts of other fuel parameters, and developing emissions solutions for off-road vehicles. Beyond 2010, the APBF-DEC project will also explore the potential to achieve even lower emissions of regulated pollutants—such as PM, NO_x, and hydrocarbons (HC)—as well as presently unregulated substances. This first annual progress report summarizes the current status of the four engine/system technology projects and contains a brief summary of the initial Phase I results for the lubricants project. Background publications, early technical reports, and other information are posted on the Web site at http://www.ott.doe.gov/apbf.shtml.

Table 1. Summary of APBF-DEC's Five Test Projects

Technologies	Test Lab	Engines/ Systems	Projects Start/Finish		Test Objectives
2 types of Integrated SCR/DPF emission control systems (ECS)	Subcontractor: Southwest Research Institute (SwRI)	2 heavy-duty Caterpillar C12 engines, 12 L SCR catalysts with DPFs	11/01	12/03	Demonstrate the low emissions made possible by using the SCR/DPF technologies and evaluate the sensitivity of emission controls to fuel variables; determine the regulated & unregulated emissions with and without emission controls; examine the durability of emission control systems; determine toxic and unregulated emission levels.
NO_x adsorber/ DPF 3 separate test projects	3 Subcontractors: -FEV Technology, Inc -SwRI - Ricardo, Inc.	3 Engines: -Passenger car 1.9 L TDI engine -Medium-duty truck engine, Duramax 6.6 L engine -Heavy-duty, 15 L Cummins ISX, DOHC engine	6/01	6/04	Demonstrate the potential to achieve stringent emission reductions from diesel engines using a system of the engine, fuel, NO_x adsorber, DPF, and thermal management technologies; set up & optimize each system; measure regulated and unregulated emissions using fuel with all four S levels; evaluate the systems' performances; determine the long-term performance and durability; examine the effects of fuel properties (other than S) on the systems.
Lubricants	Phase I Subcontractor: Automotive Testing Laboratory (ATL)	International T444E engine	4/01	5/03	Evaluate the effects of lubricant formulations (basestocks and additives) on the performance and durability of advanced diesel emission control systems; determine the effects (if any) of lubricants on S levels in engine exhaust systems. Phase I tests were completed in 9/02.

Selective Catalytic Reduction/Diesel Particle Filter (SCR/DPF) Project

Test Bed: Caterpillar C12, a heavy-duty engine, model year 2000
Testing Laboratory: Southwest Research Institute (SwRI), San Antonio, TX
Technical Monitor: Ralph McGill, Oak Ridge National Laboratory (ORNL)

Introduction to SCR/DPF Project

SCR is an emissions reduction technology that, when combined with a DPF, advanced fuel formulations, and engine technologies such as exhaust gas recirculation (EGR), can reduce NO_x and PM emissions. Two different SCR/DPF systems supplied by different catalyst manufacturers are being evaluated. The purposes of this test are to demonstrate the low diesel emissions made possible by using advanced fuels, engines, and SCR/DPF technologies; evaluate the sensitivities of emission controls to fuel variables; determine regulated and unregulated emissions with and without emission controls; and examine the emission control system's durability. The SCR/DPF project expects to complete all testing in late FY 2003 or early 2004.

Technical Approach

Technologies. The SCR/DPF project is conducting tests using a 12-liter Caterpillar engine as the basis. The heavy-duty Caterpillar engine (model C12) has a displacement of 12 liters, six cylinders, 24 valves, and a turbocharger with intercooling. The engine without modifications exhausts approximately 3.5 grams/brake horsepower-hour (g/bhp-hr) of NO_x and 0.07 g/bhp-hr of PM with D2 diesel fuel on the hot cycle federal test procedure (FTP) transient test. A low-pressure-loop EGR system (Figure 1) is added to the engine emissions control system to reduce the levels of engine-out NO_x. Two types of SCR catalysts and two types of DPFs are being used, known as System A and System B. The SCR catalysts are using urea as a reductant.* Figure 2 shows the components of the new installation.

