SRI

Summary of published papers by Southwest Research Institute on testing of Fischer-Tropsch fuels

1. Ryan III, Thomas, "Emission Performance Of Fischer-Tropsch Diesel Fuels", Southwest Research Institute, Gas-To-Liquids Processing 99 Conference, Texas, 1999.

   The paper presents a summary of results of the most recent emission studies from the use of Fischer-Tropsch diesel fuel in diesel engines. All the studies demonstrate the emission reduction realized by the use of Fischer-Tropsch diesel. The paper demonstrates that the fuel quality of high cetane, zero sulfur and zero aromatics makes it an ideal fuel for diesel blends or as a replacement for diesel in urban environments.

2. Ryan III, Thomas, and Daniel A. Montalvo, "Emissions Performance of Fischer-Tropsch Diesel Fuels," Southwest Research Institute, 1997 AIChE Spring Meeting, Texas, 1997.

   Following the California Air Resources Board (CARB) protocol for diesel engine testing, Southwest Research performed tests comparing Fischer-Tropsch diesel, CARB diesel and commercial diesel. All the emissions are significantly reduced and the reductions are attributed directly to the quality of the Fischer-Tropsch fuel.

3. Ryan III, Thomas, and Daniel A. Montalvo "Near ULEV Emission Level in a Heavy-Duty Diesel Engine Using Fischer-Tropsch Diesel Fuel," Southwest Research Institute, Texas.

   The paper compared three Fischer-Tropsch diesels with a standard U.S. diesel and a California Air Resources Board (CARB) diesel in a heavy-duty diesel engine. The conclusions are that all three Fischer-Tropsch diesels performed with similar characteristics and all significantly reduced pollutants compared to either the standard U.S. diesel or the CARB diesel. There was no engine optimization for the high quality Fischer-Tropsch diesel which it is predicted would improve the performance further.

Emission Performance of Fischer-Tropsch Diesel Fuels

~ presented by ~

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EMISSIONS PERFORMANCE OF FISCHER TROPSCH DIESEL FUEL

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ABSTRACT

Analysis of available economic data indicates that it is very likely that application of Fischer Tropsch technology in the production of diesel fuels will be a viable route to monetizing remote natural gas resources. In fact, because of the nature of the process, the resulting fuels will be premium quality and could be economically attractive. A major part of the premium value of these fuels are the emissions characteristics in modern diesel engines. There have been a number of resent studies that have focused on documenting the emissions benefits of using Fischer Tropsh (FT) diesel fuels . The purpose of this paper is to briefly summarize the most resent results and present possible reasons for the dramatic reductions that have been observed.

INTRODUCTION

The international pressure to reduce greenhouse gas effect has resulted in significant discussion of the need to improve the fuel economy of the US vehicle population through the use of diesel engines. It is possible to gain 50 percent improvements in fuel economy over conventional spark-ignition engines by this conversion, with corresponding reductions in the CO_2 emissions. However, there is also a movement in California to reduce or eliminate the use of diesel engines because of possible health effects associated with very fine diesel particulate emissions (PM). These two conflicting trends have resulted in a major international effort to improve the performance and emissions characteristics of both light and heavy-duty diesel engines. Another resent event that has resulted in significant research and development activities was the signing of the Consent Decree agreements between several heavy-duty diesel engine manufacturers and the US Environmental Protection Agency (EPA). In this agreement, the manufacturers were required to accelerate the date of implementation of the 2 gm/hp-hr NO_x standard from 2004 to 2002. The agreement also instructed the manufacturers to work towards a 1 gm/hp-hr NO_x and 0.05 gm/hp-hr PM standard by the year 2008. In addition, resent passage of the LEV II standards in California and the US Tier 2 standards expanded the size range of light duty trucks and placed the same emissions standards on both spark ignition and diesel powered vehicles.

engine equipped with the standard 1991 hardware and injection strategy. The tests were performed using a pseudo-CARB protocol for comparing the FTP Transient emissions characteristics of three different FT diesel fuels as compared to both a US average diesel fuel and to a pseudo CARB reference fuel.

Repeat hot start FTP transient tests were performed on all five test fuels using exactly the same engine settings and test procedure. The results of these tests are summarized in Figure 1, where the PM and NO_x emissions results are plotted versus each other. It can be seen that relative to the US average diesel fuel, all three FT fuels produced larger reductions in PM and NO_x emissions than the CARB reference fuel. The average results for the FT fuels were 30 percent reductions in PM, 38 percent reductions in HC, 46 percent reductions in CO, and 9 percent reductions in NO_x, relative to the US average diesel fuel. Relative to the CARB reference fuel, the FT fuels produced 26 percent reductions in PM, 20 percent reductions in HC, 36 percent reductions in CO, and 6 percent reductions in the NO_x emissions.

A similar DDC Series 60 was used by Schaberg, et al. (2), following the same procedure used by Ryan and Montalvo (1), to compare the performance of a different set of two FT fuels to the both a US average and a pseudo CARB reference fuel. The results of these tests are plotted in Figure 2. The average results for the FT fuels showed 21 percent reductions in PM, 49 percent reductions in HC, 33 percent reduction in CO, and 27 percent reductions in NO_x, relative to the average US fuel. The reductions relative to the CARB fuel were 15 percent for PM, 21 percent for HC, 23 percent for CO, and 15 percent for NO_x. The differences between the results presented by Ryan and Montalvo, and those presented by Schaberg are most likely attributable to difference in the compositions of the various reference fuels, where the reference fuel emissions were lower in for Ryan and Montalvo (1) than for Schaberg, et al. (2).

Norton, et al. (3) used a Caterpillar 3176 engine installed in a truck to compare the performance of one FT fuel to a CARB reformulated diesel fuel. The difference between a CARB reference fuel and a CARB reformulated diesel fuel is the fact the reference fuel must have less than 10 percent total aromatic content, while the reformulated fuel can have up to 30 percent total aromatic content. In this case the aromatic content of the reformulated CARB fuel was 18 percent. The transient tests were performed on a chassis dynamometer, following a simulated driving cycle designed to represent real world operation. The results of the tests indicated that the PM emissions were reduced by 24 percent, HC by 40 percent, CO by 18 percent, and NO_x by 12 percent relative to the CARB fuel.

All three of the above projects were performed in 10-12 liter, turbo-charged and high-pressure electronic unit injectors. While the engines are very similar in size,

*Number in parenthesis denotes entries in the Reference Section

(FT100), a blend of 20 percent FT in D2 (FT20), biodiesel (B20), and a blend of 15 percent dimethoxymethane in D2 (DMM15).

The results of the tests are plotted in Figure 4. Relative to the US average fuel, the FT diesel produced 38 percent lower PM, 50 percent less HC, 27 percent less CO and 6 percent less NO_x. Relative to the CARB reference fuel the reductions were 30 percent less PM, 50 percent less HC, 27 percent less CO, and 2 percent less NO_x.

DISCUSSION

In a diesel engine, the fuel is injected at high pressure into high pressure and temperature air, where it mixes, vaporizes, ignites and burns. The fuel does not ignite immediately upon injection, but rather goes through an ignition delay period. Cetane number is a measure of the fuels ignition characteristics in the diesel environment, providing a measure of the ignition delay time. During the ignition delay time, fuel is continually injected, resulting in premixing and early rapid combustion of the premixed air and fuel. This premixed combustion raises the early combustion temperature, producing overall higher combustion temperatures and correspondingly higher NO_x emissions.

In modern diesel engines, the injection systems are designed to minimize the amount of fuel injected during the ignition delay period, thus minimizing the effects of cetane number on the NO_x emissions. In these engines, the combustion process is dominated by diffusion combustion, especially at the higher load, high NO_x producing conditions. In a diffusion flame the fuel burns basically at the interface between the fuel jets and the air, in the regions where the air-fuel ratio is stoichiometric. This means that combustion occurs at the local stoichiometric adiabatic flame temperature, a temperature that is a fundamental property of the fuel, depending on the hydrogen and carbon contents. NO_x formation is an exponential function of the adiabatic flame temperature, and is, therefore, fundamentally related to the hydrogen and carbon contents of the fuel.

The fundamental relationship is demonstrated in the work reported by Ryan, et al. (7) where they performed tests in a Caterpillar 3176 engine (similar to the one described earlier), equipped with an EGR system. The experiments were designed to demonstrate the relationships between the fuel properties and emissions. A thirteen fuel matrix, designed to demonstrate the effects of aromatic content, aromatic type, and cetane number, was tested at seven different speed-load points. The results of these experiments indicated that there were no statistically significant relationships between the selected fuel properties and the NO_x emissions. The strongest relationship was between the NO_x emissions and the adiabatic flame temperature, a property of the fuel that can be computed using the fuel hydrogen and carbon contents. This relationship is shown in Figure 5.

2. Schaberg, P.W., Myburgh, I.S., Botha, J.J., Roets, P.N., Vijoen, C.L., Dancuart, L.P., and Starr, M., "Diesel Exhaust Emissions Using Sasol Slurry Phase Distillate Process Fuels", SAE 972898, Oct. 1998.

3. Norton, P., Vertin, K., Bailey, B., Clark, N.N., Lyons, D.W., Goguen, S., and Eberhardt, J., "Emissions from Trucks Using Fischer-Tropsch Diesel Fuel", SAE Paper 982526, Oct. 1998.

4. Ryan, T.W. III and Leet, J., "Natural Gas Vehicle Options: CNG/LNG/DME/Fischer Tropsch or ?" Presentation at Energy Frontiers International Meeting, Tucson, 1997.

5. Atkinson, C., Thompson, G.J., Traver, M.L., and Clark, N.N., "In-cylinder Combustion Pressure Characteristics of Fischer Tropsch and Conventional Diesel Fuels in a Heavy Duty Diesel Engine", SAE Paper 1999-01-1472, May, 1999.

6. Sirman, M. and Owens, E., "DOE/PNGV Project for Emissions Comparisons of Alternative Fuels in an Advanced Automotive Diesel Engine". DOE Fuels Workshop, Tucson, Sept. 1998.

Ryan, T.W. III, Buckingham, J., Dodge, L.G., and Olikara, C., "The Effects of Fuel Properties on Emissions from a 2.5 gm NOx Heavy-Duty Diesel Engine",

7. Dodge, L.G., Leone, D. M., Naegeli, D.W., Dickey, D.W., and Swenson, K.R., "A PC-Based Model for Predicting NOx Reduction in Diesel Engines", SAE Paper 962060, Oct. 1996.

8. Naegeli, D.W. and Moses, C.A., "Effects of Fuel Properties on soot Formation in Turbine Combustion", SAE Paper 781026, March, 1978.

