# NREL's Alternative Fuel Transit Bus Evaluation Program

Paul Norton

National Renewable Energy Laboratory
Golden, Colorado

Windsor Workshop on Alternative Fuels
Toronto, Canada
June 5, 1996

Center for Transportation Technologies and Systems

# Sponsored by the U.S. Department of Energy
# Office of Transportation Technologies

# Participants

- Battelle: Data collection and analysis
- University of Missouri: Data collection and analysis
- West Virginia University: Emissions testing
- Transit Sites
  - Bi-State Development Agency, St. Louis, MO
  - GP Transit, Peoria, IL
  - Houston Metro, Houston, TX
  - Metro-Dade Transit Authority (MDTA), Miami, FL
  - Metropolitan Council of Transit Operations (MCTO), Minneapolis/St. Paul, MN
  - Pierce Transit, Tacoma, WA
  - Triboro Coach Company (NYC DOT), New York, NY
  - Tri Met, Portland, OR

# Presentation Outline

- Purpose of Program
- Program design
- Results
- Future direction

# Purpose of Program

Perform unbiased, comprehensive evaluation of alternative fuels compared to diesel fuel in transit bus industry

- Reliability
- Cost
- Emissions
- Infrastructure/facility issues

# Purpose of Program *(continued)*

Alternative fuels

- E95/E93
- M100
- CNG
- LNG
- Biodiesel
- LPG (future)

# Program Design Targets

- OEM production engines only
- Ten test buses of each technology, split between two sites
- Control and test buses have identical vehicle specifications, except for the alternative fuel
- Routes of control and test buses are similar or buses are randomly dispatched
- Cooperation of transit agencies

