INCORPORATING OXYGEN IN DIESEL FUEL AS A MEANS OF REDUCING ENGINE EMISSIONS

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College of Earth and Mineral Sciences
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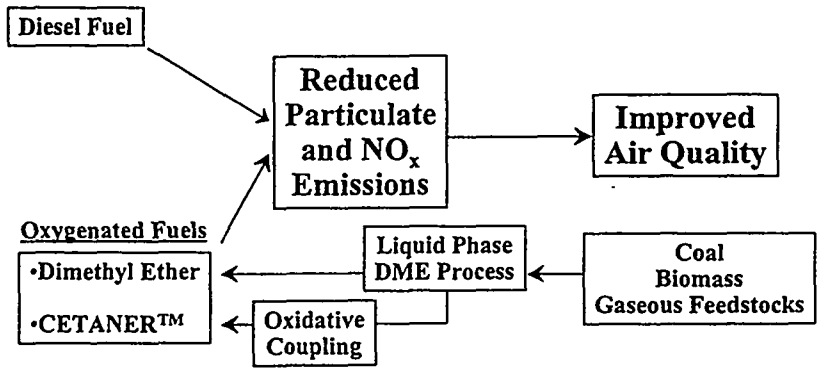
Incorporating Oxygen in Diesel Fuel



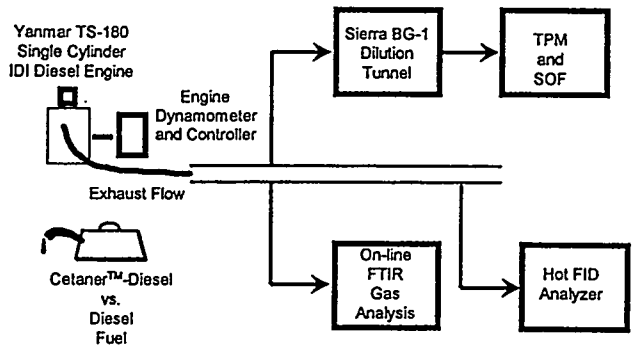
Sponsors

- Air Products and Chemicals, Inc.
- Pennsylvania Department of Environmental Protection
- Federal Energy Technology Center
- General Motors Powertrain Division
- Navistar International
- Cummins Engine Company
- Texaco Additives, Inc.
- Mobil Oil Company
- Volkswagen AG
- Champion Motor Coach
- PACCAR (Peterbilt-Kenworth)
- Lubrizol
- Ethyl Additives
- DuPont

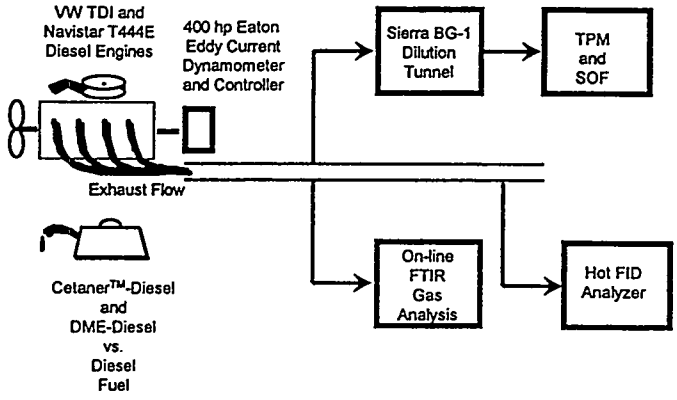
Engine and Emissions Equipment

- 400 Hp Eddy Current Dyno
- 250 Hp Eddy Current Dyno Being Installed
- 50 Hp Water-Brake Dyno
- Waukesha CFR Octane Rating Engine
- Refurbished Horiba On-Line Gas Analyzers and Sample Conditioners
- Nicolet Magna 550 FTIR Spectrometer
- HP 6890 GC with TCD and FID
- HP 5890 GC with FID
- Sierra Instruments BG-1 Micro Dilution Test Stand
- R&P Co. Inc. Series 5100 Diesel Particulate Analyzer
- California Analytical Hot-FID Analyzer
- Kistler Pressure Sensors and Crank Angle Encoders
- Navistar T444E, V-8, DI Turbodiesel with HEUI Fuel Injection
- Cummins B5.9, 6 Cyl., 24-valve, DI Turbodiesel with Electronic Controls
- Volkswagen 1.9L TDI, DI Turbodiesel
- Yanmar TS-180 Single-Cylinder IDI