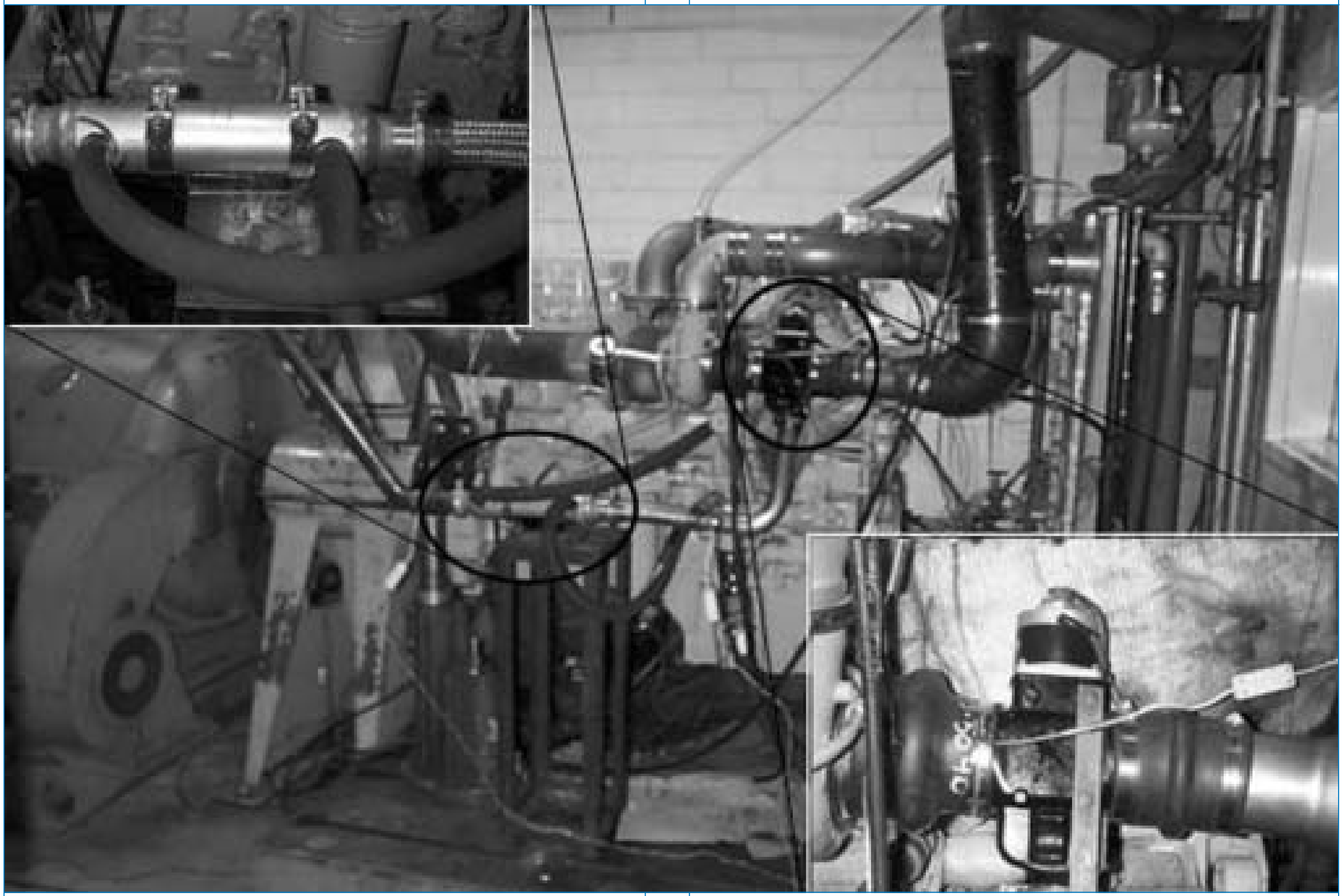

Figure 1. A low-pressure-loop EGR system is added to reduce levels of engine-out NO_x.

* Urea is considered to be a stable and safely transportable means of providing ammonia to SCR catalysts. An aqueous solution of urea, when heated, can produce ammonia that can react to reduce NO_x to nitrogen in an SCR device.

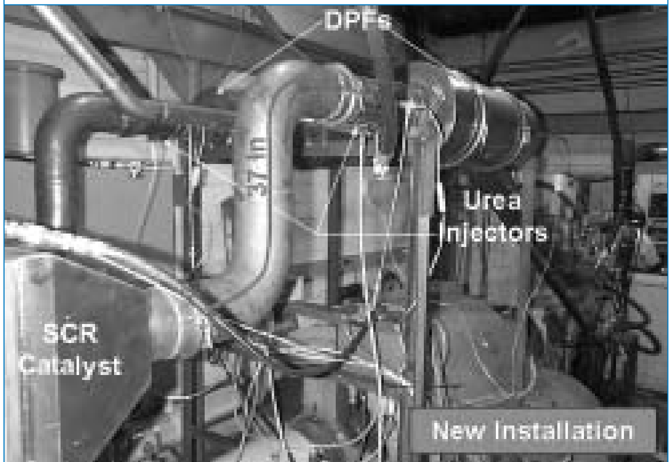

Figure 2. Location of DPFs, Urea Injectors, and SCR Catalyst

Experimental Design. The test is divided into three major activities. In the first part, the emissions control systems are added one by one to the engine, and controls are optimized for lowest possible emissions while retaining fuel economy and engine performance. This is done in separate, consecutive efforts with Systems A and B. Once the system is optimized, it is evaluated for emissions with different fuels—3-, 8-, 11-, and 30-ppm S DECSE fuel and an ultra-low-sulfur refinery fuel. In this phase of the work, regulated and unregulated emissions are measured. Unregulated emissions include soluble organic fraction (SOF), sulfate (SO_4), anhydrous ammonia (NH_3), and nitrous oxide (N_2O); formaldehyde, acetaldehyde, benzene, 1,3-butadiene, toxic nitrogen compounds, metals, and polycyclic aromatic hydrocarbons/nitrated polycyclic aromatic hydrocarbons (PAH/NPAH). In the final phase, the optimized systems are moved into a separate durability test cell where two additional Caterpillar C12 systems are set up for conducting the 6,000-hour durability test.

For the durability test, the engines will be cycled through the steady-state modes of the ESC (OICA) test cycle. During the first phase—at 2,000-hour intervals—the systems will be taken back to the emissions test cell for a complete set of emissions tests.

Test Methods. During the first 200 hours of testing with SCR/DPF System A, the system was optimized and tests were conducted to determine emissions and whether the system can meet 2007 emission regulations. These regulations will limit emissions to 0.20 g/bhp-hr for NO_x and 0.01 g/bhp-hr for heavy-duty engines. After emissions optimization, the system is transferred to the durability cell for 6,000 hours of aging in three stages of 2,000 hours each. Emissions tests are performed at the end of each stage.