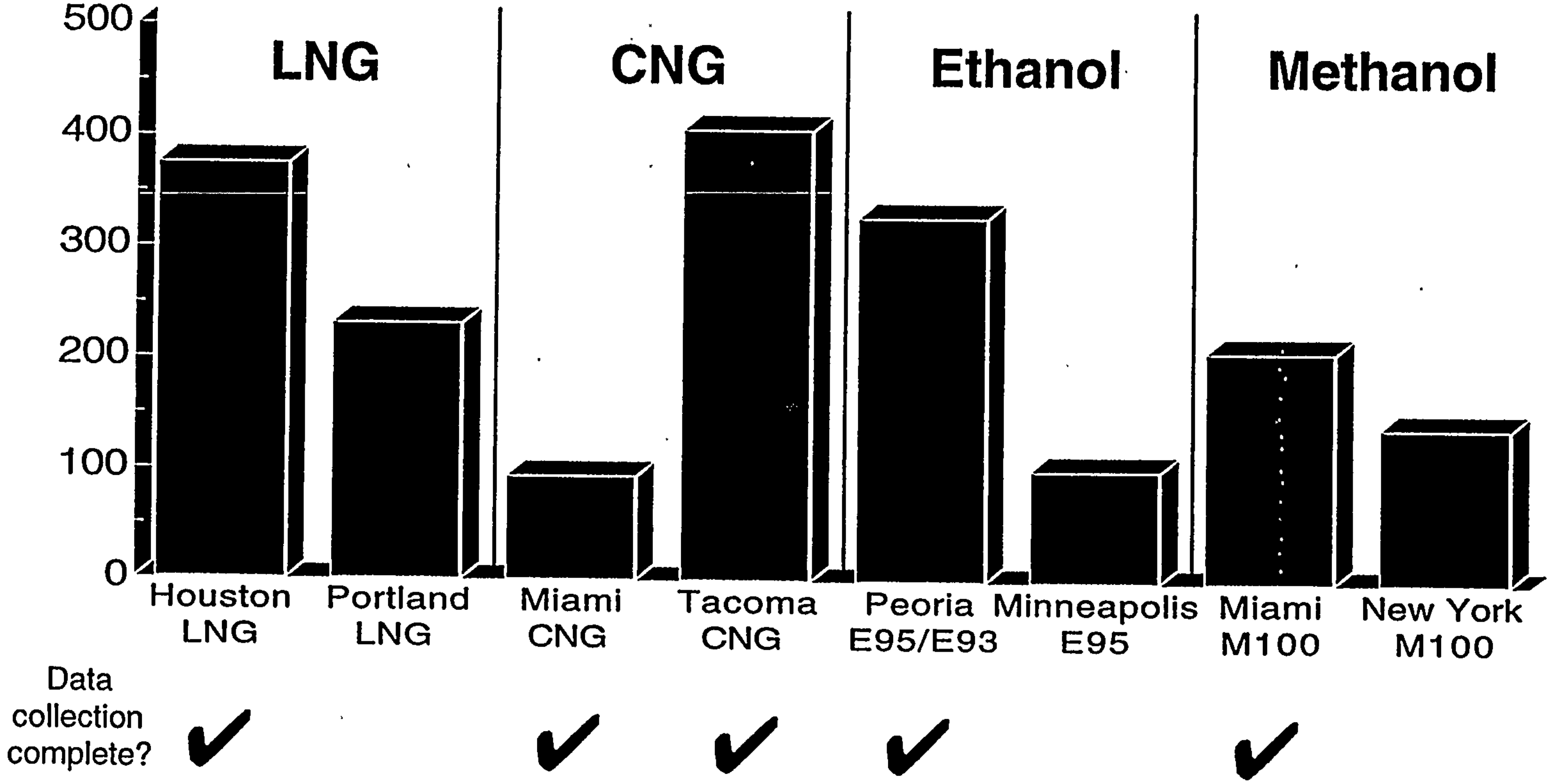
# Program Design

| Agency | Engine | Technology | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | M100 | E95 | LNG PING | LNG Si | CNG Si | BD-20 | DSL w/ Trap | DSL CNTRL | Total |
| Houston | DDC 6V92 | | | 10 | | | | | 5 | 15 |
| Portland | Cum L10 | | | | 8 | | | | 5 | 13 |
| Miami | DDC 6V92 | 5 | | | | | | | 5 | 10 |
| | Cum L10 | | | | | 5 | | 5 | 10 | 20 |
| Minneapolis | DDC 6V92 | | 5 | | | | | 5 | 5 | 15 |
| Peoria | DDC 6V92 | | 5 | | | | | 3 | | 8 |
| Tacoma | Cum L10 | | | | | 5 | | | 5 | 10 |
| New York (Triboro) | DDC 6V92/<br>Series 50 | 5 | | | | | | | 5 | 5<br>5 |
| St. Louis | DDC 6V92 | | | | | | 5 | | 5 | 10 |
| | Total | 10 | 10 | 10 | 8 | 10 | 5 | 13 | 45 | 111 |

# Data Being Recorded

- 18 months of data collection per site
- Fuel and oil additions
- All parts replaced/work done, except warranty
  - Parts replaced coded using ATA coding
  - Type of work done coded
  - Parts cost and labor hours
- Chassis dynamometer emissions (West Virginia University)