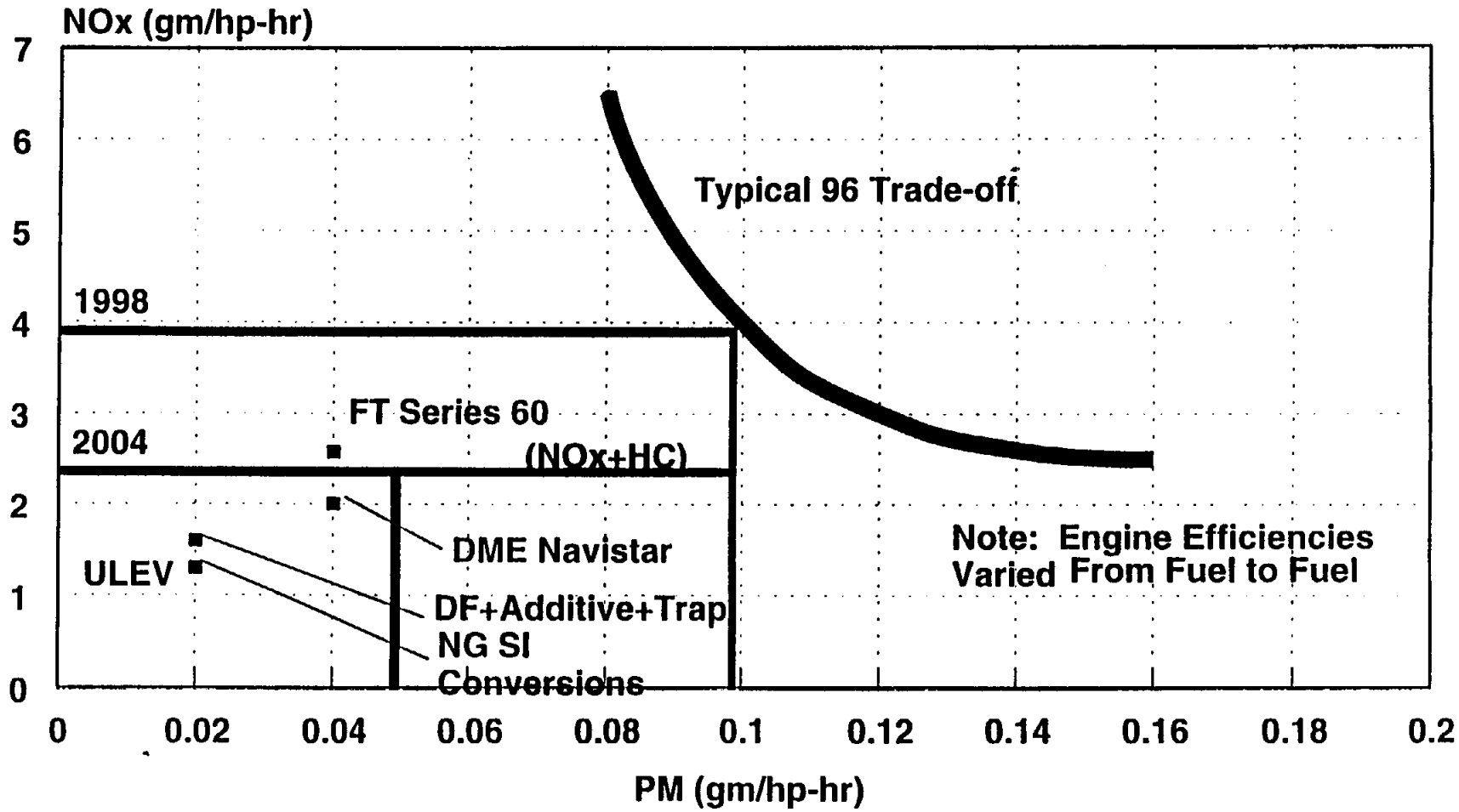

Figure 3. NOx Versus PM for Various Fuel and Engine Combination (4)

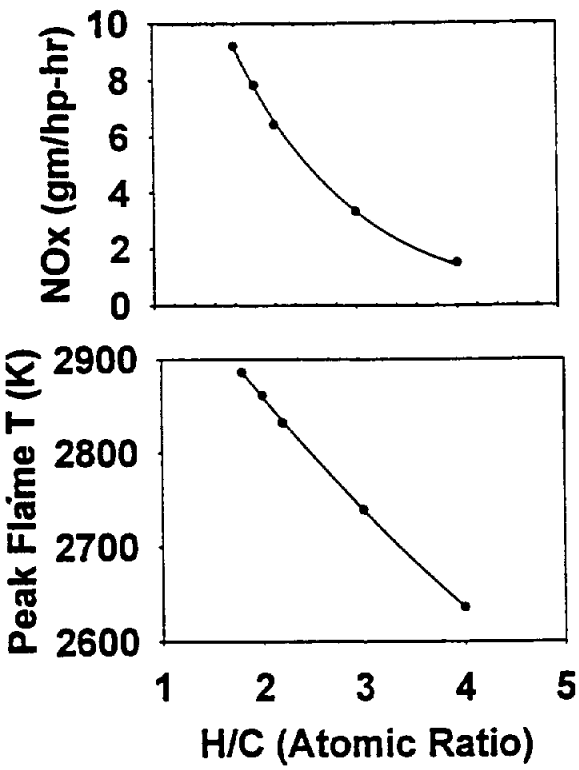

Figure 6. NO_x and Peak Flame Temperature Versus H/C Ratio

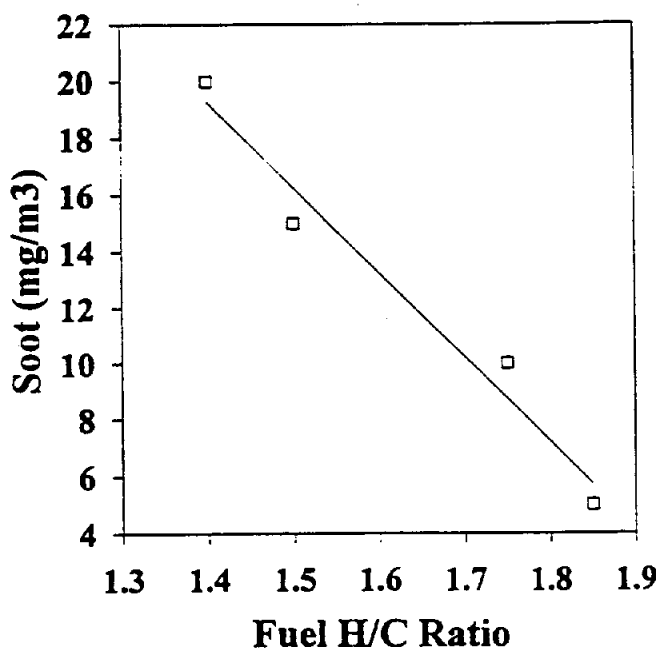

Figure 7. Soot Versus H/C Ratio (9)

EMISSIONS PERFORMANCE OF FISCHER-TROPSCH DIESEL FUELS

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ABSTRACT

Fischer Tropsch technology was developed in the early 1920's as a process for converting coal to liquid fuels. The process was refined and used extensively in Germany during World War II. Recently, Fischer Tropsch research in the areas of gasification, catalysis, and reactor design have resulted in the development of processes that produces high quality diesel fuels. Three F-T fuels, each produced by a different major oil company, have been tested in a 1991 prototype, Detroit Diesel Series 60 engine, following a procedure similar to the CARB Protocol for evaluation of reformulated diesel fuels. The results of these tests included comparisons of the emissions characteristics of the three F-T fuels to those of both a national average fuel and a pseudo-CARB reference fuel. The F-T fuels produced 38 percent less HC, 46 percent less CO, 8 percent less NO_x, and 30 percent less particulate than the national average diesel fuel. The properties of the fuel and the detailed emissions results are presented and discussed.

INTRODUCTION

Engine manufacturers and refiners have long recognized the importance of fuel quality on diesel engine performance and emissions. The Coordinating Research Council examined this issue in some detail in a series of projects designed to quantitatively document the relationships between engine performance and emissions and fuel properties and composition.[1-5]* This work was performed in what has been called a "prototype" Series 60 Detroit Diesel engine. The results of this work have indicated that cetane number and aromatic content are the primary fuel properties controlling the emissions. The most recent results of the CRC work[5] indicated that there is a linear relationship between NO_x and cetane number.

The test protocol used in the CRC work involves the use of the Federal Heavy Duty Transient Test Procedure (FTP), as specified in the Federal Register. More recently, this same engine and the FTP have been adopted as the basis for the CARB Protocol for certifying reformulated diesel fuels in California. In this procedure, the candidate fuel is tested in the Prototype Series 60 operating through the FTP. The emissions results are compared to corresponding data obtained using a highly specified reference fuel. The reference fuels, supplied by each refiner seeking to certify a reformulated diesel fuel, must meet specification on 5 different properties, including limits on cetane number, aromatic content, and polynuclear aromatic content.

*Numbers in Parenthesis Designate Entries in the Reference List.

In 1996, the Engine Manufacturers Association (EMA) signed the Statement of Principle in which they agreed to emissions standards for heavy duty diesel engines for the year 2004. The target standard included a limit of 2.5gm/hp-hr, if a "clean diesel fuel" is available, and 3.5gm/hp-hr if a clean fuel is not available. It is felt that agreement was based the assumption that the anticipated fuel contribution of 1gm/hp-hr would come from high cetane number and low aromatic content.

Work performed at Southwest Research Institute (SwRI), has indicated that the types of aromatic materials are more important than simply the total mass of aromatic material in the fuel.[6] The European Auto-Oil Program (EPEFE), recently completed and reported in a series of papers [7-13], included emissions tests of both light duty and heavy-duty vehicles and engines. The results of the heavy-duty engine tests indicated that cetane number is an important fuel property controlling emissions. The relationship between emissions and fuel density and aromatic content were less clear.

The previous work performed at SwRI (6) demonstrated that diesel fuels derived from Fischer Tropsch liquids have very high cetane number and are essentially free of aromatic compounds and sulfur. Engine experiments also indicated that the emissions produced with of these fuels are low relative to typical petroleum derived diesel fuels.

OBJECTIVE

The primary objective of this study was to evaluate Fischer-Tropsch (FT) diesel fuel as a low emissions diesel fuel.

TEST APPARATUS AND PROCEDURES

A screening test procedure based on transient emissions measurement procedures developed by the EPA for emissions regulatory purposes was used. A prototype 1991 Detroit Diesel Corporation Series 60 was used in the screening procedure for comparing transient emissions using a reference fuel and a candidate equivalent fuel. The screening procedure, described herein for FT fuels, utilized several hot-start transient tests run in a specific sequence using five diesel fuels.

Fuels. This group of fuels included a low-sulfur emissions 2D reference fuel identified as Fuel 2D; three candidate Fischer-Tropsch (FT) fuels identified as Fuels B1, B1, and B3; and a "pseudo" California reference fuel, designated Fuel PCR. The FT test fuels, Fuels B1 (SwRI 2097), B2 (SwRI 2050), and B3 (SwRI 2094), for this study were provided through Bechtel Group Inc.; while Fuels 2D (SwRI 2045) and PCR (SwRI 2121) were provided by SwRI. Fuel D2 was selected to be representative of a typical US diesel fuel, with a cetane number of 45.5 and a total aromatic content of 32 percent. Fuel PCR represents what could be considered a California Reference fuel, with a cetane number of 50.2 and a total aromatic content of 8.7 percent.

Test Procedure. Transient cycle emissions of HC, CO, NO_x, total particulate (PM), sulfate, soluble organic fraction (SOF) of PM, and volatile organic fraction (VOF) of PM were obtained over repeat hot-start tests. The test process incorporated steps for instrumentation and sample system

calibration, changing fuels, establishing engine performance, transient testing, sample analysis, and review of emissions data.

Emission results of H.C., CO, NO_x, total particulate matter (PM), sulfate, and SOF in units of g/hp-hr; BSFC (by carbon balance) in units of lb/hp-hr; and work in units of hp-hr were accumulated over several hot-start transient tests. The VOF emission levels obtained in this study are reported as percent of PM, and include analysis of unburned oil as percent of VOF. A data-assessment process from the Quality Assurance (QA) Plan used in emissions testing of CARB equivalent fuel candidates was used to review the precision and accuracy of selected emissions data obtained in this program.

Test Engine and Setup. The heavy-duty diesel engine used in this study was a prototype 1991 DDC Series 60. Some characteristics of the engine are given in Table 1. The engine, as installed in a transient-capable test cell, had a nominal rated power of 330 hp at 1800 rpm. It was designed to use an air-to-air intercooler; however, for dynamometer test work, a test cell intercooler with water-to-air heat exchanger was used. No auxiliary engine cooling was required. This engine had been used in other fuel studies, so it was ready for test work in this program.

TABLE 1. CHARACTERISTICS OF THE PROTOTYPE 1991 DDC SERIES 60 HEAVY-DUTY DIESEL ENGINE

Engine Configuration and Displacement	6-Cylinder, 11.1 Liter, 130 mm Bore x 139 mm Stroke
Aspiration	Turbocharged, Aftercooled (Air-to-Air),
Emission Controls	Electronic Management of Fuel Injection and Timing (DDEC-II)
Rated Power	330 hp at 1800 rpm with 108 lb/hr Fuel
Peak Torque	1270 lb-ft at 1200 rpm with 93 lb/hr Fuel
Injection	Direct Injection, Electronically Controlled Unit Injectors
Maximum Restrictions Exhaust Intake	 2.9 in. Hg at Rated Conditions 20 in. H_2O at Rated Conditions
Low Idle Speed	600 rpm

Intake air for the engine was obtained from the humidity- and temperature-controlled engine inlet air system, such that the EPA NO_x correction factor was 1.00 ± 0.03. Both intake and exhaust restrictions were set with dampers. Engine coolant systems were closed-loop, using a 50/50 mixture of ethylene glycol and water.

Engine flywheel torque was measured directly using a calibrated torquemeter in the drive coupling connecting the engine to the motor/load dynamometer system. During the emissions test work, the engine's fuel control signal ("throttle" position) was changed using a servo-controller. The servo-controller activity was based on control signals sufficient to cause the engine to operate over the transient command cycle. To judge how well the engine followed the transient cycle command, engine responses were compared to engine commands and several statistics were computed for comparison to tolerances specified for the transient Federal Test Procedure (FTP). The engine control and response statistics were checked to ensure that the FTP validation criteria were met, or adjustments were made to improve the statistics prior to actual testing.