In addition to an EGR system, the test setups for both systems include a split exhaust with each leg consisting of a DPF, urea injection system, and an SCR catalyst in series. A single cleanup diesel oxidation catalyst is installed after the exhaust legs are recombined at the tailpipe.

Interim Results

Interim results of tests for System A indicated:

- As received, the Caterpillar test engine had transient NOx/PM emissions of 3.5/0.07 g/bhp-hr.
- All low-sulfur fuels (e.g., 6-, 8-, 15-, and 30-ppm plus the low-sulfur refinery fuel-BP15) using a fresh System A produced emissions close to, but not below, the 2007 regulatory emission standards for NOx and below the PM standards for both the steady-state and transient emissions tests.

The low-pressure-loop exhaust gas recirculation (EGR) system, with a DPF, was calibrated to yield more than a 50% reduction in NO_x and a 90% reduction in PM when using 3-ppm S fuel and a low-pressure loop EGR, in comparison to engine-out results with 350-ppm S fuel.

NOx Adsorber/Diesel Particle Filter Projects

Introduction to Three NO_x Adsorber/DPF Projects

Three laboratories are testing NO_x adsorber catalyst/DPF technologies on three different vehicle/engine platforms to assess their emission reduction performance and to evaluate the effects of fuel composition on the durability of the emission control components. The three laboratories are conducting similar tasks to develop and refine regeneration and desulfurization strategies, measure regulated and unregulated emissions, and evaluate each system's performance with varying fuel sulfur levels over transient and steady-state cycles. The projects test the integration of selected engines/vehicles, emission control systems (ECSs), and optimized engine management systems. The goal is to enable these systems to operate effectively on 8- and 15-ppm S fuels and meet federal emission standards that will go into effect in 2007.

The NO_x adsorber catalyst is a flow-through exhaust emissions control device with the potential to significantly reduce NO_x emissions in diesel engine exhaust. When combined with a DPF, the system can also oxidize the diesel PM, HC, and some unregulated emissions. The three separate vehicle/engine platforms are demonstrating the potential of low-sulfur fuel to achieve stringent emission reductions in diesel engines of different size classes, using a system that includes the engine, fuel, NO_x adsorber catalyst, DPF, and other thermal management technologies.

Experimental Design. The experimental designs for the three NO_x adsorber projects are fairly similar. Each involves aging and periodicly evaluating of one or two ECS configurations with a combination of four fuel S levels. Tests will be conducted using 0.6-, 8-, 15-, and 30-ppm S fuels, but the focus will be on the comparison between 8- and 15-ppm S fuels. Baseline engine-out emissions for 8- and 15-ppm S fuels will also be included as part of this testing. At selected points during the aging, evaluations will occur using a ULS refinery fuel called BP15. At these points, detailed emission sampling will take place and include the measurement of unregulated and toxic emissions (e.g., SOF/SO_4, PAHs, metals, and nitroxy-alkanes). The testing will include emission evaluations over appropriate test cycles (FTP, US06, and Highway fuel economy test for the light- and medium-duty applications; and heavy duty FTP and OICA-13 steady-state for the heavy-duty application). The ECSs will be aged for 300 hours with 8- and 15-ppm S fuels. Emissions evaluations will occur at 50-hour intervals during this part of the testing and will include duplicate and triplicate sampling. After 300 hours one system will undergo additional durability testing. Currently, the length of durability testing is between 1,000 and 2,500 hours, depending on the application. Emissions evaluations will occur at 100-hour intervals during this part of the testing, with occasional duplicate tests to determine the precision of the measurements.

Passenger Car NOx Adsorber/Diesel Particle Filter

Test Bed: Audi A4 Avant with a 1.9 liter (L) TDI engine
Testing Laboratory: FEV Engine Technology, Inc., Auburn Hills, MI
Technical Monitor: Matthew Thornton, NREL

Technical Approach

Technologies. Evaluations will be conducted on three Audi prototype 1.9 liter (L) TDI engines installed in the engine test cell. A fourth engine will be installed in the vehicle, which is a 2001 model year Audi A4 Avant with advanced engine controls and advanced ECS technologies (two different ECSs will be evaluated for this project). The engine specifications are: in-line four cylinders, displacement of 1.9 liters, rated power of 100 KW @ 4,000 revolutions per minute (rpm), a turbocharger, a common rail fuel injection system, and four valves per cylinder. The Audi's underbody configuration and "down-pipe" placement allow room to install the ECS components (see Figure 3), which include a pre-catalyst, an underbody NO_x adsorber catalyst, and a catalyzed DPF. Figure 4 is a schematic of the ECS.

Test Methods. The ECSs will be aged in the engine test cell with the majority of the emissions evaluations also occurring in the engine test cell. Limited evaluations will occur with the ECSs installed on the vehicle in order to validate the engine test cell results. Analyzers will be strategically placed before and after the individual ECS components to gain a clear understanding of the gaseous emissions going into and coming out of each component. All of the gaseous and PM emissions will be collected in the engine test cell using a constant volume sampling (CVS) method in a dilution tunnel.

Figure 3. The passenger car underbody accommodates the ECS components.

Interim Results

Accomplishments during FY 2002 included acquiring and preparing all the required hardware, assembling the technologies (e.g., the prototype engines), and receiving the first set of NO_x adsorber catalysts and DPFs. The ECS for the test cell was degreened and will be used for the base calibration work and to measure the storage capacity of the NO_x adsorber catalyst.