# Total Mileage on Alternative Fuel Buses
(thousands of miles)



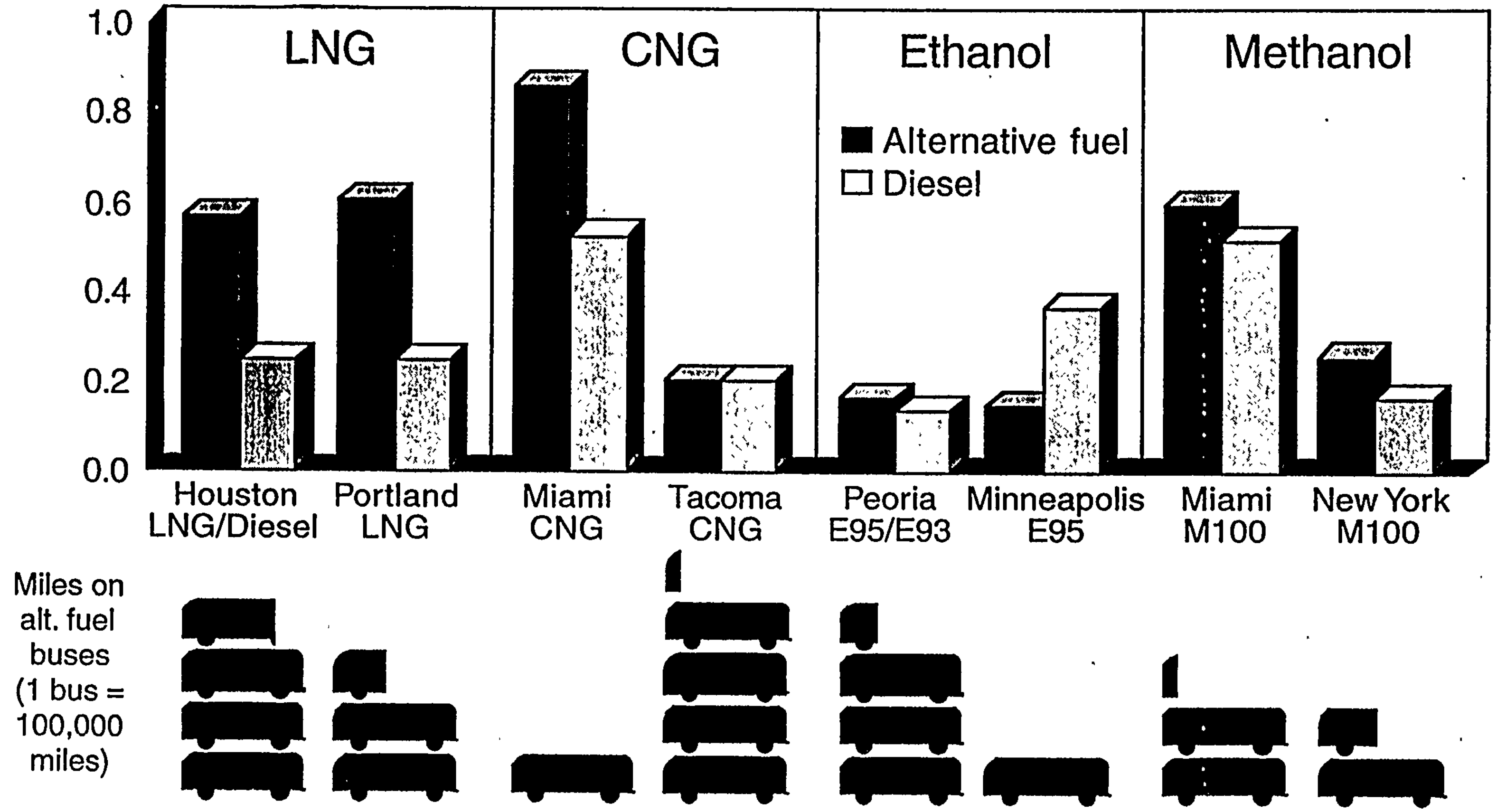
*Center for Transportation Technologies and Systems*