Fuel System. Fuel was supplied to the engine connection and returned from the "engine spill" connection at atmospheric pressure using a "day tank" maintained at a level controlled by a simple float valve. Fuel supplied to the "day tank" was provided through a pump and filter arrangement drawing fuel from the bulk drum (55 gallon drum). The temperature of the fuel delivered to the engine was monitored (as specified by the manufacturer) and controlled to range from a minimum of 68°F to a maximum of 110°F.

After completing test work on a selected fuel, a drum of the next fuel was normally staged in the test cell area one day or more prior to its intended use so that it would be stabilized at room temperature (68 to 86°F). As outlined below, the API gravity of the selected fuel was measured to cross check the identity of the fuel. After approval to switch fuels was given, fuel system lines, filters, heat exchanger, and return tank were drained. New fuel filters and the supply tank were filled with the selected fuel. With the exhaust routed into the constant volume sampling (CVS) system, the engine was operated on the selected fuel at moderate load, and the fuel return spillage was collected. The initial three gallons of this return fuel were discarded. Additional return fuel was periodically monitored for API gravity. If the API gravity of the return fuel did not agree with that of the selected fuel, it also was discarded. Usually after a total of four to five gallons had been returned, the API gravity of the return fuel agreed with that of the selected fuel supplied.

After the return fuel showed evidence that it was in fact the desired test fuel, the engine was taken to rated power conditions and held for a period of time to set the intake and exhaust restrictions to the manufacturer's recommended transient restrictions. After about 5 to 10 minutes, "power validation" readings were taken. Power validation pertains to recording engine performance data along with various engine parameters at rated power and peak torque. After checking high-idle and low-idle parameters, the engine was taken back up to rated power conditions, and the intake and exhaust restrictions were checked to meet the "typical" values used during transient testing.

Torque Map. - The engine was "torque mapped" according to the transient FTP procedure, using full rack from slightly below low-idle speed to above rated speed and increasing engine speed at a rate of 8 rpm per second. Data from this transient torque map were used in conjunction with the FTP-specified speed and load percentages to form a transient command cycle. This performance-based transient command cycle is characteristic of the fuel and engine combination. For this work, the performance-based transient cycle was termed a "fuel-derived transient cycle," because only the fuel was changed and no engine adjustments were made.

Prior to a hot-start transient test sequence for emission measurement purposes, a preconditioning sequence was followed after changing fuels or after any engine operation other than a hot-start transient cycle. The preconditioning sequence consisted of two practice transient cycles (without 20-minute soak) run with exhaust through the CVS tunnel, and with all particulate filter sampling stations in operation utilizing unrecorded filter media.

Heavy-duty diesel engine emission standards are based on the "transient FTP test" results of the engine tested over cold-start and hot-start operation. The same engine control or fuel-derived transient command cycle is used in both cases. For purposes of this study, only hot-start transient cycles were employed for emission characterization.

Regulated and Unregulated Emissions Sampling and Analyses. Regulated and selected unregulated emissions were measured during hot-start transient cycles. Regulated emission measurements and sampling techniques were based on transient emission test procedures specified by the EPA in CFR 40, Part 86, Subpart N for emissions regulatory purposes. For the purposes of this study, regulated emissions of H.C., CO, NO_x, and particulate matter (PM), along with unregulated emissions of sulfate and SOF, were measured as described in the following paragraphs.

Hydrocarbon (HC) emissions were determined using a heated FID as prescribed in the FTP for transient emissions testing. Hydrocarbon emissions determined from CVS dilute samples are dependent on background measurement. Background hydrocarbon levels of the CVS dilution air were determined with on-line heated FID just before and after each transient test, and the averaged "background" level was used for computation of the HC emissions. On-line FID background HC levels were relatively constant during the transient test.

Carbon monoxide and CO_2 emissions were determined from dilute exhaust samples collected in a sample bag using NDIR instruments set up according to applicable EPA FTP. Measurement of CO_2 was of interest because it was used in the calculation of fuel consumption by carbon balance, along with CO and HC emissions. Oxides of nitrogen (NO_x) were determined using the CVS with a heated sampling train. The NO_x concentration of the continuous sample was determined by chemilumine- scence (CL) and integrated over the transient test cycle. EPA NO_x correction factors for engine inlet air humidity and temperature were applied.

Total particulate is defined as any material collected on a fluorocarbon-coated glass fiber filter at or below the temperature of 51.7°C (125°F), excluding condensed water. Total particulate emissions were determined using a double-dilution technique specified in the EPA 1988 transient FTP for heavy-duty diesel engines. The double-dilution system utilized dry gas meters to measure the flow of dilution air and the total flow through a set of 90 mm Pallflex (T60A20) filters positioned in series. Combined weight gain from this pair of filters, one primary and the other a backup, was used to determine the total particulate.

Additional samples of PM were collected during each transient cycle for determination of SOF and sulfate. SOF was determined by extracting particulate-laden 47 mm Pallflex filters using a micro-Soxhlet apparatus with toluene-ethanol solvent, as specified by CARB. An ion chromatograph procedure was used to assess the sulfate levels contained in PM samples collected

on 47mm Fluoropore filter media during the transient test work. Sulfate is collected as "particulate," and its weight is assessed as part of PM emission. The CARB protocol has a provision for correction of PM emission for differences in fuel sulfur content. This correction of PM for sulfate contains no provision to correct for the water of hydration typically associated with the sulfate aerosol. It is well documented in several Society of Automotive Engineers technical papers that fuel sulfur is oxidized during combustion to form SO_2 and SO_3, and that SO_3 further combines with water vapor to form sulfate (i.e., sulfuric acid and related species).

VOF results were obtained with a unique DER direct filter injection gas chromatographic (DFI\GC) analytical technique using 90 mm Pallflex particulate filters. The particulate filter samples used for this study were generated during selected hot-start transient emissions evaluations of each test fuel. Known fractions of the primary and secondary 90 mm Pallflex particulate filters were carefully folded so that no particulate matter was exposed; then the filter fractions were placed into the DFI/GC injector. The injector was subsequently placed into a cool zone of the DFI/GC to allow any oxygen in the system to be purged without the loss of any sample by desorption. When all oxygen was purged from the system, the injector was inserted into the hot zone of the DFI/GC, where all volatile material was desorbed and deposited onto a cool chromatographic column. A GC temperature program was then run to separate the desorbed compounds by boiling point. This boiling point separation (or distribution) was analyzed for the unburned lubricating oil contribution to the VOF by mathematically superimposing a boiling point chromatogram of the test engine oil onto the boiling point chromatogram for the filter sample. The total VOF was quantified against the external calibration standard of fresh lubricating oil. Please note that it is difficult to accurately quantify the fuel contribution to VOF because partially oxidized lubricating oil and fuel, as well as unburned fuel, are not separated using this technique. Therefore, for this analysis, the portion of the VOF not attributed directly to unburned lubricating oil may be referred as "other," rather than labeling it as "fuel."

TEST RESULTS

The test process was modified for Fuels B2 and B3 during this project as required to accommodate the limited quantities of these two fuels. Nevertheless, testing of Fuels B2 and B3, along with Fuels 2D, B1, and PCR followed the intent of the test plan, making it possible to obtain a good estimate of engine performance and emissions with each test fuel.

The torque-map results obtained with the prototype 1991 DDC Series 60 heavy-duty diesel engine using Fuels 2D, B1, B2, B3, and PCR are presented in Figure 1. Initial torque information shown for Fuel 2D was the basis for the transient command cycle used for all subsequent hot-start emissions test runs on the engine.

Because an engine's full load performance is proportionally dependent on the mass of fuel injected into the engine (assuming similar heating values in energy per unit mass), engine performance levels on any fuel can be expected to vary in direct proportion to the fuel's density, relative to the density of Fuel 2D. Average torque readings with Fuels B1, B2, and B3 were correspondingly about 5, 9, and 5 percent lower than on Fuel 2D, apparently because these fuels were less dense than Fuel 2D.

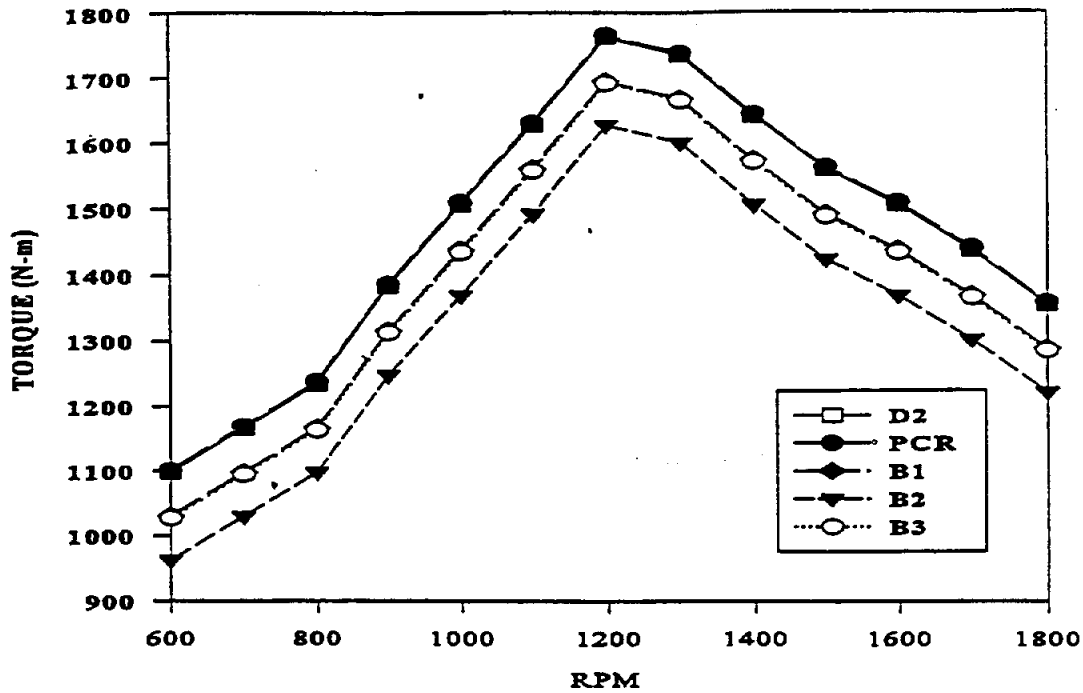

FIGURE 1. ENGINE TORQUE MAPS ON THE FIVE (5) TEST FUELS

Average torque obtained with Fuel PCR, a fuel with density similar to Fuel 2D, was less than 1 percent higher than Fuel 2D.

Figure 2 illustrates that average hot-start transient emission levels of HC, CO, NO_x, PM, and SOF obtained with Fuels B1, B2, and B3, were all lower than those using Fuels PCR and 2D. Compared to Fuel 2D, the FT fuels showing the largest decrease in emissions were Fuel B1 for HC (46%), Fuel B2 for CO (47%), both Fuels B1 and B3 for NO_x (9%), Fuel B2 for PM (32%), and both Fuels B1 and B3 for SOF (47%). Figure 3 illustrates the relative NO_x and PM levels obtained on the test fuels using Fuel 2D as the reference fuel. Although NO_x was lowest with Fuel B3, PM was lowest with Fuel B2.

SUMMARY

The main objective of this study was to evaluate the effects Fischer-Tropsch (FT) derived diesel fuels have on emissions from a heavy-duty truck engine. A screening test procedure was used based on transient emissions measurement procedures developed by the EPA for emissions regulatory purposes. Hydrocarbon, CO, NO_x, PM, sulfate, SOF, and VOF emissions were determined using a prototype 1991 DDC Series 60 heavy-duty diesel engine, run over the EPA Federal Test Procedure (FTP) hot-start transient cycle, using five fuels. A low sulfur, emissions grade 2D fuel, Fuel 2D, was used as reference for comparison to three FT fuels, Fuels B1, B2, and B3; and one "pseudo" reference fuel, PCR.