Combustion Laboratory
Single-Cylinder Engine Test Cell



Combustion Laboratory
Multi-Cylinder Engine Test Cell



Effect of Oxygenated Cetane Improver on Diesel Engine Combustion and Emissions

A Proposal to the Strategic Alliance Committee

by
André L. Boehman and Peter J.A. Tijm

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Objectives

- **Examine Emissions and Combustion Behavior of Diesel Fuels Doped with Oxygenates**
- **Clarify the Effects of an Oxygenate with High Cetane Number**
- **Study Both Emissions Reductions and Combustion Behavior by Sampling the Exhaust and Monitoring In-Cylinder Pressure**

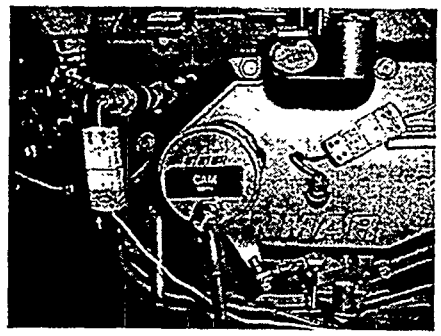
Benefits of Cetaner™

- **Development of Transportation Fuel Additives from Synthesis Gas**
  - → **Complies with US DoE Federal Energy Technology Center "Vision 21" Mission - Cleaner and More Efficient Use of Coal**
  - → **Producing Cetane Enhancers from Inexpensive Feedstocks**
  - → **Projected to Have a Cost Equal to Diesel Fuel**

Comparison of Some Oxygenated Fuel Additives

Property	Chemical formula	Cetane Number	Characteristics
Diesel	$C_{10-15}H_{18-28}$	40-55	base fuel, tendency to soot and form NO_x during the diesel combustion process due to chemical and physical properties
Diethyl Ether (DEE)	$C_2H_5OC_2H_5$	55 - 60	gas, unstable fuel, offers minimal improvement to cetane number
Dimethyl Ether (DME)	CH_3OCH_3	55-60	gas, not readily mixed with diesel fuel, offers minimal improvement to cetane number
Dimethoxy Methane (Methylal, DMM)	$CH_2(OCH_3)_2$	55 - 60	liquid, boils at 50° C
Methyl *tert*-butyl ether (MTBE)	$CH_3OC(CH_3)_3$	< 5	liquid, negative impact on cetane number, potential carcinogen that is showing up in California water reservoirs because of its use in reformulated gasoline
Methanol	CH_3OH	5	liquid, high octane number, difficult to autoignite, low solubility in diesel fuel
Cetaner	mixture	60-125	liquid, high cetane number, soluble in diesel fuel, mixture of dimethoxymethane (DMM), 1,2-dimethoxy-ethane (DMET) and methanol

Yanmar TS180 Single-Cylinder IDI Diesel Engine in the 50 hp Test Cell



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Oxygenate Blends Evaluated

Oxygenate Blended	Structure	Notation	Wt% oxygen	Blend Ratio
diethylene glycol methyl ether	$CH_3OC_2H_4OC_2H_4OH$	DGME	40.0	10/90
Triethylene glycol dimethyl ether	$CH_3O(C_2H_4O)_3CH_3$	Triglyme	36.0	11/89
Diethylene glycol dimethyl ether	$CH_3O(C_2H_4O)_2CH_3$	Diglyme	35.8	11/89
1,2-dimethoxyethane	$CH_3O(C_2H_4O)_1CH_3$	Glyme	35.6	11/89
CETANER™ *		CETANER™	36.5	11/89
96% Glyme	$CH_3OCH_2CH_2OCH_3$		(35.6)	
4% dimethoxymethane	$CH_3OCH_2OCH_3$		(59.3)	
Methyl Soyate	Mixed esters	Me Soyate	11.0	35/65

*Simplified mixture chosen to represent a potential CETANER™ formulation.