# Results

- Reliability
- Operating Costs
- Emissions

# Reliability

# Vehicle Reliability—Road Calls/1000 Miles

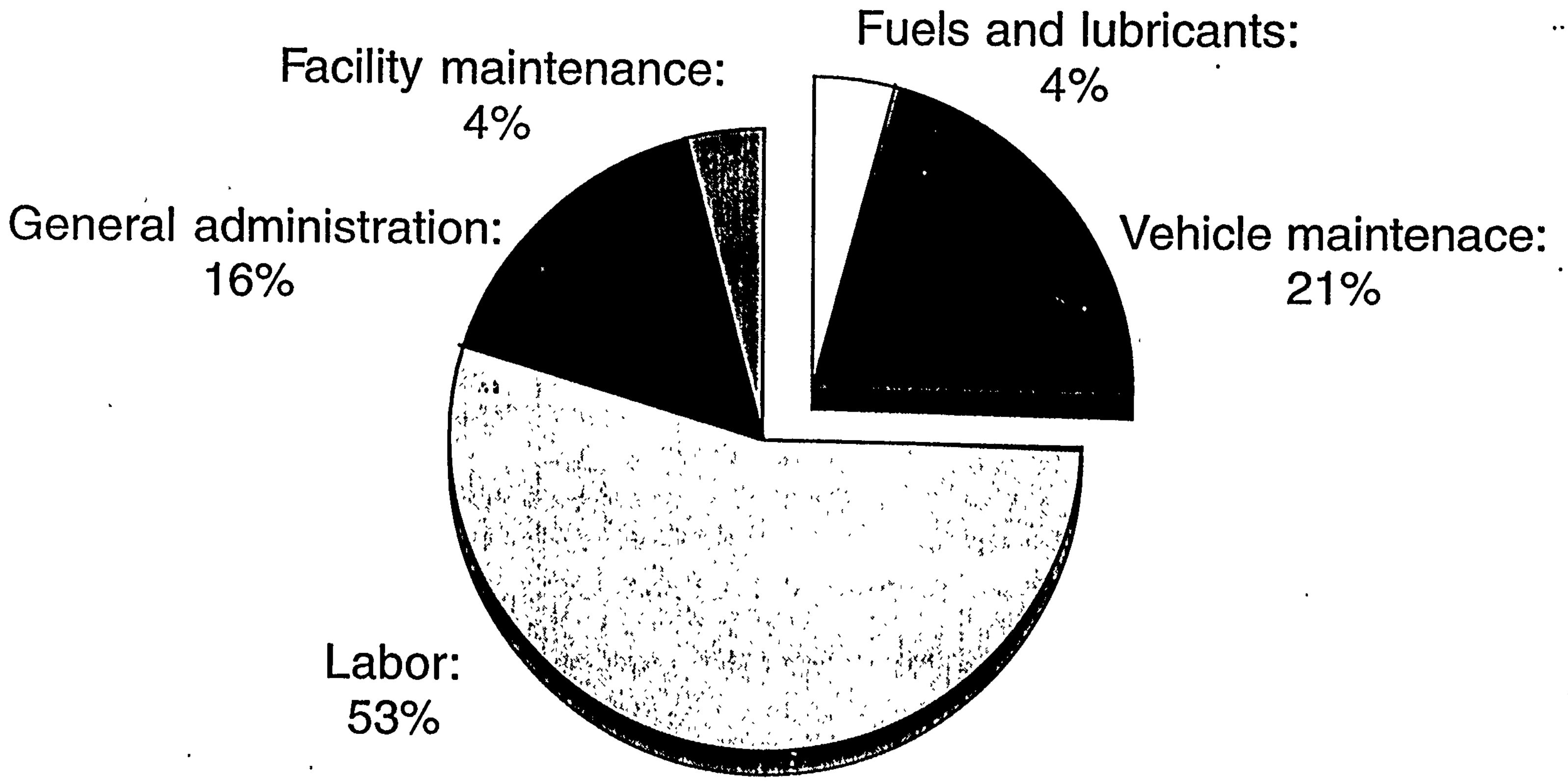


SQP4-B119315