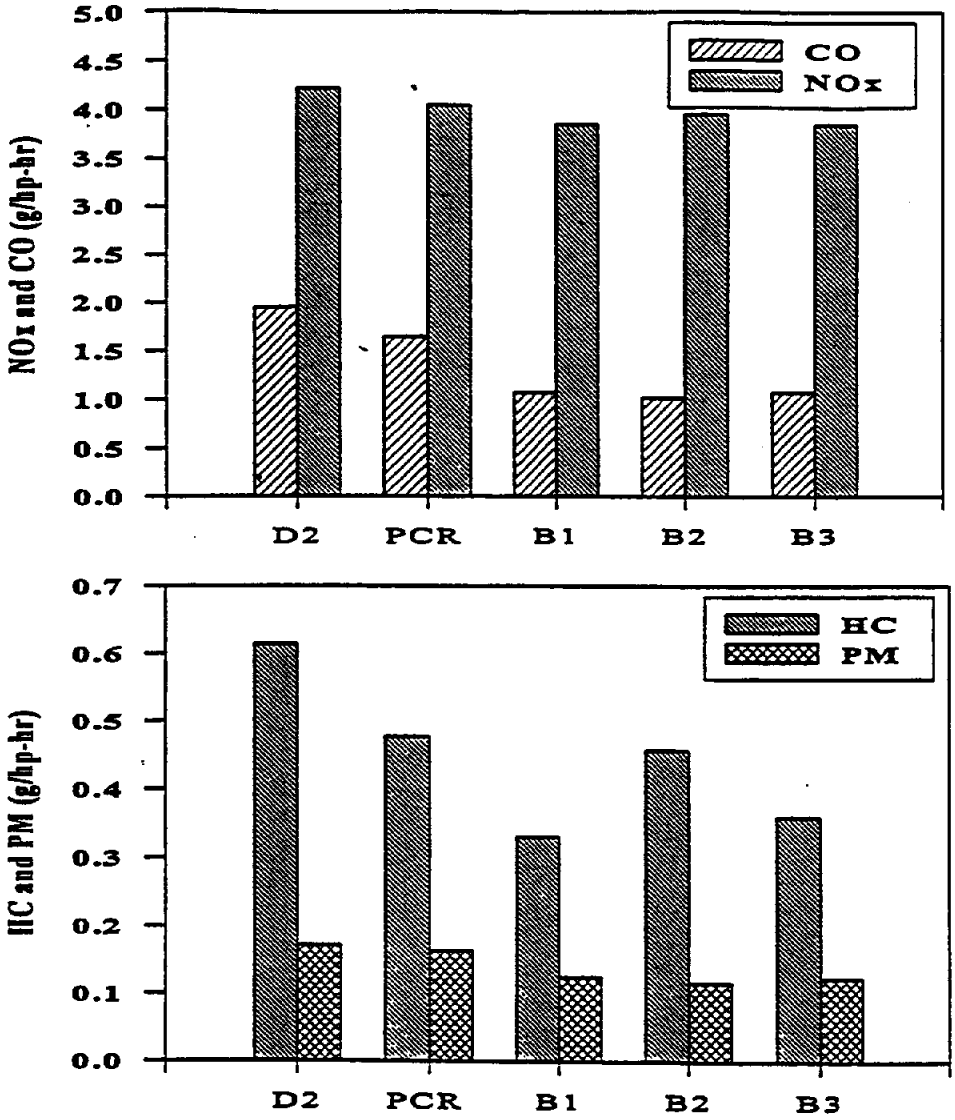

FIGURE 2. AVERAGE HOT-START TRANSIENT EMISSIONS

Average torque levels over the engine operating speed range with Fuels B1, B2, and B3 were correspondingly about 5, 9, and 5 percent lower than on Fuel 2D. Whereas, average torque levels obtained with Fuel PCR were about 1 percent higher than on Fuel 2D.

Average emissions of HC, CO, NO_x, PM, and SOF obtained with Fuels B1, B2, B3, and PCR were all less than with reference fuel, Fuel 2D. Furthermore, all these emissions were lower with FT fuels than on Fuel PCR. Fuel B1 had lowest HC, and Fuel B2 had lowest CO. Both Fuels B1 and B3 had low NO_x, but Fuel B2 had lowest PM. Both Fuels B1 and B3 also had low SOF. On average, the FT fuels produced 8% less NO_x, 30% less PM, 38% less HC, 46% less CO than the US

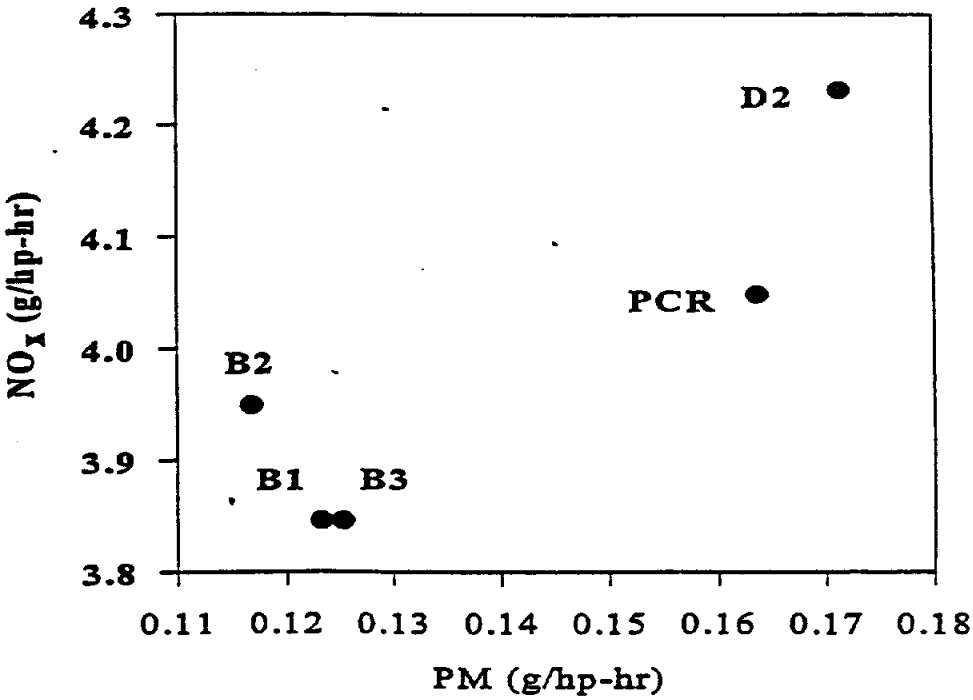

FIGURE 3. AVERAGE HOT-START TRANSIENT EMISSIONS NO_X VERSUS PM

average diesel fuel. Compared to the pseudo-CARB reference fuel, the FT fuels produced 4% less NO_x, 26% less PM, 20%less HC, and 36% less CO. These results are possibly biased by the fact that the transient torque demand cycle used for the FTP tests were all based on the torque map developed with fuel D2. It is possible that the PM, HC , and CO emissions would have been lower for the FT fuels if the torque demand cycles were changed for each fuel.

The emissions of VOF and unburned oil using FT fuels were lower than those produced by Fuels PCR and 2D. Fuel B3 had the lowest VOF and unburned oil emissions of the FT fuels.

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Future Work

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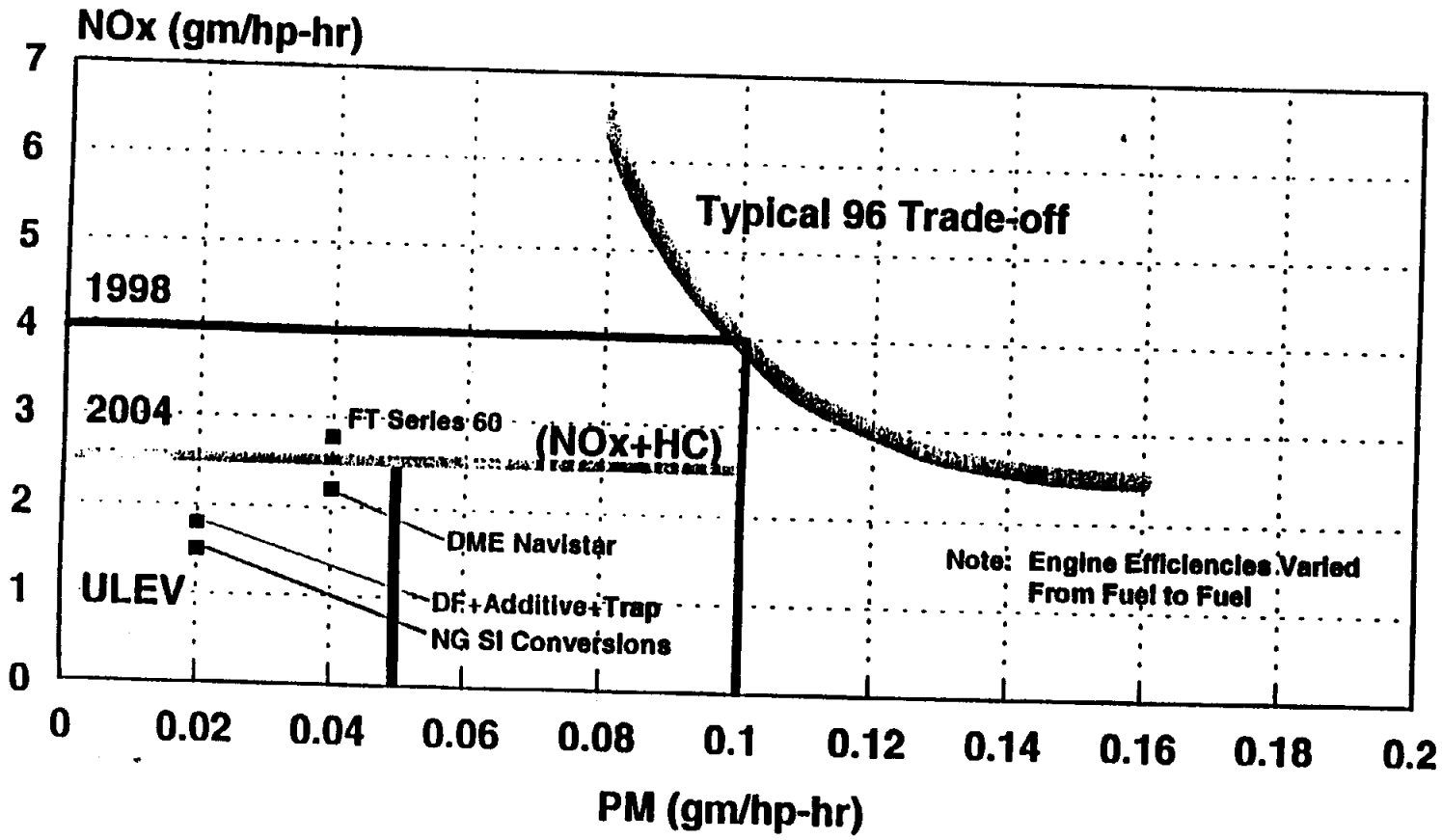
Emissions Comparisons



Conclusions

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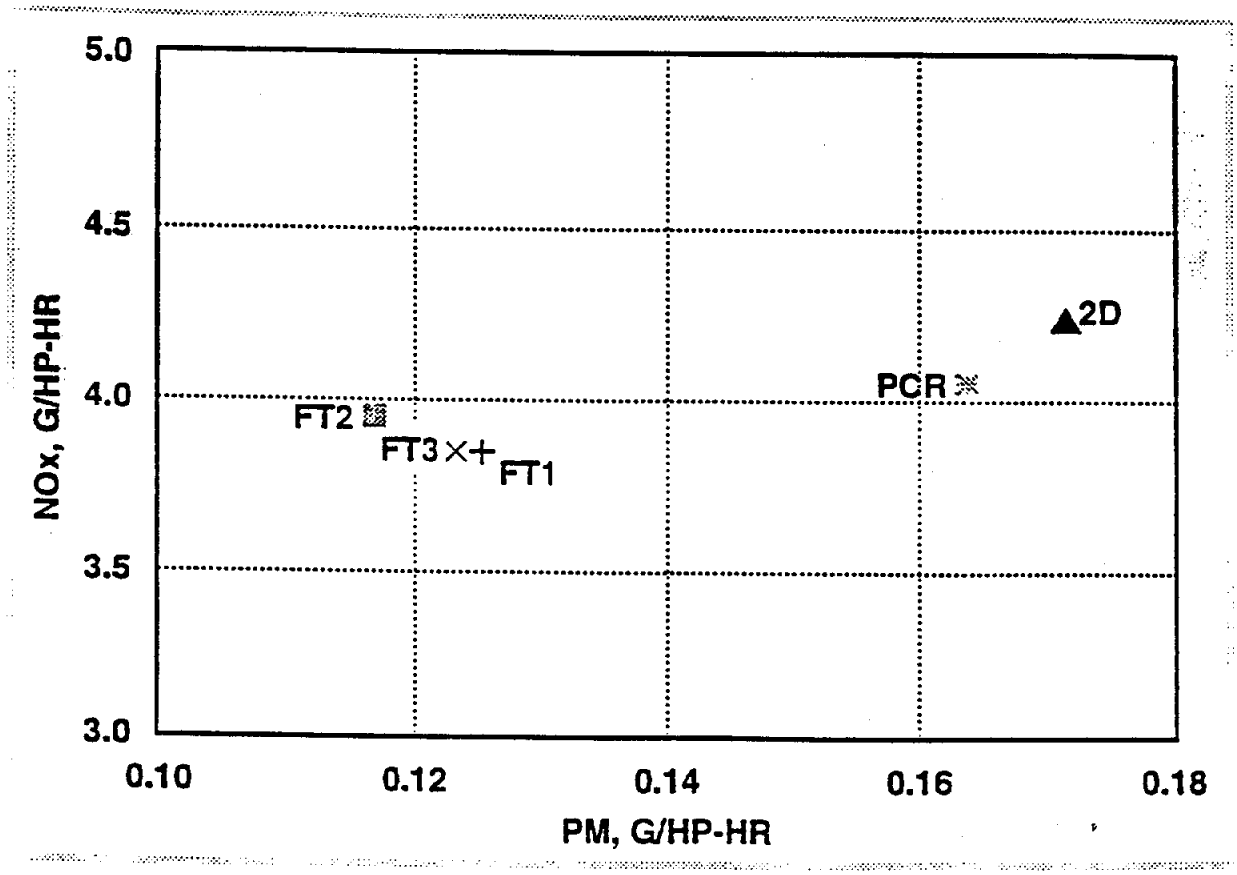
- Compared to US Fuel, F-T Fuels Showed:
  - 30 % Reduction in PM
  - 8.3% Reduction in NO_x
  - 46 % Reduction in CO
  - 38 % Reduction in HC
- Compared to Pseudo-CARB fuel:
  - 26 % Reduction in PM
  - 4 % Reduction in NO_x
  - 36 % Reduction in CO
  - 20 % Reduction in HC