Oxygenated Fuel Properties

Oxygenate Blend Tested	Saybolt Viscosity (SUS), 100°F	Gravity (°API)	Cloud Point (°F)	Flash Point (°F)	Heat of Combustion (BTU/lb)
ASTM Specification	32.6-40.1	Min 30	Max 0	Min 125	------
Premium Diesel Fuel	34.8	45	<0	160	19,707
DGME	35.7	41	<0	157	19,118
Triglyme	32.3	44	<0	173	18,909
Diglyme	34.0	51	<0	147	18,856
Glyme	32.0	48	<0	<67	18, 613
CETANER™	34.3	45	<0	<67	18,867
Methyl Soyate	41.4	43	8	180	18,793

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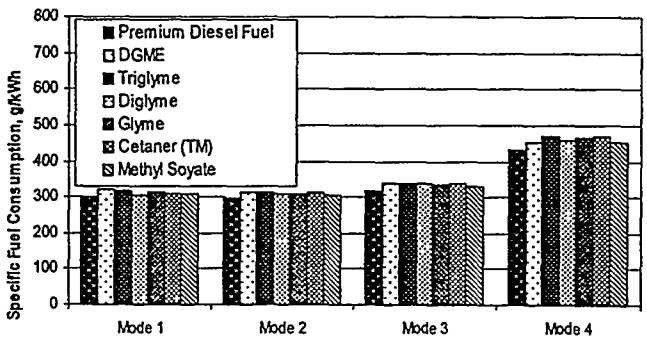
Total Brake-Specific Particulate Emissions, g/kWhr

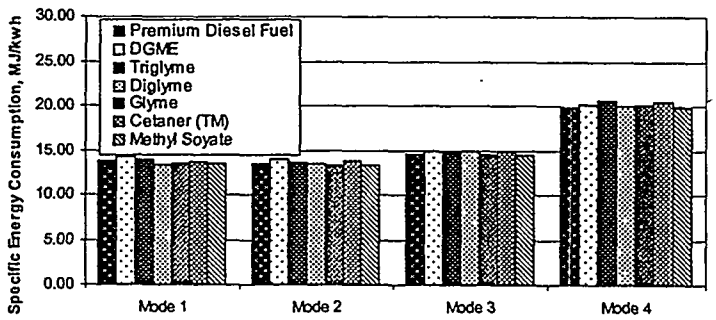
Oxygenate Fuel Blend Evaluated	% wt Oxygen In Blend	BS PM, g/kWhr	% Reduction from Baseline (*)
Premium Diesel Fuel	—	0.728	—
DGME	4.12	0.661	9.3 ± 8.2%
Triglyme	3.96	0.607	16.6 ± 5.3%
Diglyme	3.94	0.511	29.8 ± 6.8%
Glyme	3.97	0.512	29.7 ± 7.0%
CETANER™	4.00	0.524	28.0 ± 5.8%
Methyl Soyate	3.88	0.539	26.0 ± 8.1%

* Error range based upon 95% Confidence Interval.