*Center for Transportation Technologies and Systems*

# Operating Costs

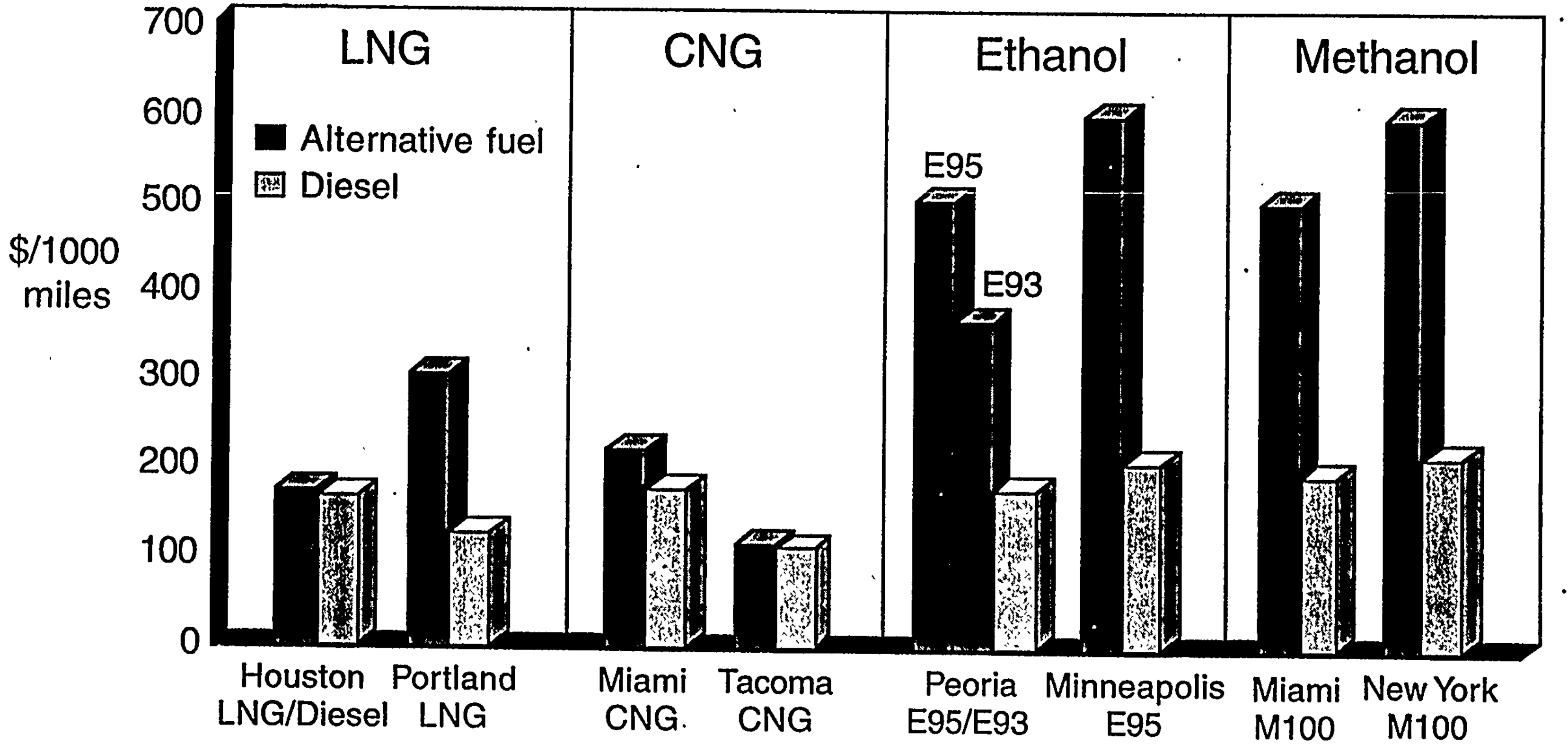
# Cost Breakdown for Transit Bus Operations