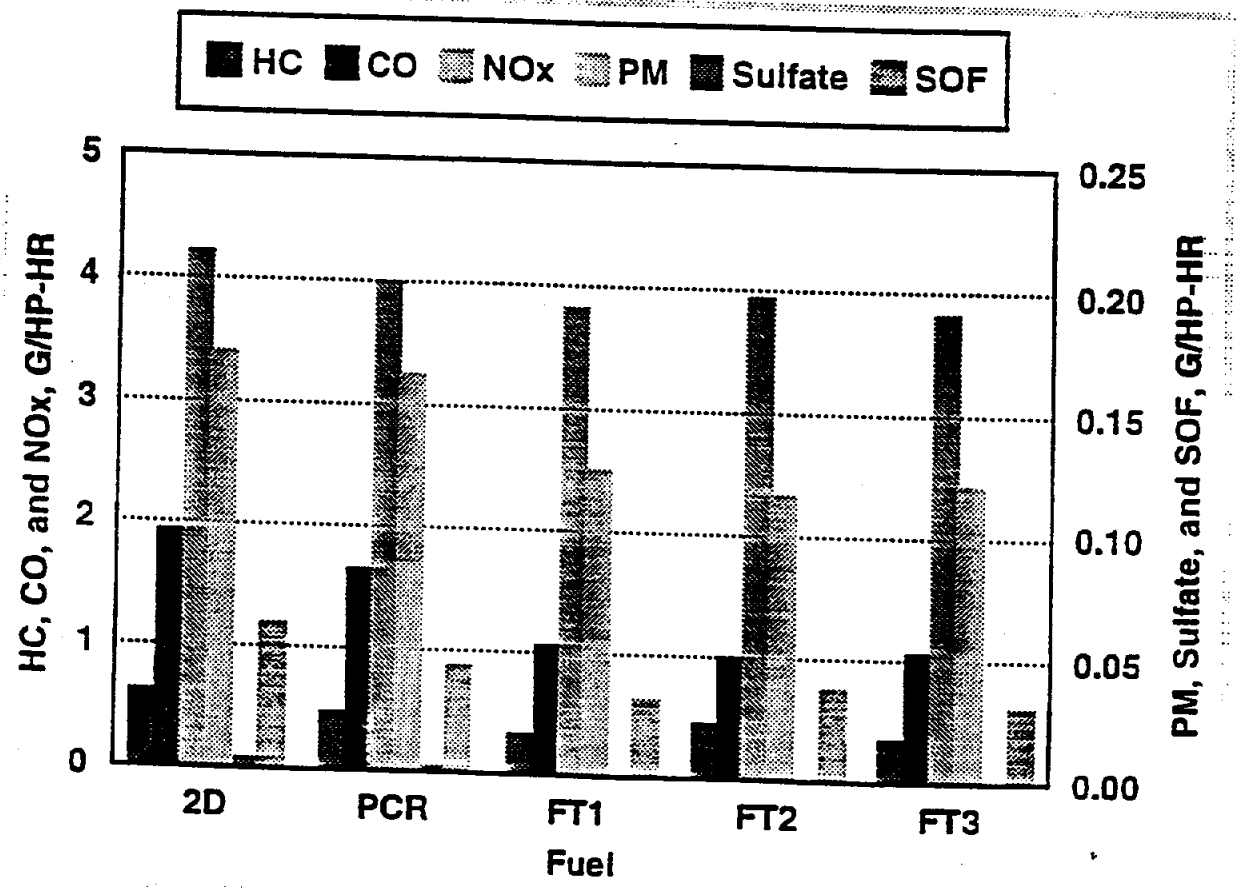
Analysis of Total Particulate From A Prototype 1991 DDC Series 60

Test Fuel	Hot-Start Emissions, g/hp-hr			
	Total PM	SOF	VOF	UBLO
2D	0.172	0.060	0.022	0.010
PCR	0.164	0.044	0.025	0.010
FT1	0.125	0.032	0.021	0.008
FT2	0.117	0.038	0.019	0.008
FT3	0.123	0.032	0.018	0.007

Average Hot-Start Transient Emissions of NO_x and PM Using Fuel 2D As Reference Fuel



Average Hot-Start Transient Emissions in 1991 Prototype DDC Series 60 Engines



Near ULEV Emission Level in a Heavy-Duty Diesel Engine Using Fischer Tropsch Diesel Fuel

Prepared by

Thomas W. Ryan III
Daniel A. Montalvo

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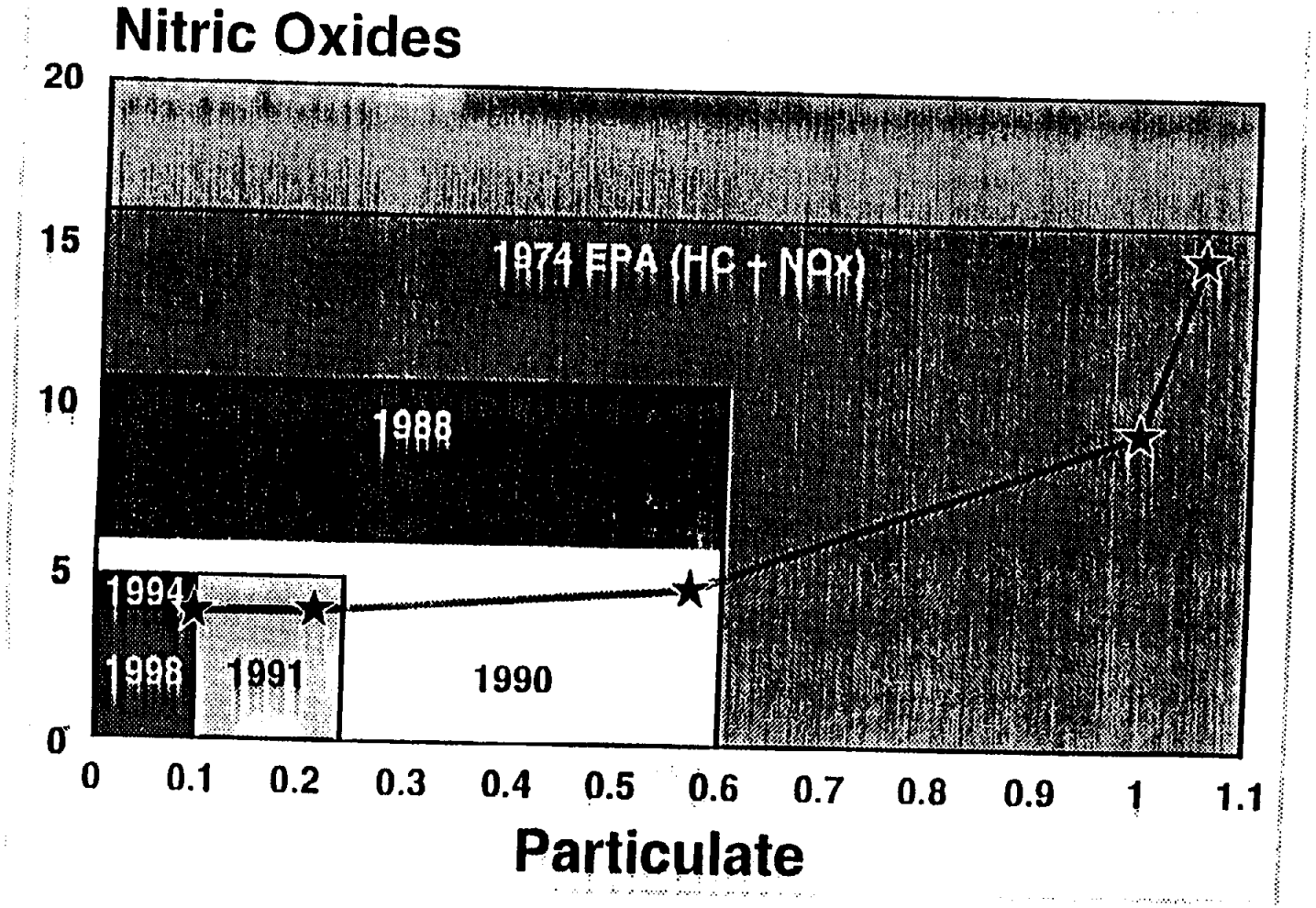
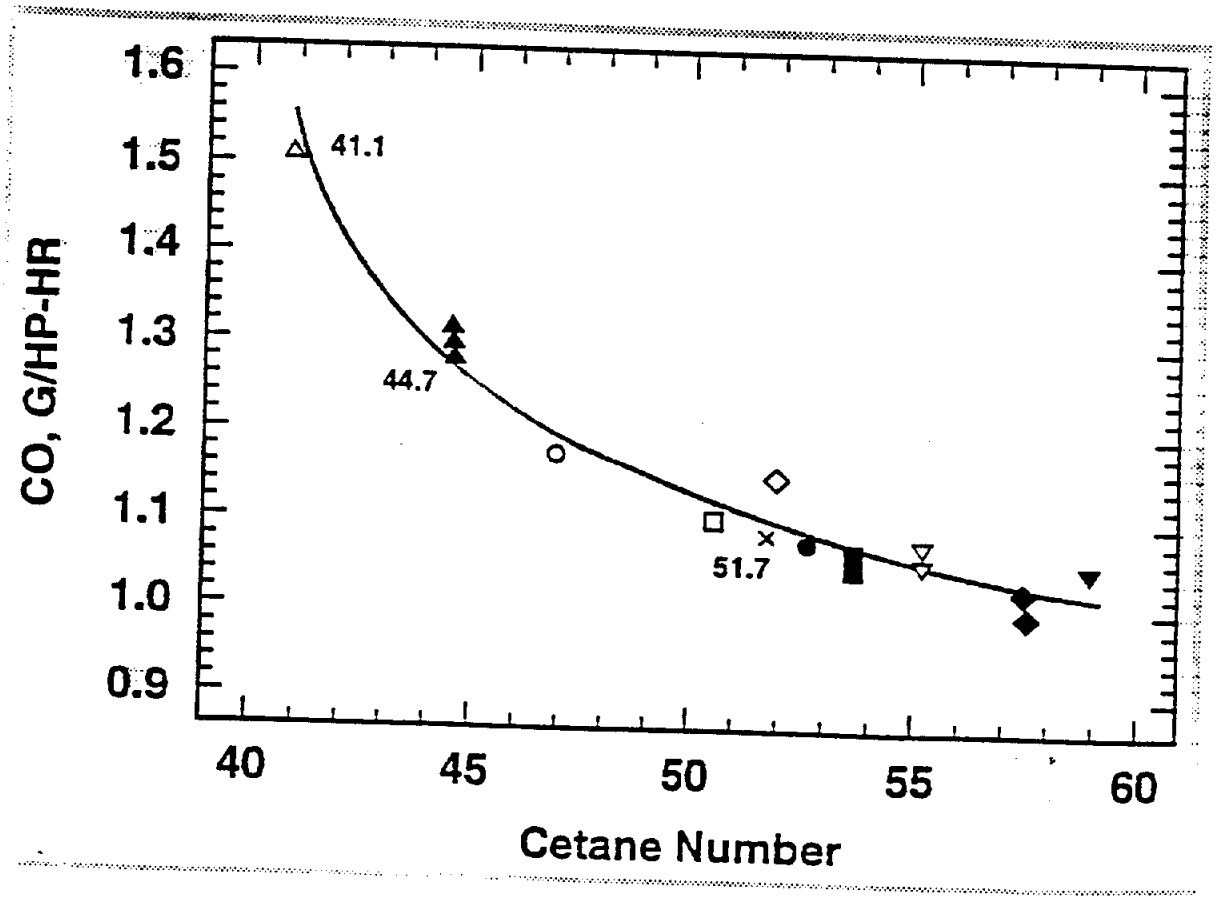
Outline