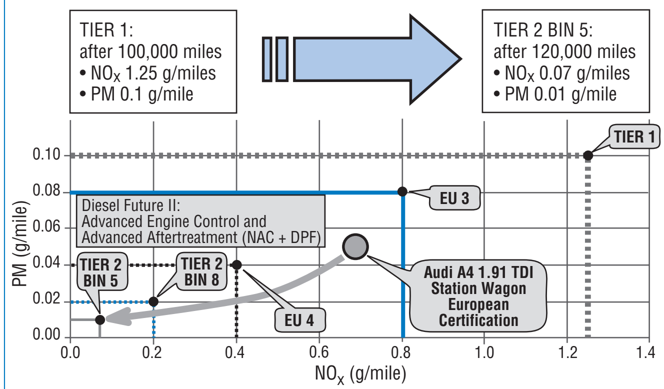

Figure 5. The passenger car project's goal is to meet federal emission standards.

The EGR strategy has been optimized to reduce engine-out NO_x emissions to approximately 0.4 g/mile over the FTP drive cycle with minimal increased fuel consumption. The rapid warm-up strategy has also been defined. During FY 2003, the regeneration and desulfurization strategies will be defined and the core aging and evaluation testing will begin for both ECS configurations using 8-ppm and 15-ppm S fuels. This will include aging of one system for 1,000 hours. Figure 5 shows the goal set for the passenger car project to meet federal emission standards.

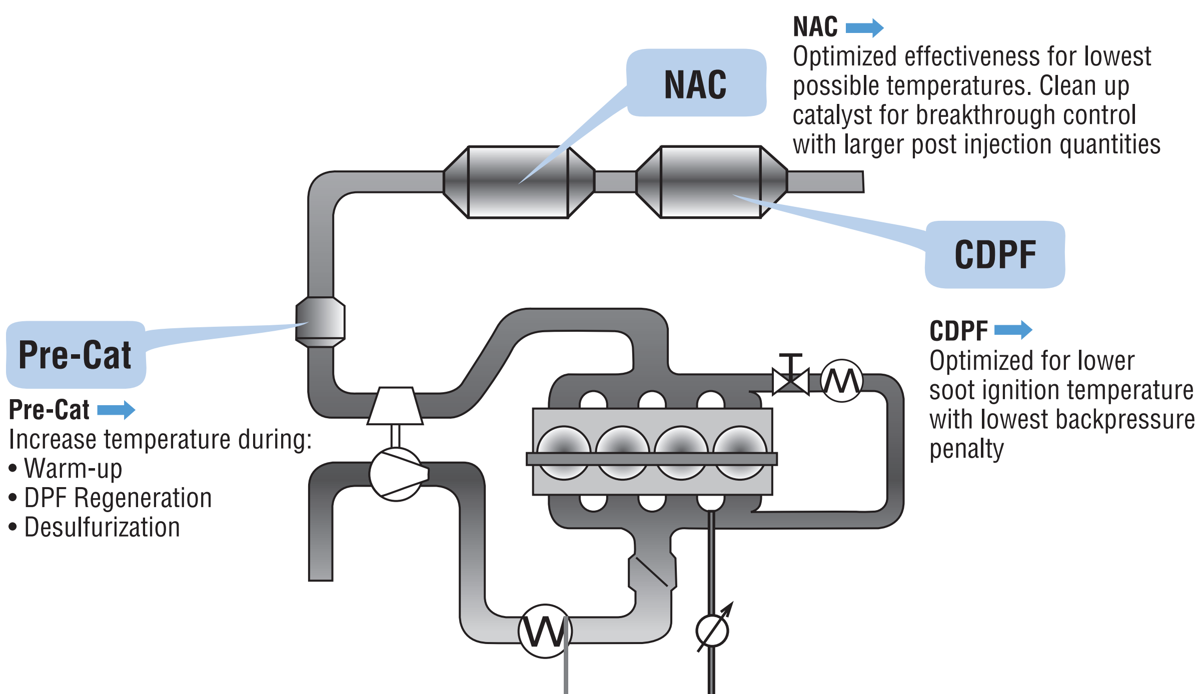

Figure 4. This schematic illustrates the passenger car's emission control system.

Medium-Duty Truck/SUV NOx Adsorber/Diesel Particle Filter

Test Bed: 2500 series Chevrolet Silverado, with a Duramax 6.6L engine
Testing Laboratory: SwRI, San Antonio, TX
Technical Monitor: Matthew Thornton, NREL

Technical Approach

Technologies. Two 2002 Duramax 6.6L engines rated at horsepower 300, with turbocharger, direct fuel injection, and EGR are being used in this project. The test vehicle is a 2002 model year Chevrolet Silverado. The major advantage of the Silverado is its underbody geometry (see Figure 6), which allows space for additional emission control components. The emission components to be added for the tests are an NO_x-adsorber and a catalyzed DPF, which will be integrated with in-pipe supplemental fuel injection to provide the systems with sufficient reductant.

Test Methods. A dual-leg ECS will be aged in the engine test cell with all of the emissions evaluations also occurring in the test cell. Analyzers will be strategically placed before and after the individual components to gain a clear understanding of the gaseous emissions going into and coming out of each component. All of the detailed gaseous and PM emissions will be collected in the engine test cell, using a dilution tunnel with CVS. The dual leg ECS used for this project is shown in Figure 8.

Interim Results

The Duramax 6.6L engine has been installed in the engine test cell where all emission evaluations will be performed. Initial tests were conducted over the light-duty test procedures in late summer to provide engine-out data needed to properly size the components in the ECS. Extensive work on thermal management/generation and reducing engine out emission levels has been completed. This has included re-mapping the EGR system, introducing intake throttling, and developing and integrating a diesel fuel burner. ECS optimization and calibration work focusing on further minimizing the NO_x emission levels and reducing the fuel penalty has been initiated and will continue through March 2003. The aging and evaluation tasks will begin in April 2003. The project is scheduled to be completed in April 2004.