SQP4-B119317

*Center for Transportation Technologies and Systems*

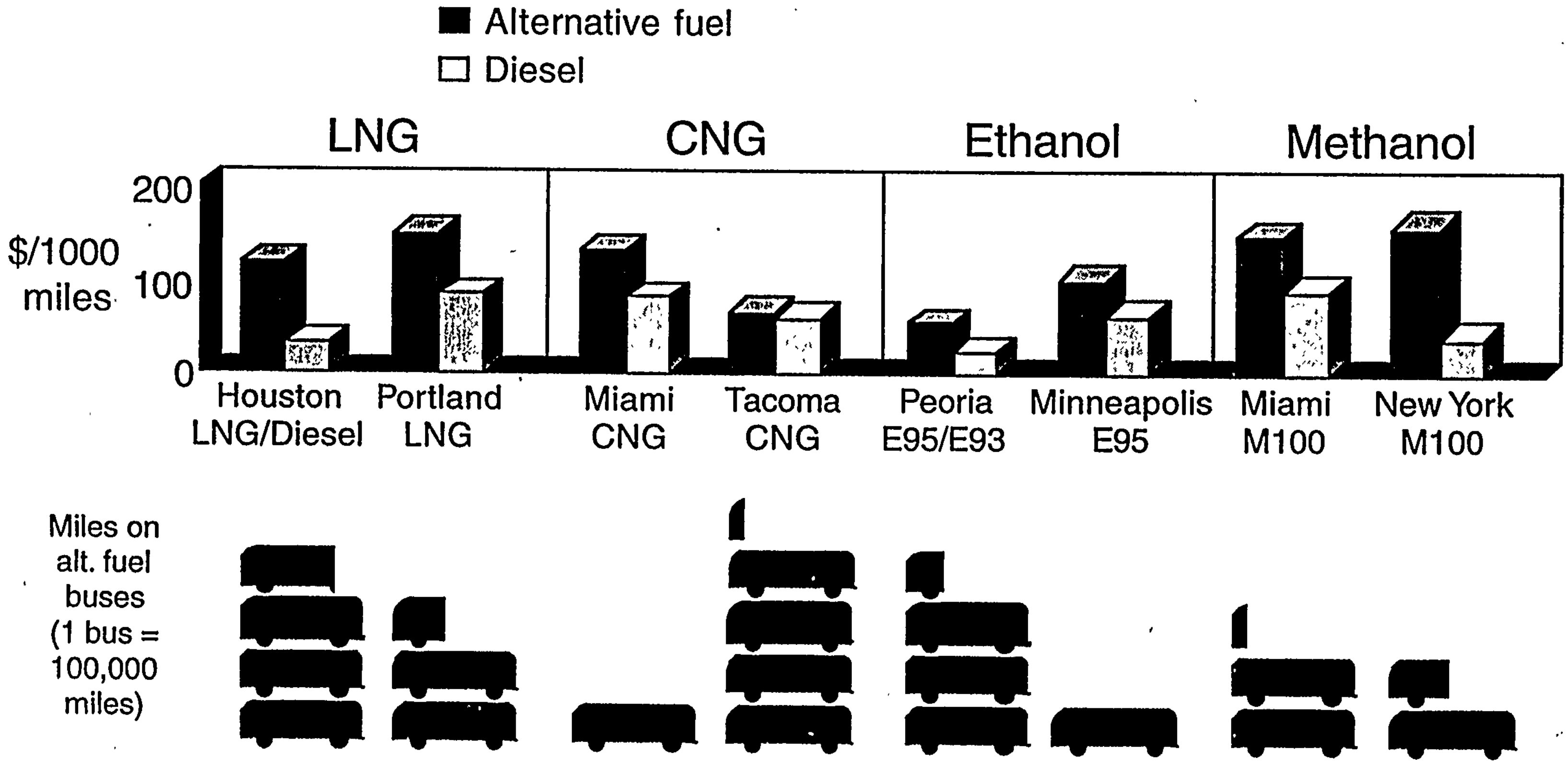
# Fuel Costs/1000 miles



SQP4-B119318

*Center for Transportation Technologies and Systems*

# Maintenance Costs/1000 Miles
# (Alternative Fuel-Affected Systems Only)



SQP4-B119319

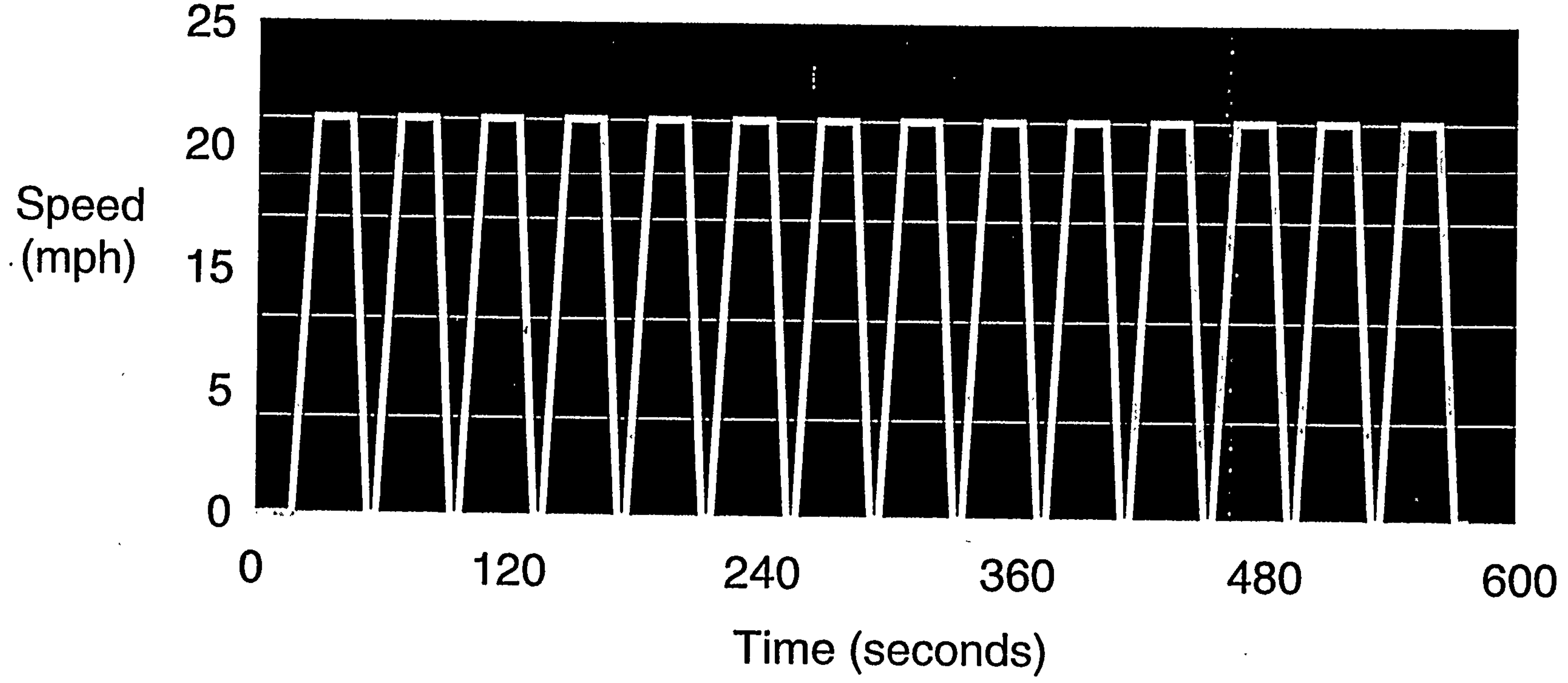
*Center for Transportation Technologies and Systems*