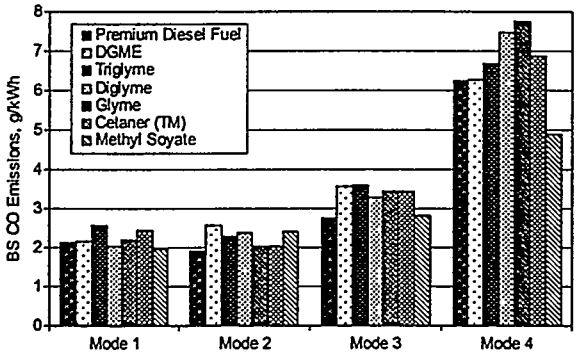
Specific Fuel Consumption



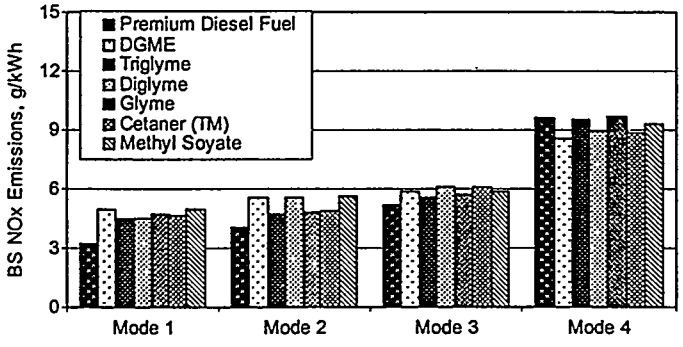
Specific Energy Consumption



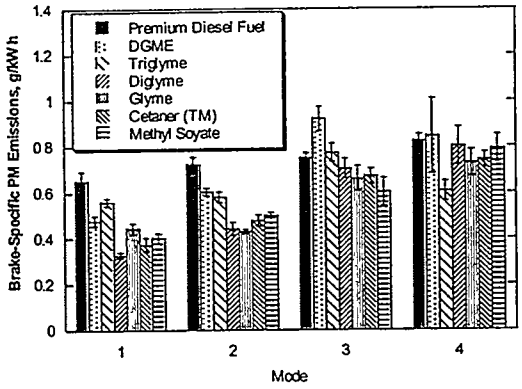
Specific CO Emissions



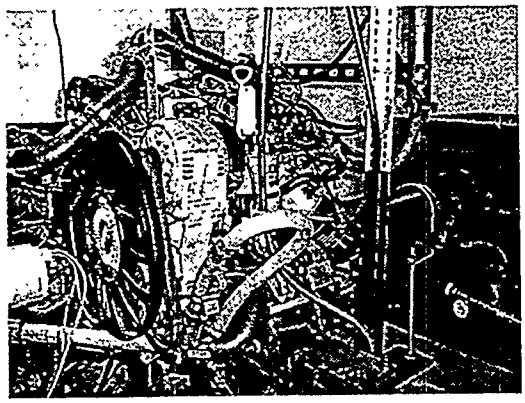
Specific NOx Emissions



Total Particulate Emissions

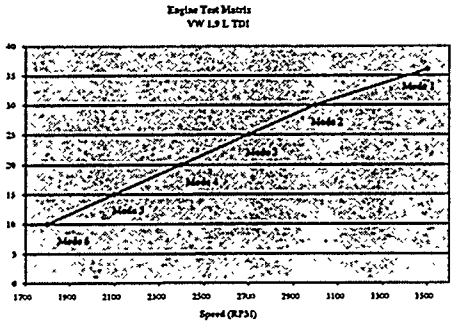


VW 1.9L TDI Turbo Diesel Engine
Multi-Cylinder Engine Test Cell

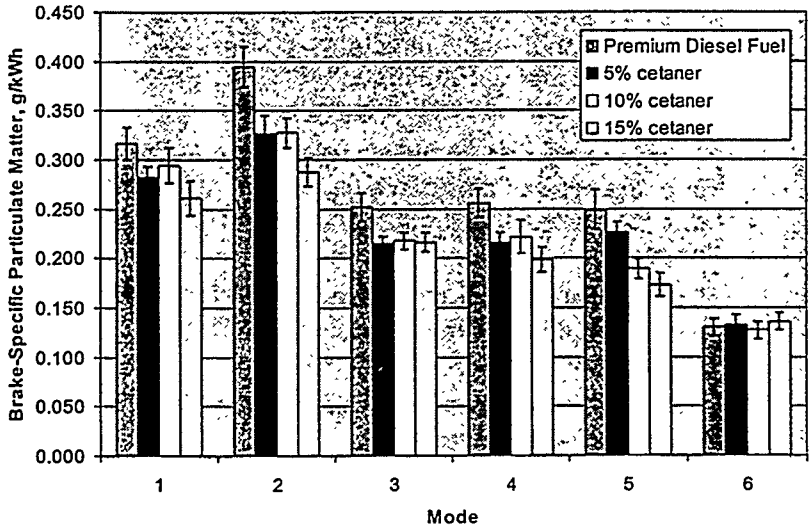


TDI Testing Protocol

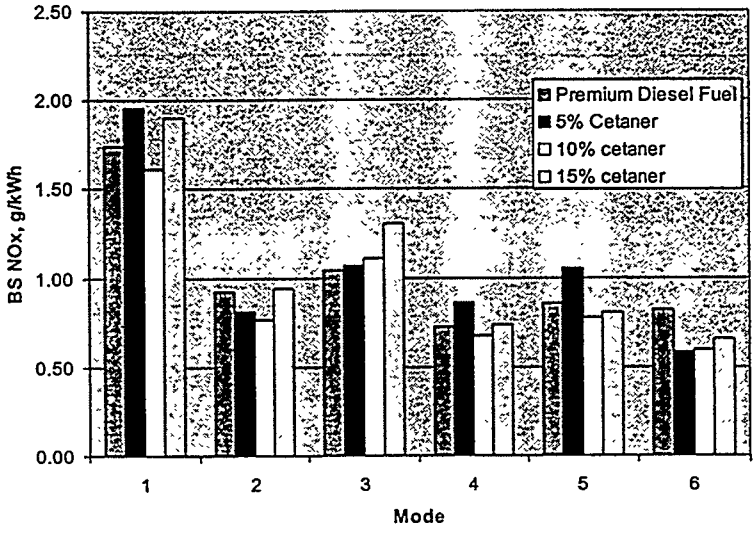
	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
Speed (RPM)	3500	3000	2700	2400	2100	1800
% rated speed	100%	85.7%	75%	68.6%	60%	51.4%
Power (hp)	36	30	25	20	15	10
% rated Power	85.6%	71.4%	59.5%	47.6%	35.7%	23.8%
Torque (ft-lb)	55.70	52.52	48.63	43.71	37.51	30.89
Torque (mV)	138.2	130.3	120.7	108.6	93.1	76.7



Total Brake-Specific Particulate Emissions, g/kWhr



Brake-Specific NOx Emissions, g/kWhr



Conclusions

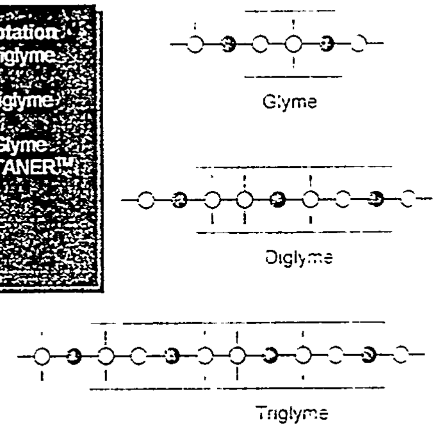
- Oxygenated blends can achieve up to ~30% particulate matter reduction in diesel fuels when blended at a level of 4% oxygen content
- There are significant differences between the effectiveness of different oxygenates - presumably due to molecular structure and accessibility to oxygen
- Specific Fuel Consumption increased for all the oxygenated fuel blends, but Specific Energy Consumption remained unchanged
- CETANER™ has demonstrable performance benefits over other oxygenated fuels

Impact of Molecular Structure

all oxygenates are not the same

Oxygenate Blended	Structure	Notation
Triethylene glycol dimethyl ether	$CH_3O(C_2H_4O)_3CH_3$	Triglyme
Diethylene glycol dimethyl ether	$CH_3O(C_2H_4O)_2CH_3$	Diglyme
1,2-dimethoxyethane	$CH_3O(C_2H_4O)_1CH_3$	Glyme
CETANER™		CETANER™
20% Glyme	$CH_3OCH_2CH_2OCH_3$	
80% Diglyme	$CH_3O(C_2H_4O)_2CH_3$	

* CETANER™ formulation for latest tests



Future Work

- Complete VW TDI testing sequence
- Monitor combustion and heat release rates using Kistler pressure probe and [illegible] encoder in the Yanmar single-cylinder engine
- Move to laboratory and field tests in Cummins B[illegible] turbodiesel engine