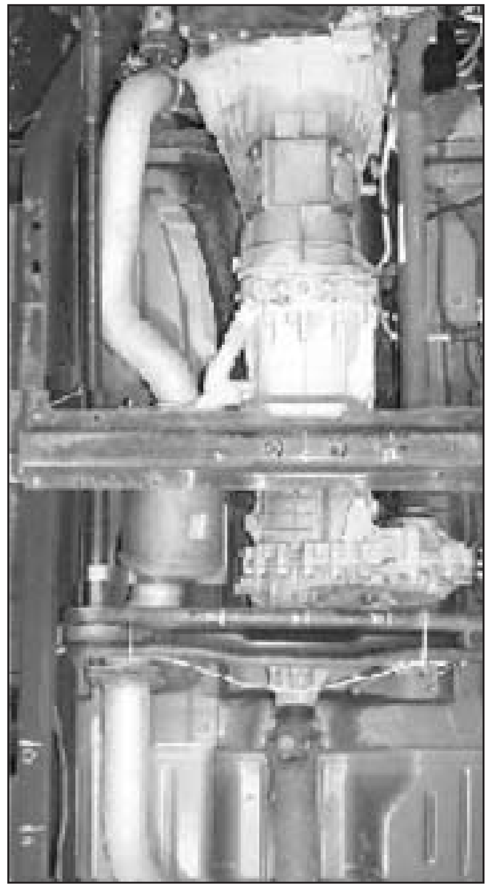

Figure 6. The truck underbody is shown in the test cell.

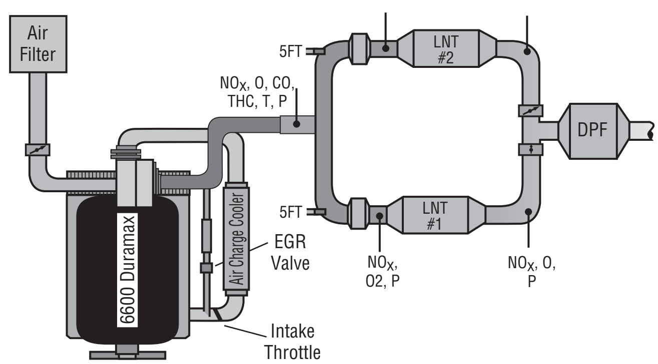

Figure 7. ECS Configuration B

Heavy-Duty NOx Adsorber/Diesel Particle Filter

Test Bed: 15L Cummins ISX, DOHC engine
Testing Laboratory: Ricardo, Inc., Burr Ridge, IL
Technical Monitor: Shawn Whitacre, NREL

Technical Approach

Technologies. Two types of control systems are being evaluated—a single-leg NO_x adsorber catalyst system and a twin-bed NO_x adsorber catalyst system. Regeneration and desulfurization strategies are being developed to enable the system to meet emission targets while minimizing the fuel economy penalty associated with their operation. The FY 2002 focus has been devoted to the test cell setup (see Figure 9) and acquiring and installing hardware. The test engine is a Cummins ISX diesel, 15-liter engine rated at 475 horsepower, using dual overhead camshafts, four valves per cylinder, central electronic unit injectors, variable geometry turbocharger, cooled EGR, and electronic controls. The base engine emissions are approximately 2.5 g/bhp-hr for NO_x and 0.1 g/bhp-hr for PM.

Test Methods. The test objectives are to evaluate the effect of fuel sulfur levels on the engine and aftertreatment system performance, emissions, and fuel economy, and the durability of the catalyst. Engine control systems are being designed to permit regeneration and desulfurization over heavy-duty transient and under steady-state conditions. The single-leg system will be required to cycle lean/rich to regenerate the NO_x adsorber catalyst. The dual system will utilize supplemental fuel injection into the exhaust to achieve regenerating conditions. However, cycling the engine from lean to rich places additional demands on the engine, turbocharger, and EGR system, so durability effects on the engine may need to be examined further.

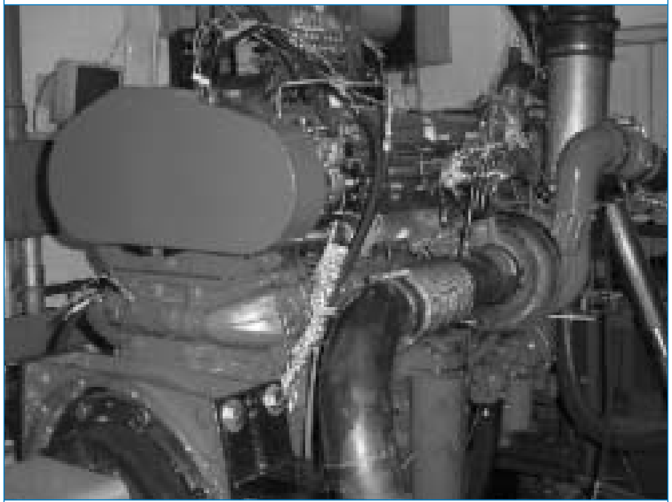

Figure 8. The heavy-duty NO_x engine is shown in the test cell.