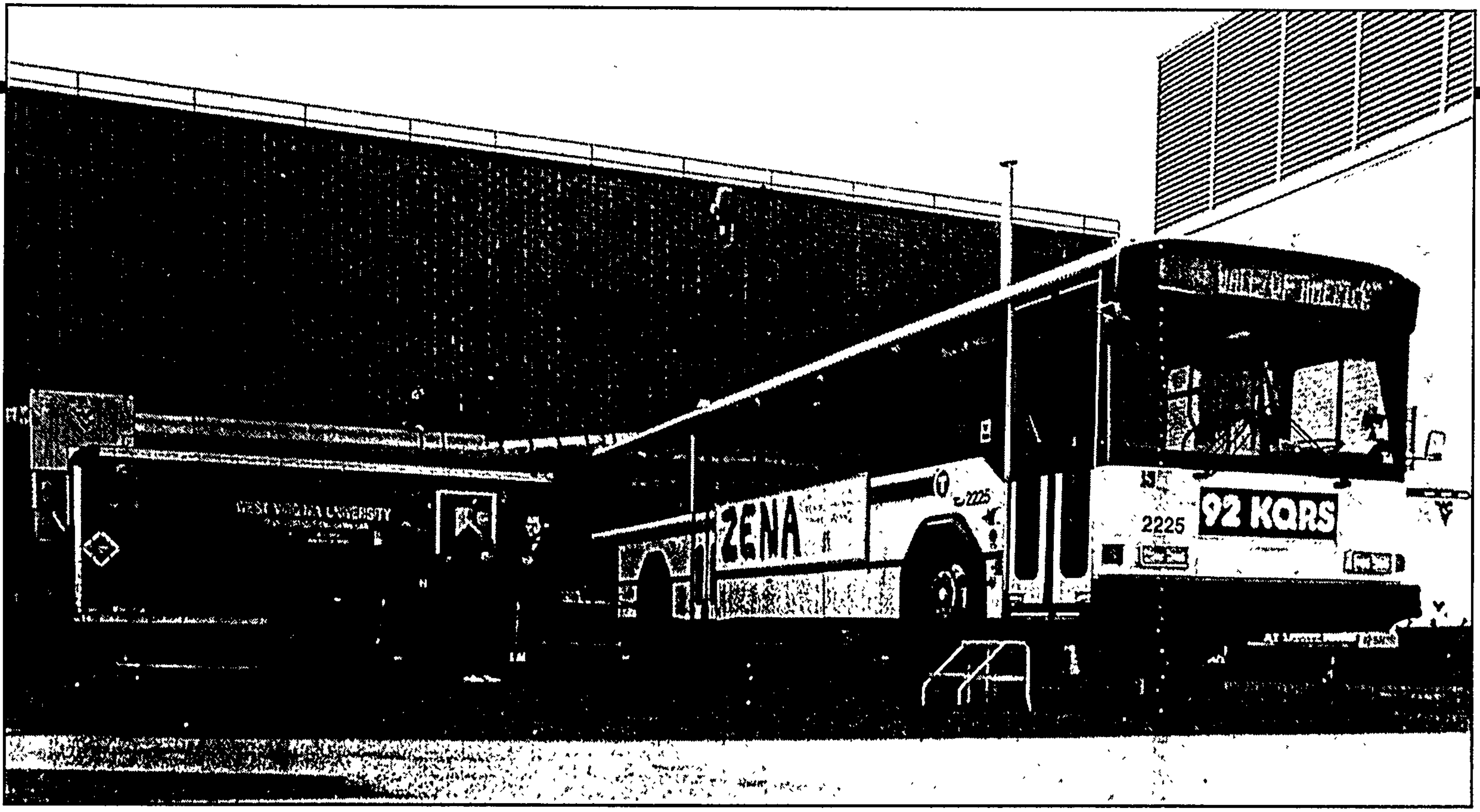
# Emissions Results

# Emissions Test Procedures

- West Virginia University transportable **chassis** dynamometer
- Central Business District (CBD) test cycle
- Tested annually at transit site