- Background
- Objective
- Procedure
- Results
- Future

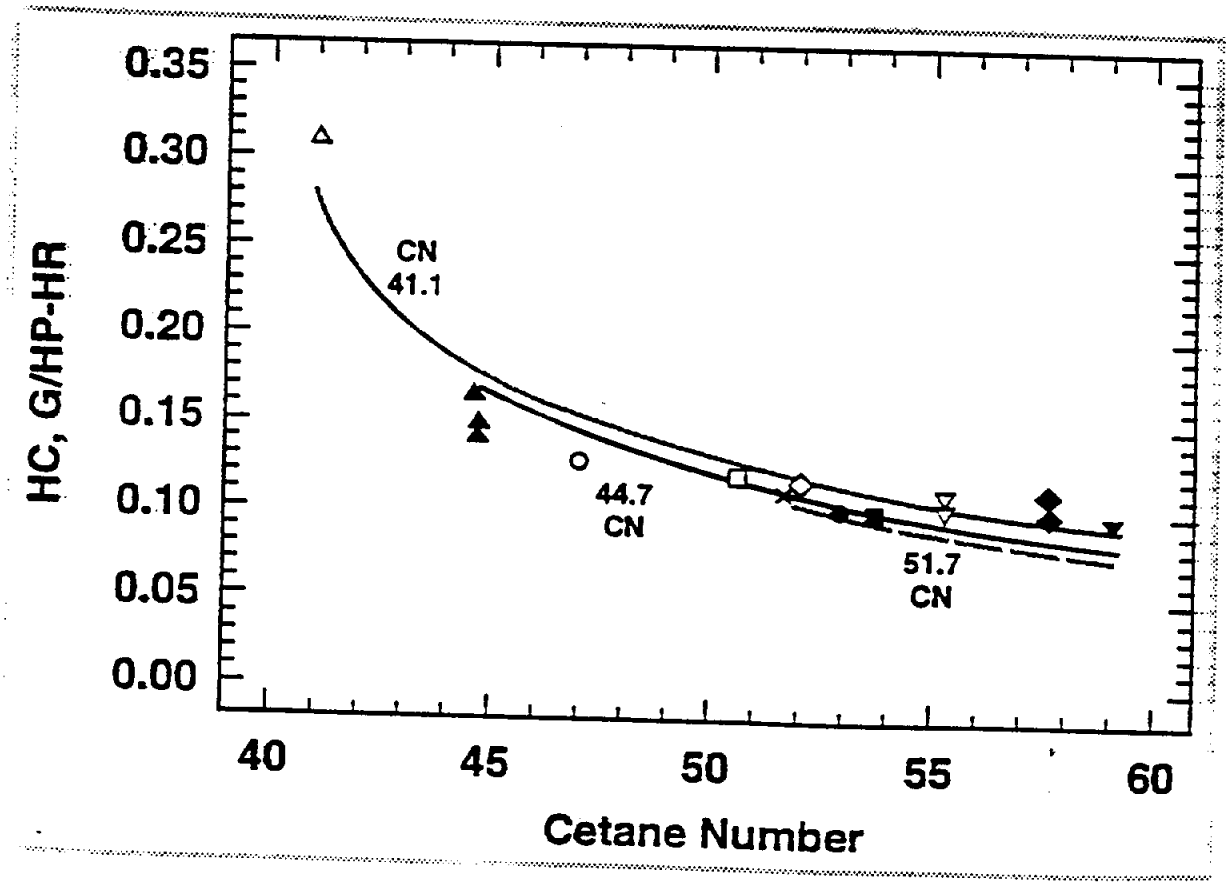
Heavy-Duty Diesel Engine Emissions Standards



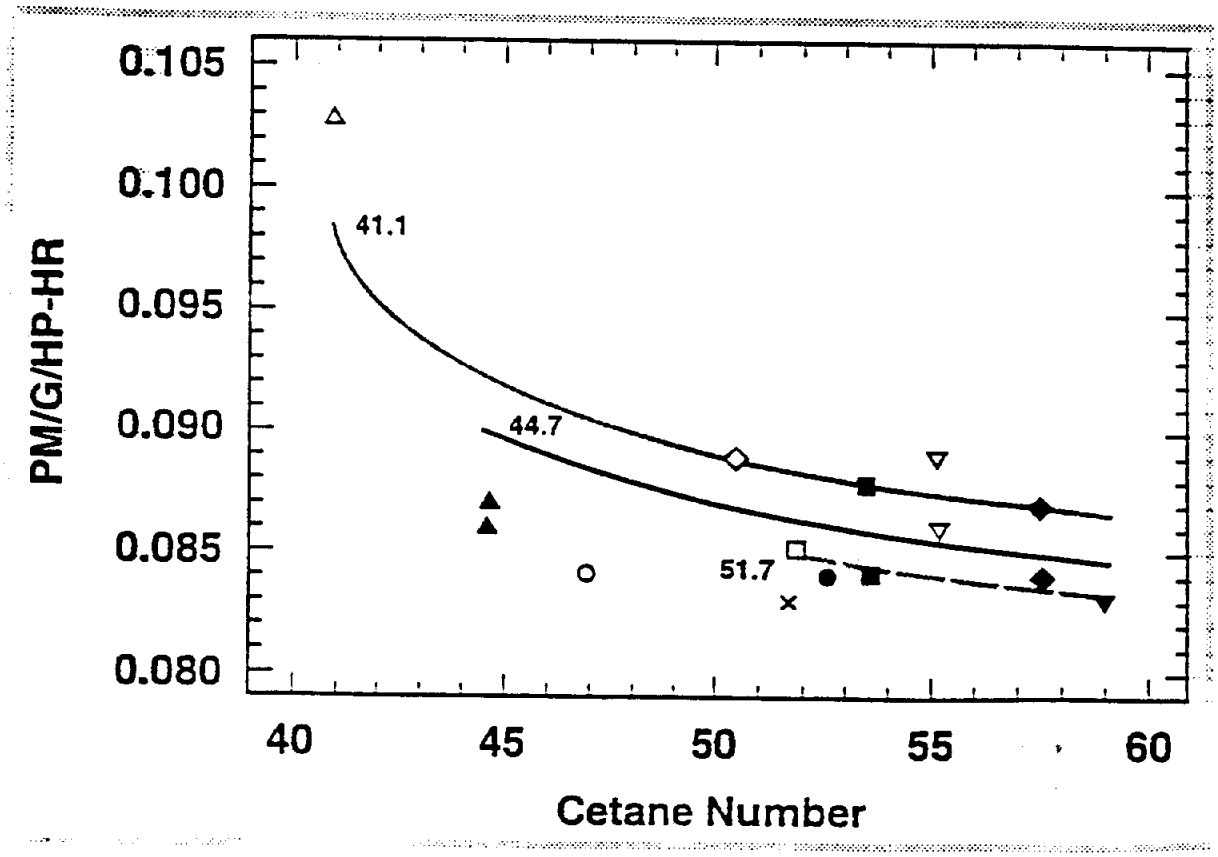
CRC VE-10 Project Model Predicted Composite CO Emissions for Base Cetane Number and Chemically-Induced Cetane Number Increase



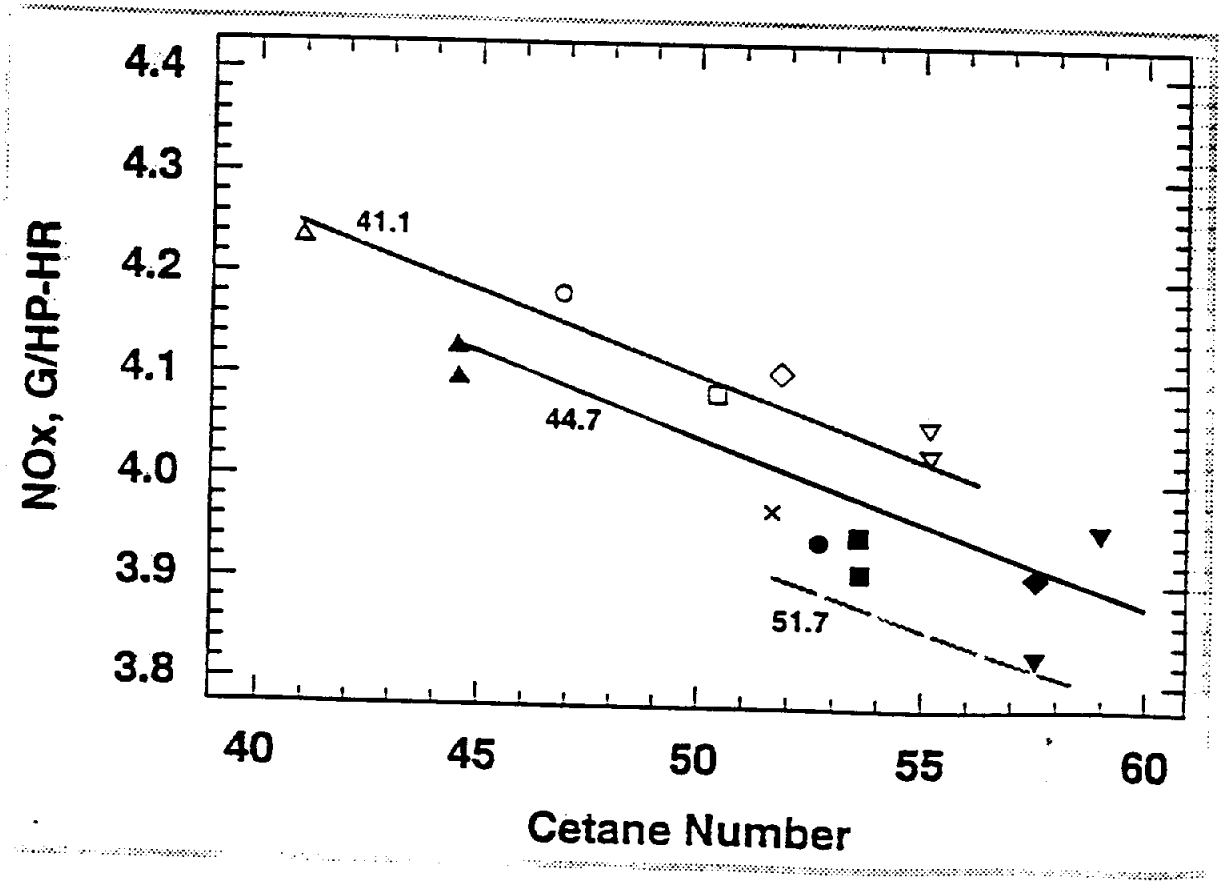
CRC VE-10 Project Model Predicted Composite HC Emissions for Base Cetane Number and Chemically-Induced Cetane Number Increase



CRC VE-10 Project Model Predicted Composite PM Emissions for Base Cetane Number and Chemically-Induced Cetane Number Increase



CRC VE-10 Project Model Predicted Composite NO_x Emissions for Base Cetane Number and Chemically-Induced Cetane Number Increase



Diesel Fuel Reformulation
Simple Outline

	Federal 1993	California 1993 Formula	California Reference
Sulfur (wt%)	0.05	0.05	0.05
Aromatics (v%)	35	10	10
Polycyclic (v%)			1.4
Nitrogen (wt%)			0.001
Cetane Number			48
Cetane Index	40	40	
Gravity (API)			33-39
Viscosity (cSt@40)			2.0-4.1
Distillation			SPECIFIED