Reformulated Clean Burning Diesel Demonstration Program

Funded by
the South Coast Air Quality Management District

- Determine Engine Combustion and Emissions for Blends of Diesel Fuel and Cetaner in Medium-Heavy Duty Engine Application
- Develop an Operational Database and Optimized Engine Parameters for Use of Cetaner in Medium-Heavy Duty Engine Applications
- Verification of Laboratory Engine Performance Data Through On-Road Field Testing

- The Energy Institute
- Air Products and Chemicals, Inc.
- USA PRO
- University of California - Berkeley
- Cummins Engine Co.
- PACCAR (Kenworth-Peterbilt)

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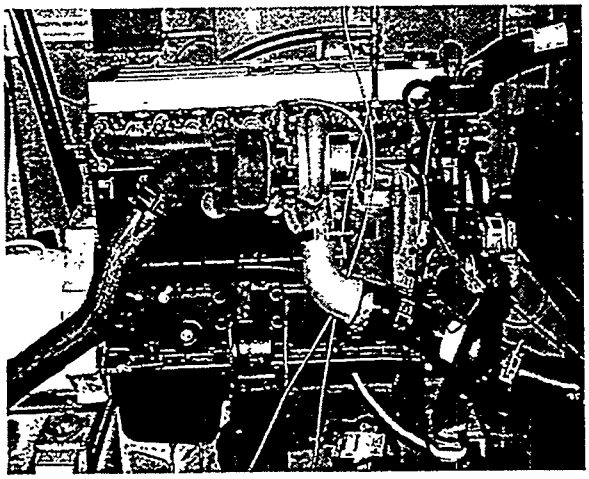
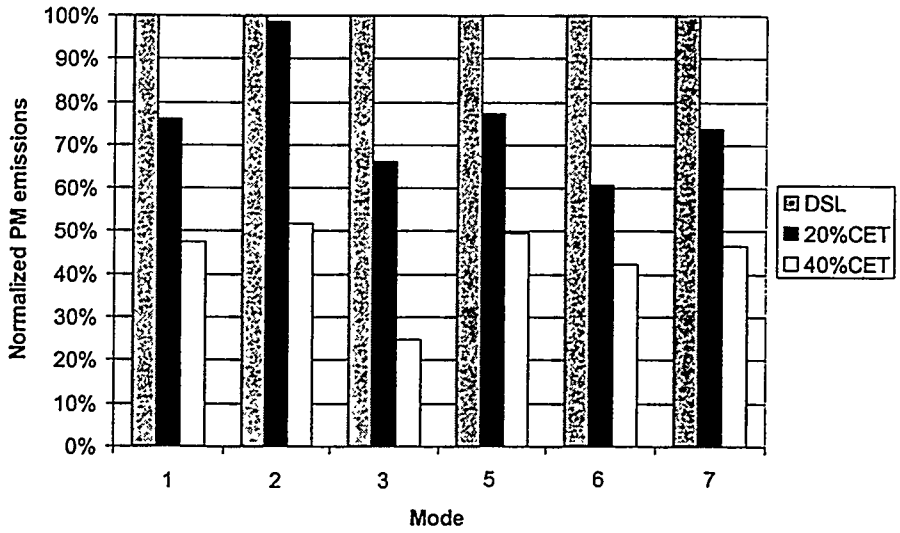
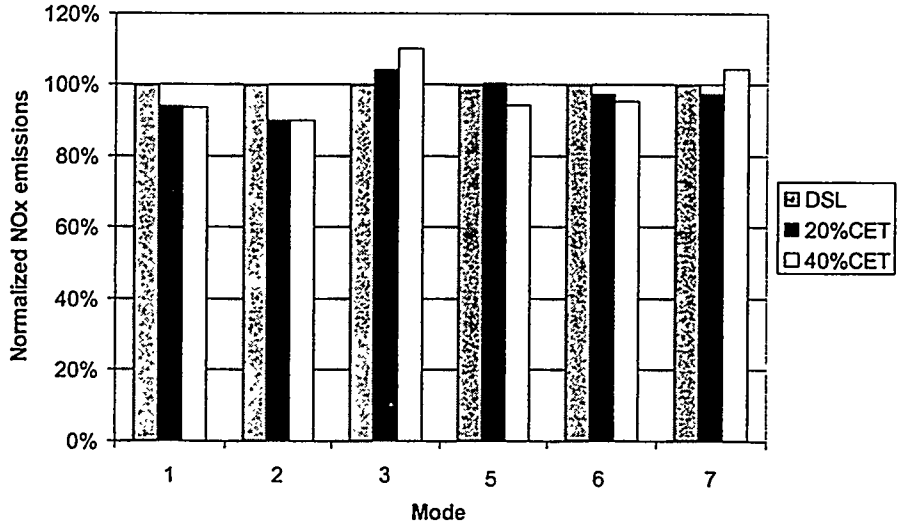
Cummins 5.9L V-8 Turbodiesel in the 250 hp Test Cell