The goal is to achieve the 2010 federal heavy-duty emission standards of 0.20 g/bhp-hr for NO_x and 0.01g/bhp-hr for PM, which will require a 90% reduction of both pollutants from the current levels. Beginning in 2004, the durability requirements of emission systems will be extended to 435,000 miles, which poses another challenge because NO_x adsorber catalysts are readily poisoned by sulfur, even at modest levels.

Interim Results

During FY 2002, the project concentrated on installing the Cummins ISX engine in the test cell, receiving components for both emission control systems, installing the secondary fuel injection system for regenerating the NO_x adsorber catalyst, and developing the NO_x regeneration strategy for the ECS. Initial preliminary results indicate that the fresh NO_x adsorber catalyst can reduce NO_x emissions by 85% and, at peak efficiency, by up to 98%. Other preliminary emission results under transient conditions have been encouraging, with the composite FTP results falling below 0.20 g/bhp-hr NO_x. These tests were conducted without a clean-up catalyst (i.e., DOC) so the actual HC and CO emissions should be lower when the full system is being used. These preliminary tests used 0.6-ppm S fuel and have demonstrated the capabilities of the system in a near sulfur-free exhaust. No further work is planned with the dual NO_x adsorber catalyst system. Durability tests will be conducted on the single-leg NO_x adsorber catalyst system using 8- and 15-ppm S fuels.

Lubricants

Test Bed: International T444E, 7.3 L engine, with retrofits
Testing Laboratory: Automotive Testing Laboratories (ATL), East Liberty, OH
Technical Monitor: Shawn Whitacre, NREL

Introduction to Lubricants Project

The APBF-DEC lubricants project is being conducted in two phases (see Figure 10) in parallel with the four engine hardware technology projects. The role of the lubricants project is to determine which, if any, lubricant-derived components in engine-out emissions are detrimental to the performance or durability of vehicle emission control systems. There is growing concern in the technical community that the potential effects of S and ash in lubricant oils can poison or interfere with the performance of some of the new emission control technologies. These devices are sufficiently sulfur sensitive and their durability requirements—particularly in heavy-duty engines—are so extensive that reducing the fuel S level may not be enough if other sources of catalyst poisons remain. For example, the sulfur and ash in lubricant oils may poison the NO_x adsorber catalyst or plug the DPF.

In 2004, the EPA will extend the requirement for the durability of the ECS on heavy-duty engines to 435,000 miles. This emphasizes the need for engine fluids that do not hinder the system's performance over time. The heavy-duty emission standards that go into effect in 2007 will be the first standards (for both PM and NO_x) to require catalytic emission control systems.

This APBF-DEC lubricants study is expected to help define the future needs for lubricant formulations for both light-duty and heavy-duty diesel engines in time for industry to develop "catalyst compatible" formulations and for engine manufacturers to design engine hardware that tolerates modified oil chemistry.

(Note to readers: More information is presented on this project than for the four preceding projects because the lubricants project is closer to completion. Phase I was completed in late FY 2002; Phase II is expected to be completed in mid-FY 2004.)

Technical Approach

Experimental Design. Several questions aided in designing the lubricants test. Are the differences in the engine-out emissions attributable to oil properties? How much of an impact results from the properties of additives or base oil? Can species in emissions be directly predicted from the properties of the oil and fuel? Is it possible to identify indirect relationships between engine-out emissions and oil properties? Phase I concentrated on acquiring and analyzing emissions data to determine how lubricant-derived components affect engine-out emissions and which components have the potential to affect the performance and durability of vehicle emission control systems. Analyses of 57 lubricant evalua-

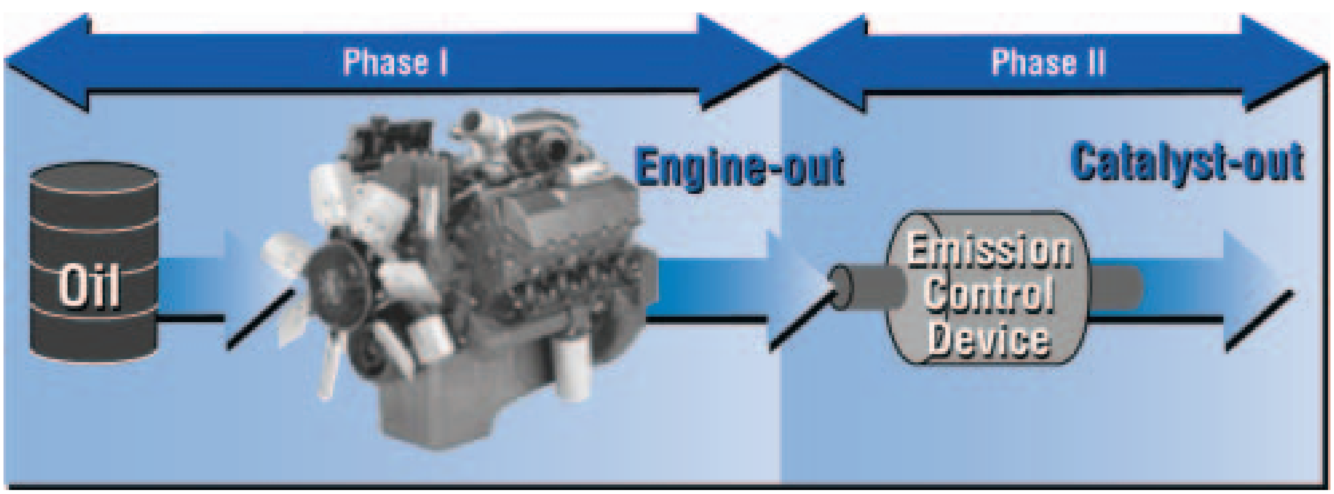

Figure 9. This two-step approach is being used in the lubricants project.

tions were conducted in back-to-back runs. Tests of the oil/additives combinations were performed at the beginning and end of the tests, as well as before and after aging.