Statement of Principles

- Agreement between EMA, EPA and CARB
  - 2.0 gm/hp-hr NO_x by 2004
  - 2.4 gm/hp-hr NO_x + HC by 2004
  - 0.1 gm/hp-hr PM
- Contingent on Availability of Clean Diesel Fuel by 2003
  - 3.4 gm/hp-hr NO_x + HC without Clean Fuel

Desired Fuel Specification

- 1998
  - 50 Cetane Number
- 2004
  - 10 Percent Aromatic Content
  - 60 Cetane Number

Objective

- The Objective of this Project was to Compare the Emissions Characteristics of Three Different Fischer Tropsch Diesel Fuels to Current Diesel Fuels

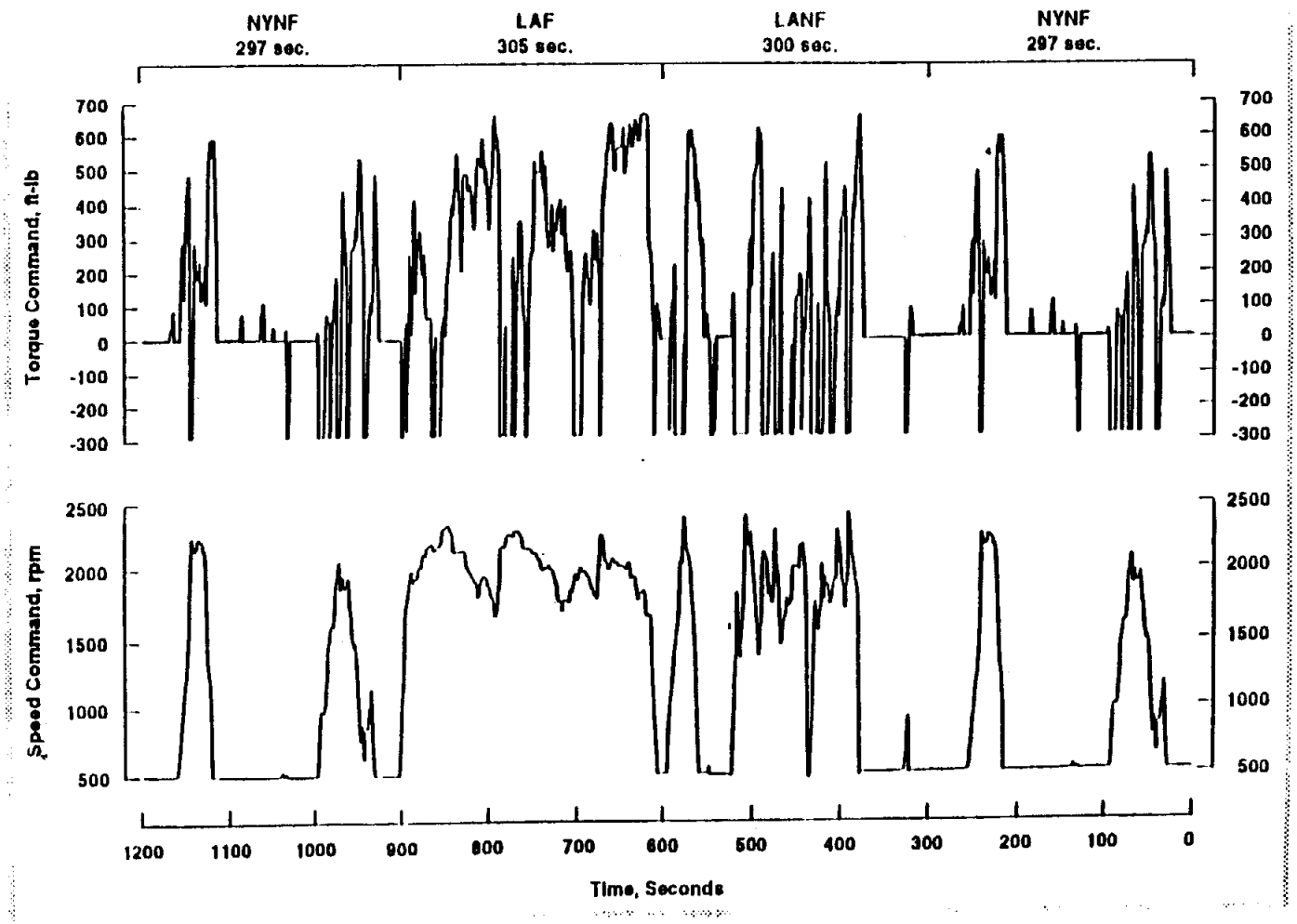
Approach

- Acquire Three Different F-T Fuels
- Acquire Two Different Current Fuels (Pseudo-CARB Reference Fuel and a US Fuel)
- Test all Five Fuels using Pseudo-CARB Protocol

CARB Protocol

- Produce a "Reference Fuel" as the Baseline
  - 10 Percent Aromatic
  - 48 Cetane Number
- Run Test and Reference Fuels in a 1991 Detroit Diesel Series 60
- Follow Stringent Test Procedure
- Test Fuel Emissions as Low as Reference Fuel

Graphic Representation of Torque and Speed Commands for the Transient FTP Cycle



Characteristics of the Prototype 1991 DDC Series 60 Heavy-Duty Diesel Engine

Engine Configuration and Displacement	6-Cylinder, 11.1 Liter, 130 mm Bore x 139 mm Stroke
Aspiration	Turbocharged, Aftercooled (Air-to-Air)
Emissions Controls	Electronic Management of Fuel Injection and Timing (DDEC-II)
Rated Power	330 hp at 1800 rpm with 108 lb/hr Fuel
Peak Torque	1270 lb-ft at 1200 rpm with 93 lb/hr Fuel
Injection	Direct Injection, Electronically Controlled Unit Injectors
Maximum Restrictions Exhaust Intake	 2.9 in. Hg at Rated Conditions 20 in. H_2O at Rated Conditions
Low Idle Speed	600 rpm

Test Fuels Properties

TEST	METHOD	2D	PCR	FT1	FT2	FT3
Distillation	D86					
IBP, °F		376	410	338	348	382
10%		438	446	427	394	448
50%		501	488	590	458	546
90%		587	556	646	536	620
EP %		651	652	672	562	640
Cetane No.	D613	45.5	50.2	>74.0	>74.0	74.0
Cetane Index	D976	47.5	46.7	80.5	72.9	77.2
	D4737			94.1	77.9	87.6
Gravity	D1298					
API @ 60°F		36.0	36.6	49.1	52.5	49.1
Density G/ML @ 15°C				0.7832	0.7688	0.7830
Specific Gravity @ 60/60		0.8447	0.8419	0.7835	0.7690	0.7833
Sulfur, WT %	D2622	.033	0.0345	<0.001	<0.001	<0.001
Flash Point °C	D93	70.6	82.2	60	62.2	80.6
Cloud PT., °C	D2500	-16.6	-15.5	8	-23	-12
Pour PT., °C	D97	-26		11	-20	-16
Viscosity @ 40°C, cSt	D445	2.75	2.79	3.85	1.58	2.66
BOCLE Scuff, Grams				1850	1700	2300

Test Procedure

Day One

- Purge Fuel System with US Fuel
- Establish Full Rack Torque Curve on US Fuel for Use in the FTP Demand Curves
- Perform 3 Hot-Start FTP Tests
- Purge Fuel System with Fuel B1
- Perform 3 Hot-Start FTP Tests

Test Procedure

Day Two

- Perform 3 Hot-Start FTP Tests
- Purge Fuel System with Pseudo-CARB Fuel
- Perform 3 Hot-Start FTP Tests

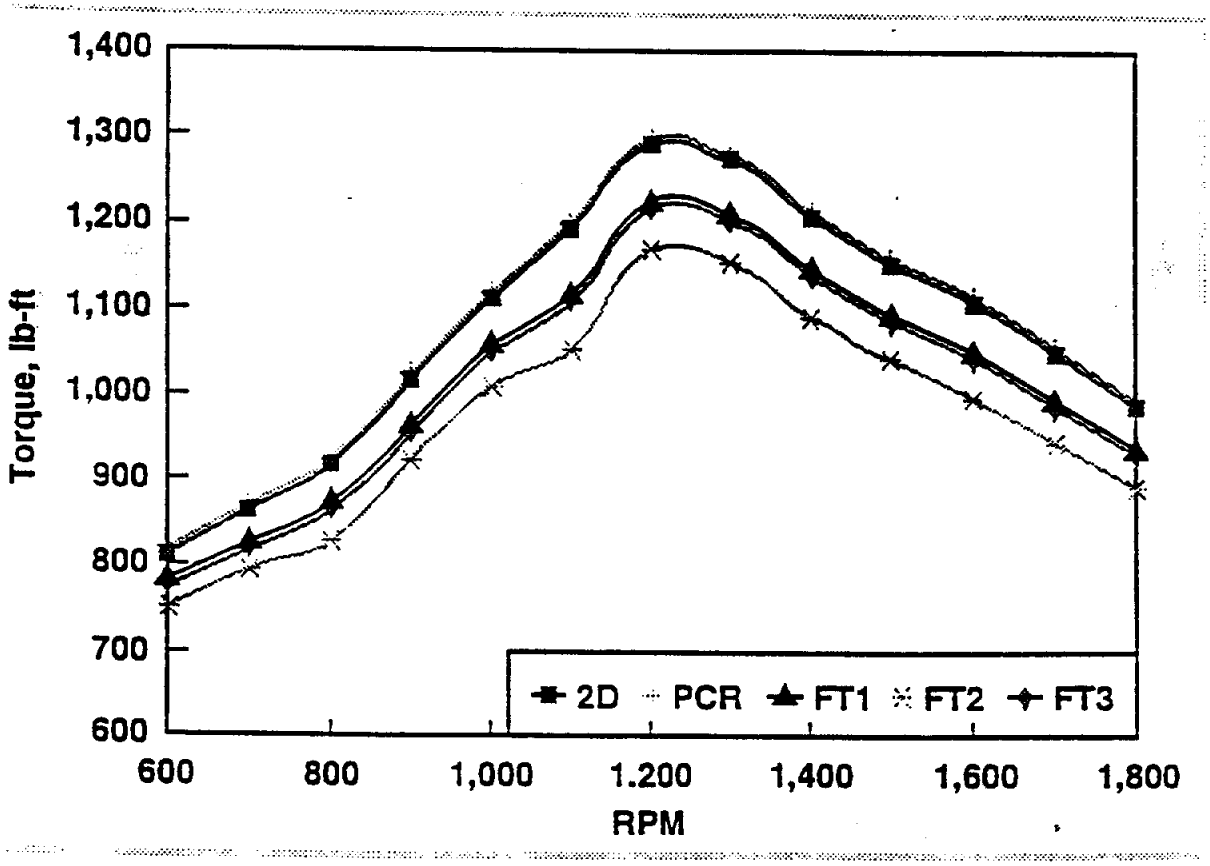
Day Three

- Perform 3 Hot-Start FTP Tests
- Purge Fuel System with Fuel B2
- Perform 3 Hot-Start FTP Tests

Fuel Change Procedure

- Confirm Fuel Identification by Gravity
- Drain the Entire Fuel System
- Change Fuel Filters and Fill System with Fuel
- Run Engine and Purge Return, Checking Gravity
- Run Power Validation and Confirm Restrictions