PM COMPARISON BY MODE



NOx COMPARISON BY MODE



Current Status

- Cummins B5.9 Engine Installed in the Test Cell and has been Operated on the AVL 8-Mode Test
- Cummins is Machining the Head for Pressure Probe Installation
- UC-Berkeley Testing is Ongoing
- Dodge Ram Truck Has Been Received by USA PRO from Chrysler Test Fleet for 18 Month Period
- Field Emissions Measurement Strategy Under Development with Assistance from Clean Air Technology and R&P Co.
- US EPA Supporting Collaborative Work with Our Field Emissions System

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Development of a Dimethyl Ether (DME)-Fueled Shuttle Bus Demonstration Project

A Project Sponsored by the Pennsylvania Department of Environmental Protection
with
Additional Support from the Federal Energy Technology Center

Air Products and Chemicals, Inc.
The Pennsylvania Transportation Institute
and
The Energy Institute at Penn State

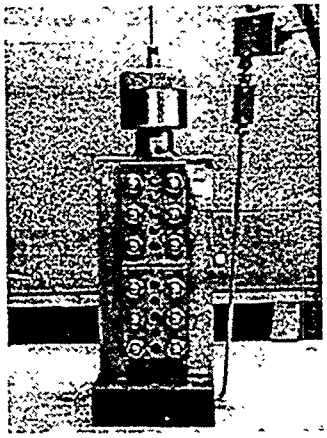
Objectives

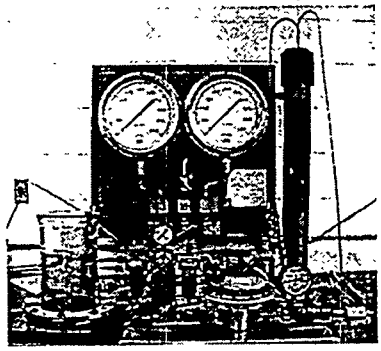
- Determine the Emissions and Combustion Performance for DME-Diesel Fuel Blends
- Determine Injection System Durability Criteria for Use of DME-Diesel Blends
- Determine the Viscosity and Bulk Modulus of DME-Diesel Blends
- Develop Protocol for DME Fueling Based on Fuel Blends
- Detailed Speciation of Particulate Matter
  - → Said to be smokeless, but perhaps not under all conditions
- How Much DME is Optimal?
- Demonstrate DME-Diesel Fueling in a Campus Shuttle and Operate the Shuttle on DME-Diesel

Research Plan
Blending and Additives

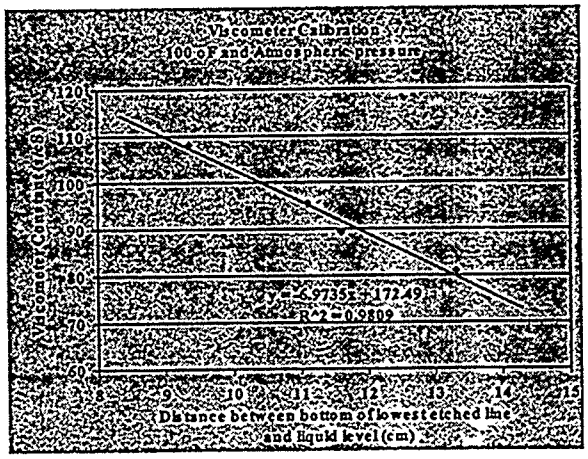
- Combine Lubricity Studies with Engine Combustion Studies
- Prior to Running DME/Diesel Blends, Examine Their Phase Behavior, Viscosity, Compressibility and Wear Rate Characteristics
- Protect Fuel Injectors and Pump by Anticipating Fuel Mixtures that will Lead to Excessive Wear
- Examine Several Lubricity Additives: Lubrizol, Ethyl and Methyl Soyate