Technologies. The tests were conducted on a 1999 International T444E-HT engine, which was installed at Automotive Testing Laboratories (ATL) in East Liberty, OH. The engine is direct-injected, electronically controlled, turbocharged, and aftercooled, with a displacement of 7.3L in a V8 configuration with two valves per cylinder. It is equipped with a Siemens electronic control unit and hydraulically actuated electronic unit injectors. Additional hardware was installed to allow EGR and closed crankcase ventilation (CCV) (see Figure 11). Such systems are expected to be common on engines meeting EPA's 2004 and 2007 emission regulations. Figure 12 depicts the impingement system for measuring sulfur dioxide.

Test Methods. Testing included evaluations of a matrix of additives and base oils selected from each of the four major base oil groups—as defined by API. The additive packages were provided by five different suppliers and were selected to represent a range of current and future additive technologies. One reference oil was selected and tested periodically to characterize drift in the measurement system or engine performance. Base oils from four oil groups were used, each with different levels of S: Group I—4,800 to 5,000 ppm S; Group II—5 ppm S; Group III—20 ppm S; and Group IV—zero ppm S. Oils tested contained varying levels of ash, S, calcium (Ca), zinc (Zn), nitrogen (N), phosphorus (P), boron (B), chlorine (Cl), molybdenum (Mo), and magnesium (Mg).

Interim Results—Phase I

Mass balances were conducted for each of the critical parameters. Predicted emission rates for each species were estimated based upon fuel and lubricant properties and fuel and lubricant consumption rates. Data presented here compare predicted rates with the actual measured rates. As shown in Figure 13, calcium emission rates are directly correlated with the concentration of calcium in the oil, independent of any given additive formulation. However, only 46% of the calcium in the oil is emitted and measured in the PM. Several theories, including deposition in the lube oil filter, have been proposed. Clearly, though, the oil is not uniformly consumed.

Figure 14 illustrates the mass balance results for zinc. Like calcium, zinc emissions are directly correlated to the concentration in the tested formulation with 43% estimated

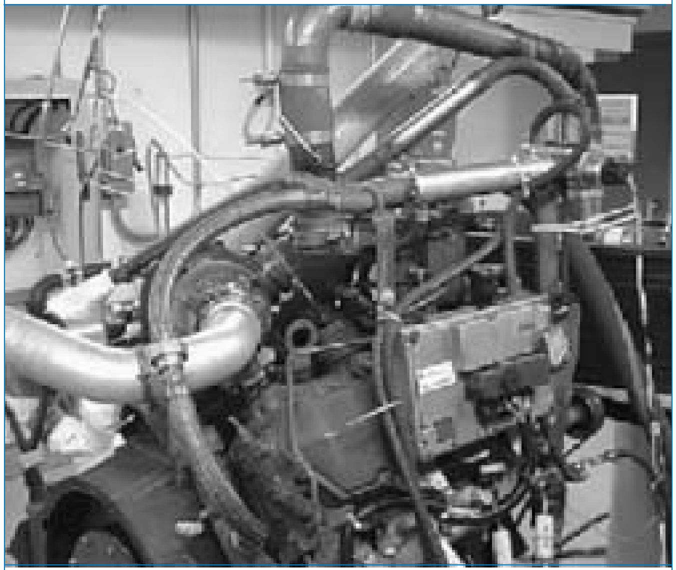

Figure 10. Additional hardware was installed to allow EGR and closed crankcase ventilation.

Figure 11. The SO_2 Impingement System

recovery. However, one formulation showed a measurable deviation, suggesting this oil is consumed by a mechanism dissimilar to the rest. Because most of the zinc is derived from the very surface-active zinc dialkyl-dithiophosphate (ZDDP) anti-wear agent, it is believed that a majority of the "missing" zinc has been deposited on metal surfaces.

Phosphorous emissions are shown in Figure 15. With the exception of one oil, the recovery of phosphorus is consistent with predictions (90%) and highly correlated with the phosphorus concentration of the oil. The emission rate from "Oil C" was nearly four times the predicted rate, suggesting that it

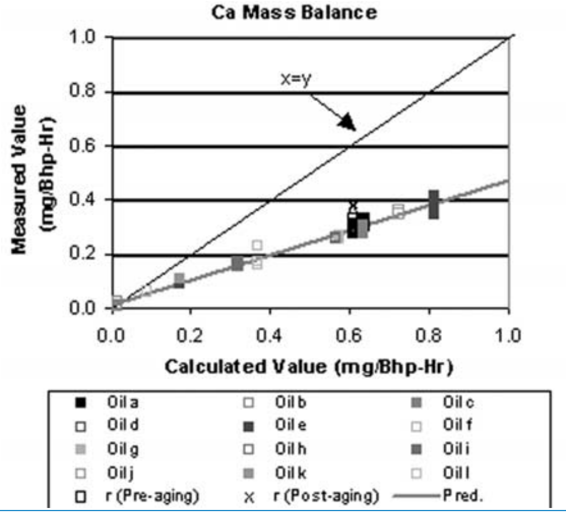

Figure 12. Emission rates are directly correlated with the concentration of calcium in the oil, independent of any given additive formulations.