Average Transient Torque Maps of the Prototype 1991 DDC Series 60



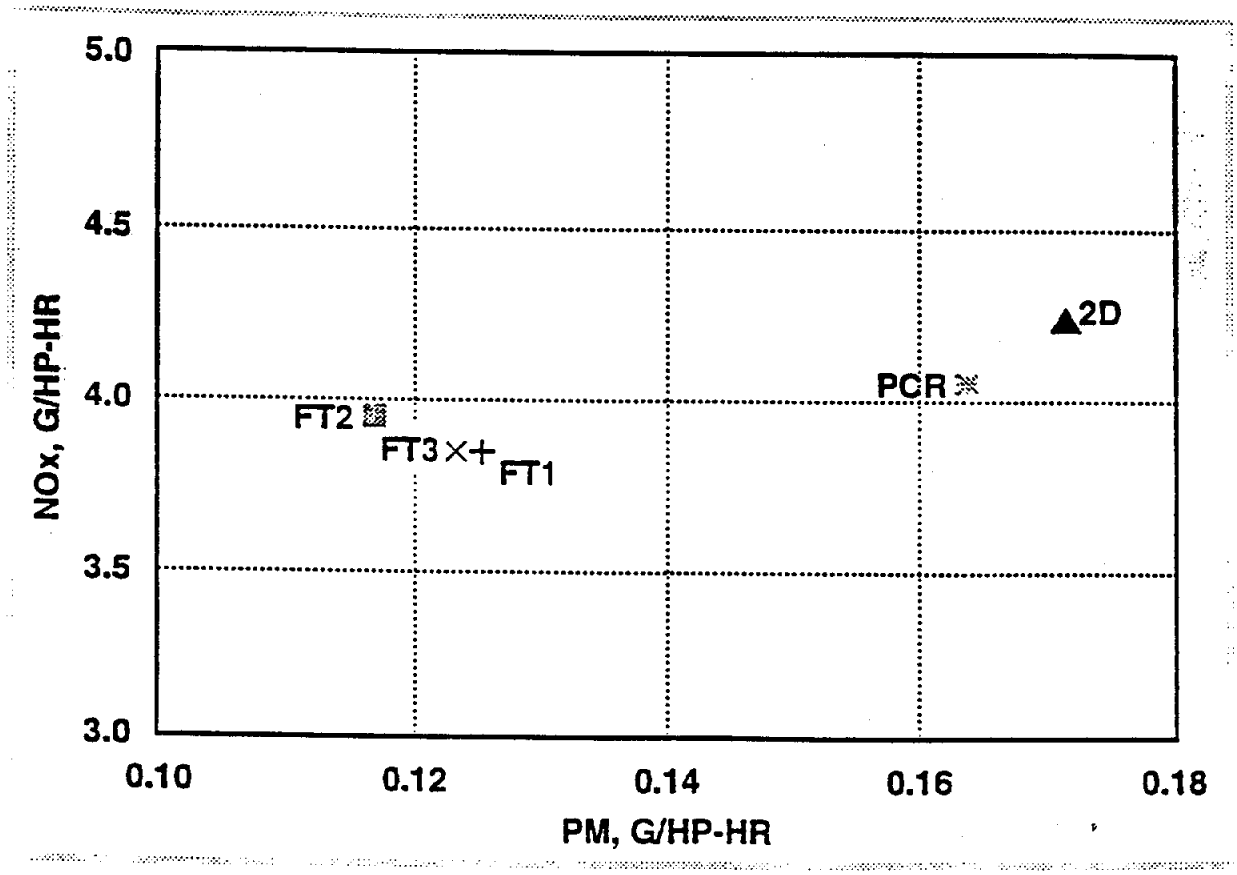
Hot-Start Transient Emissions From A Prototype 1991 DCC Series 60

	Fuel Code	Hot-Start Transient Emissions, g/hp-hr					
		HC	CO	NOx	PM	Sulfate	SOF
	2D	0.588	1.953	4.232	0.170	0.0032	0.053
	2D	0.597	1.987	4.258	0.172	0.0032	0.060
	2D	0.610	1.987	4.254	0.171	0.0035	0.059
2D Mean		0.5983	1.9757	4.2480	0.1710	0.00330	0.0573
Std. Dev.		0.0111	0.0196	0.0140	0.0010	0.00017	0.0038
Coeff. of var., %		1.8	1.0	0.3	0.6	5.2	6.6
	FT1	0.386	1.132	3.822	0.124	0.0006	0.029
	FT1	0.319	1.088	3.812	0.125	0.0007	0.034
	FT1	0.331	1.064	3.805	0.125	0.0006	0.031
FT1 Mean		0.3453	1.0947	3.8130	0.1247	0.00063	0.313
Std. Dev.		0.0357	0.0345	0.0085	0.0006	0.00006	0.0025
Coeff. of var., %		10.3	3.2	0.2	0.5	9.1	8.0

Summary of Hot-Start Transient Emissions From A Prototype 1991 DDC Series 60

	Hot-Start Transient Emissions, g/hp-hr					
	HC	CO	NOx	PM	Sulfate	SOF
Overall 2D Mean	0.6142	1.9483	4.2318	0.1715	0.00313	0.0605
Std. Dev.	0.0187	0.0333	0.0201	0.0010	0.00022	0.0046
Coeff. of var., %	3.1	1.7	0.5	0.6	6.9	7.7
Overall PCR Mean	0.4780	1.6453	4.0477	0.1637	0.00342	0.0436
Std. Dev.	0.0193	0.0215	0.0366	0.0021	0.00050	0.0047
Coeff. of var., %	4.0	1.3	0.9	1.3	14.5	10.8
Overall FT1 Mean	0.3313	1.0733	3.8457	0.1253	0.00050	0.0322
Std. Dev.	0.0274	0.0352	0.0536	0.0010	0.00017	0.0040
Coeff. of var., %	8.3	3.3	1.4	0.8	33.5	12.3
Overall FT2 Mean	0.4578	1.0233	3.9490	0.1168	0.00020	0.0385
Std. Dev.	0.0054	0.0133	0.0010	0.0013	0.00008	0.0031
Coeff. of var., %	1.2	1.3	0.0	1.1	40.8	8.1
Overall FT3 Mean	0.3608	1.0798	3.8455	0.1233	0.00068	0.0320
Std. Dev.	0.0316	0.0223	0.0101	0.0017	0.00029	0.0032
Coeff. of var., %	8.8	2.1	0.3	1.4	42.6	9.9

Average Hot-Start Transient Emissions of NO_x and PM Using Fuel 2D As Reference Fuel



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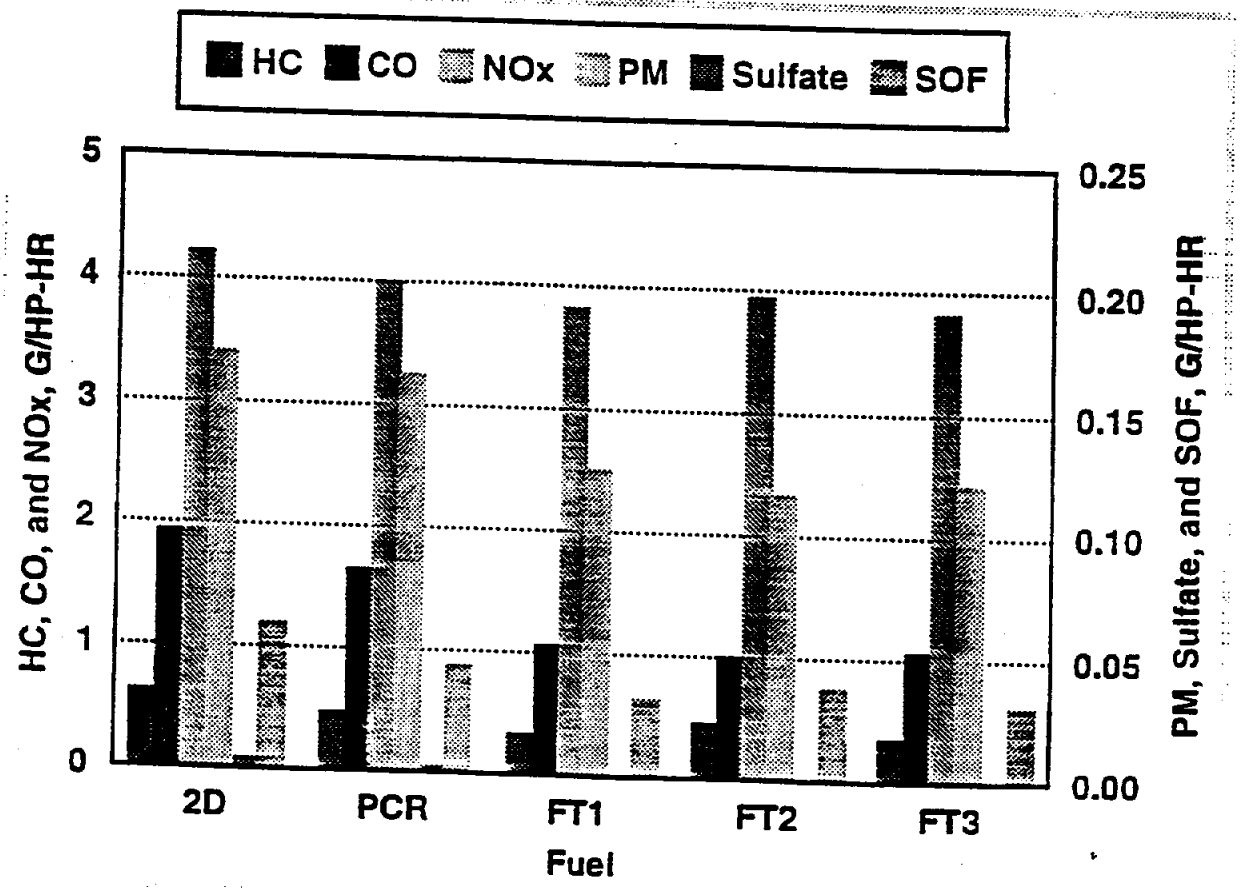

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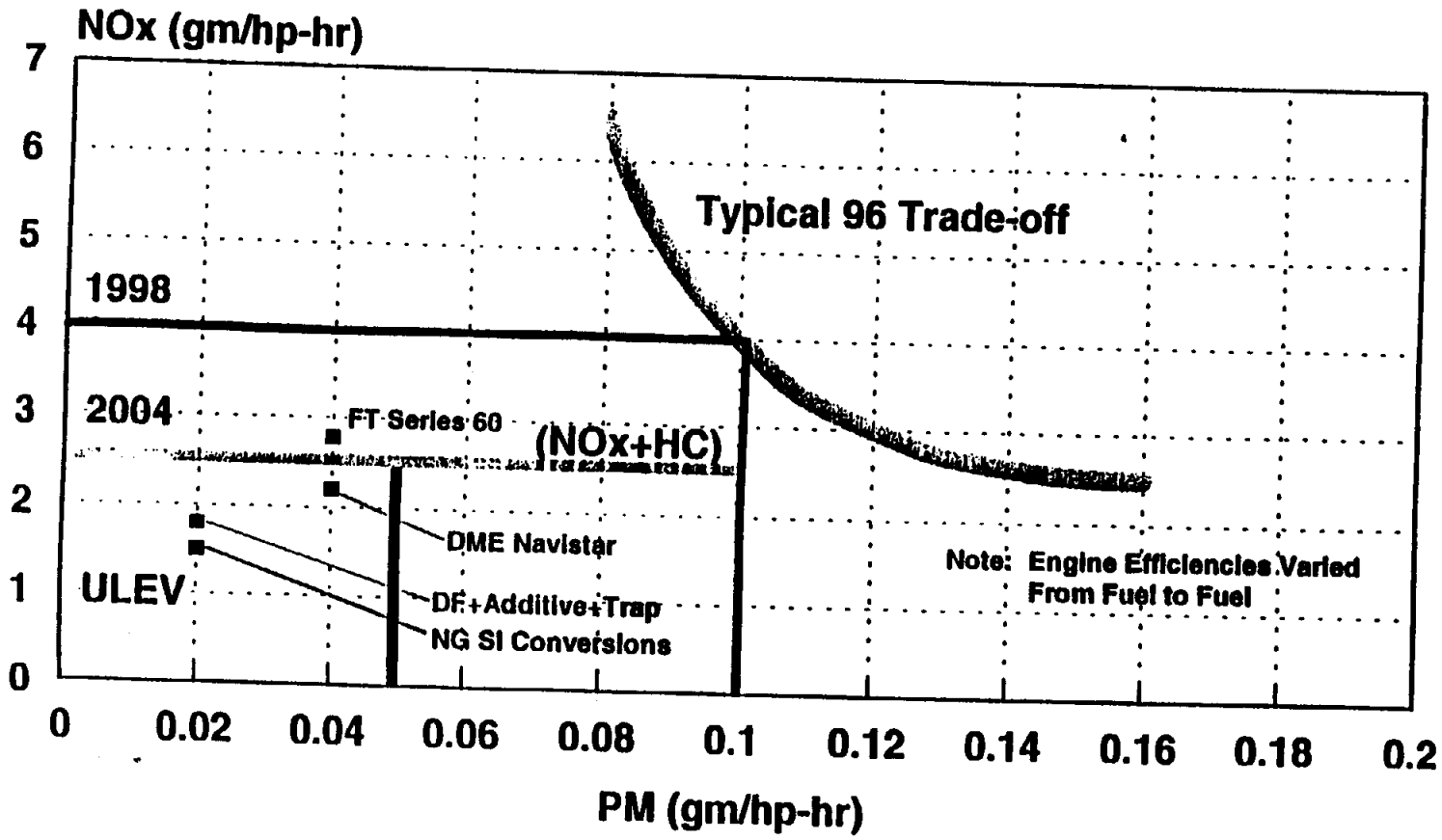

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