High Pressure Viscometer

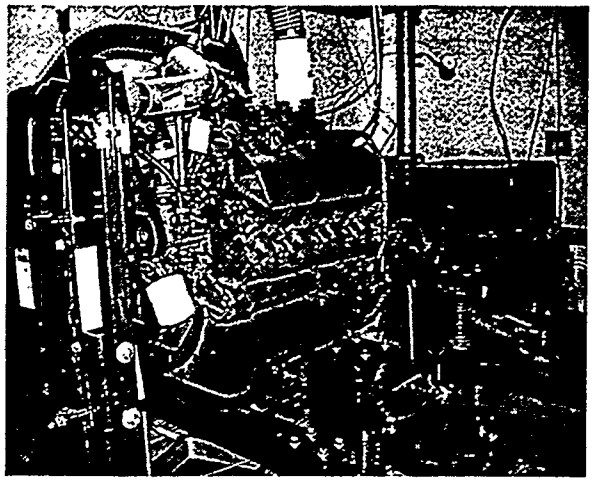




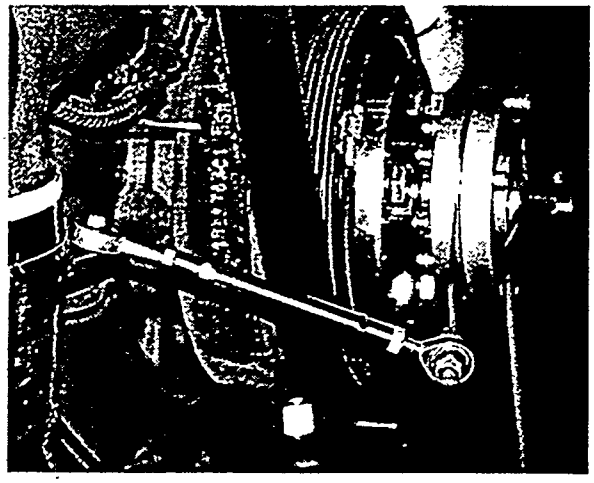
High Pressure Viscometer
Initial Determination of Viscometer Constant



Navistar T444E V-8 Turbodiesel in the 400 hp Test Cell



CAM Encoder Mounted on Navistar T444E V-8 Turbodiesel



Current Status

- Navistar Engine Acquired and Installed in the Test Cell
- Engine Dressed with Help from Allegheny Truck and Navistar
- Pressure Sensor and Crank Angle Marker Operational
- High Pressure Viscometer Operational for Measurements of Viscosity and Bulk Modulus of DME-Diesel Blends
- Penn State Fleet Services Has Acquired the Champion "Defender" Shuttle Bus
- PTI has Performed Emissions, Performance and Efficiency Tests on the Shuttle Bus on Diesel Fuel
- DME/Diesel Fuel Delivery System Under Construction

Acknowledgement

- Peter Tijm, Fran Waller, Bob Quinn of Air Products and the Strategic Alliance Committee
- Mike Nowak and John Winslow of DoE/FETC
- Susan Summers of PA/DEP
- Fred Minassian and Cindy Sullivan of SCAQMD
- Pranab Das, X. Gui, David Schuh and Len Stanley of Navistar
- Vinod Duggal and Peter Woon of Cummins
- Rafal Sobotowski of BP Oil Company (now with Cummins Engine Company)
- Gib Jersey of Mobil Oil Company
- Tony Zarger of GM Powertrain
- Bill Buscher formerly of Texaco Inc.
- Allen Aradi of Ethyl Additives, Inc.
- John Lueszler, DuPont