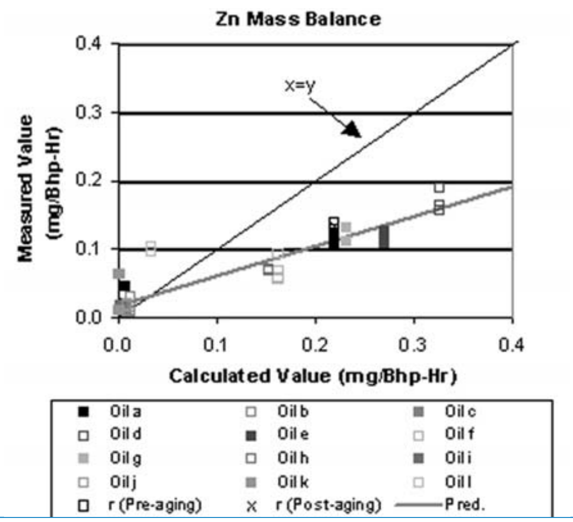

Figure 13. The mass balance results for zinc, whose emissions are directly correlated to the concentration in the tested formulation with 43% estimated recovery.

is preferentially consumed in this formulation. This particular formulation contains a very low zinc concentration, suggesting that it utilizes non-traditional anti-wear chemistry (i.e., no ZDDP). As such, the phosphorus is more volatile and is emitted at a higher rate than predicted by the measured total oil consumption rate. This is a critical finding because it illustrates the danger in specifications utilizing chemical limits (e.g., controlling phosphorus levels in oils may not have the desired effect).

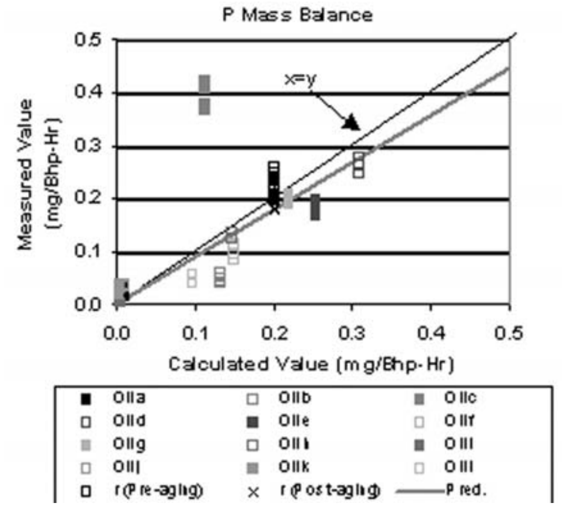

Figure 14. With the exception of one oil being tested, the recovery of phosphorus is consistent with predictions (90%) and highly correlated with the phosphorus in the oil.

Because of the well-documented impact of sulfur on the durability of NO_x adsorber catalysts, particular scrutiny has been given to the impact of lubricant-derived sulfur on emissions of this catalyst poison. Figure 16 shows SO_2 emissions for the various additive and basestock combinations tested here. Additives A-F were tested in each of the four basestock groups, while additives G-L (and the reference oil R) were tested exclusively in the Group II stock. Of the four basestocks tested, only the Group I stock had significant sulfur content (approximately 5,000 ppm S). The others were hydro-treated (II and III) or synthetic (IV, PAO). For reference, additive B contained almost no sulfur, while additive E contributed 6,590 ppm S in the additive system alone. In general, SO_2 emission rates do not correlate well with the sulfur concentration in the oil. Perhaps the most significant comparisons are between the B and E blends. While the total sulfur content with E is much greater than B, SO_2 emissions are quite similar within a given basestock. Basestocks do not have a significant effect either, although the synthetic (Group IV) tends to give the lowest SO_2 emissions, independent of the additive system.

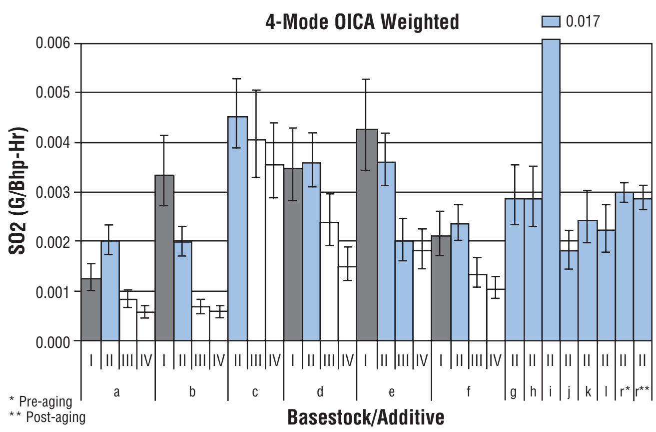

Figure 15. This graphic shows the SO_2 effects of the various additive and basestock combinations tested.

Phase II

Phase II is investigating techniques to determine if lubricant formulations have an impact on the performance and durability of the ECS on diesel engines. Methods to increase the lubricant-derived exhaust emission components by up to tenfold are being developed to accelerate catalyst aging tests. The results from Phase II, coupled with Phase I results, are expected to provide guidelines for (1) lubricant formulation (e.g., basestock selection and additive chemistry) and (2) guidelines for engine manufacturers and ECS suppliers.

Questions to be answered during Phase II include:

- How emissions change as a function of oil consumption,
- How the oil type affects the relationship of emission changes,
- How oil consumption during acceleration affects emissions,
- Whether the difference among oil consumption and engine acceleration rates can be used to predict the combined effects, and
- Whether the higher oil consumption rates can be replicated by adding specific components to the test oil.

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