# Chassis Dynamometer Test Cycle



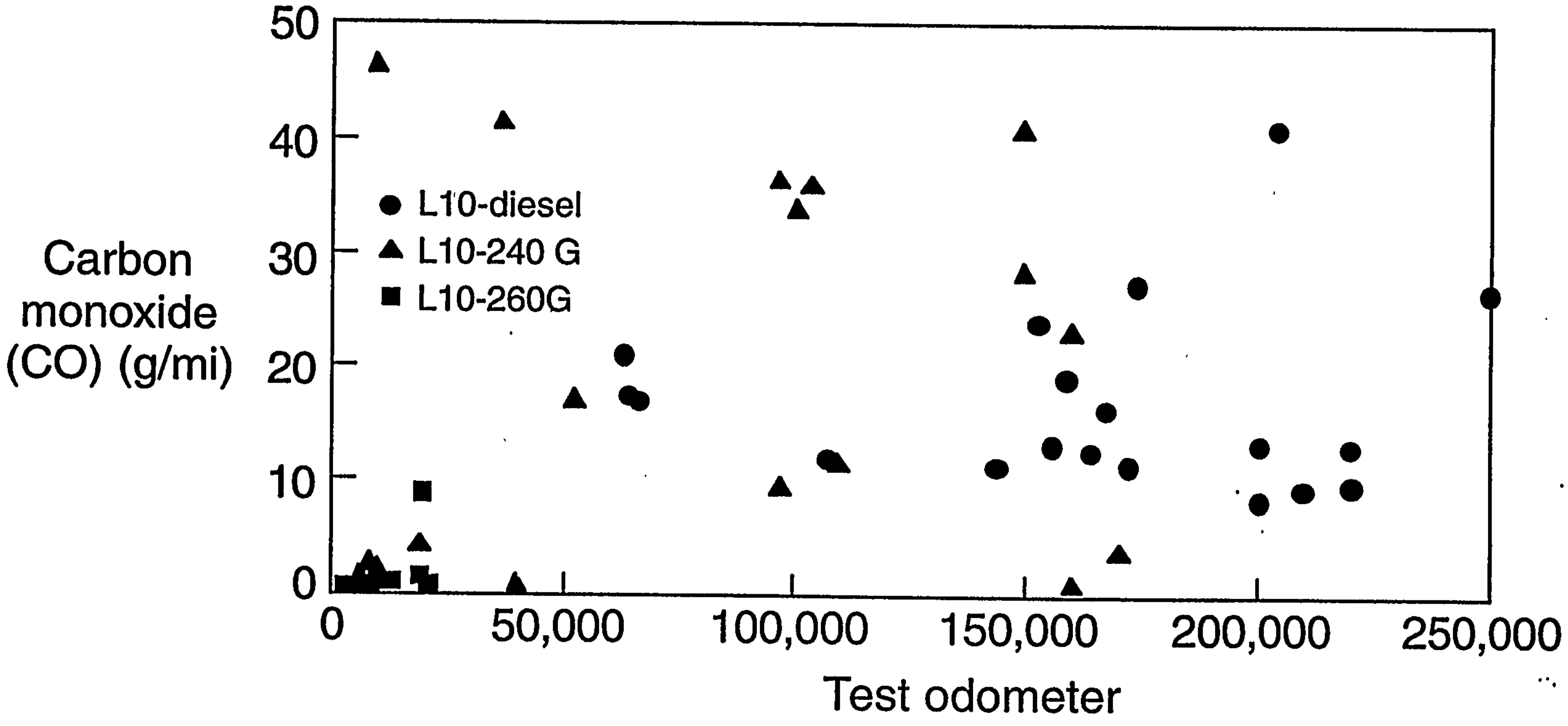


*Center for Transportation Technologies and Systems*

# Emissions Test Results

- Unexpected chassis dynamometer results compared with engine dynamometer data
- Early generation alternative fuel buses have greater variability than diesel buses
- Working with OEMs to identify causes

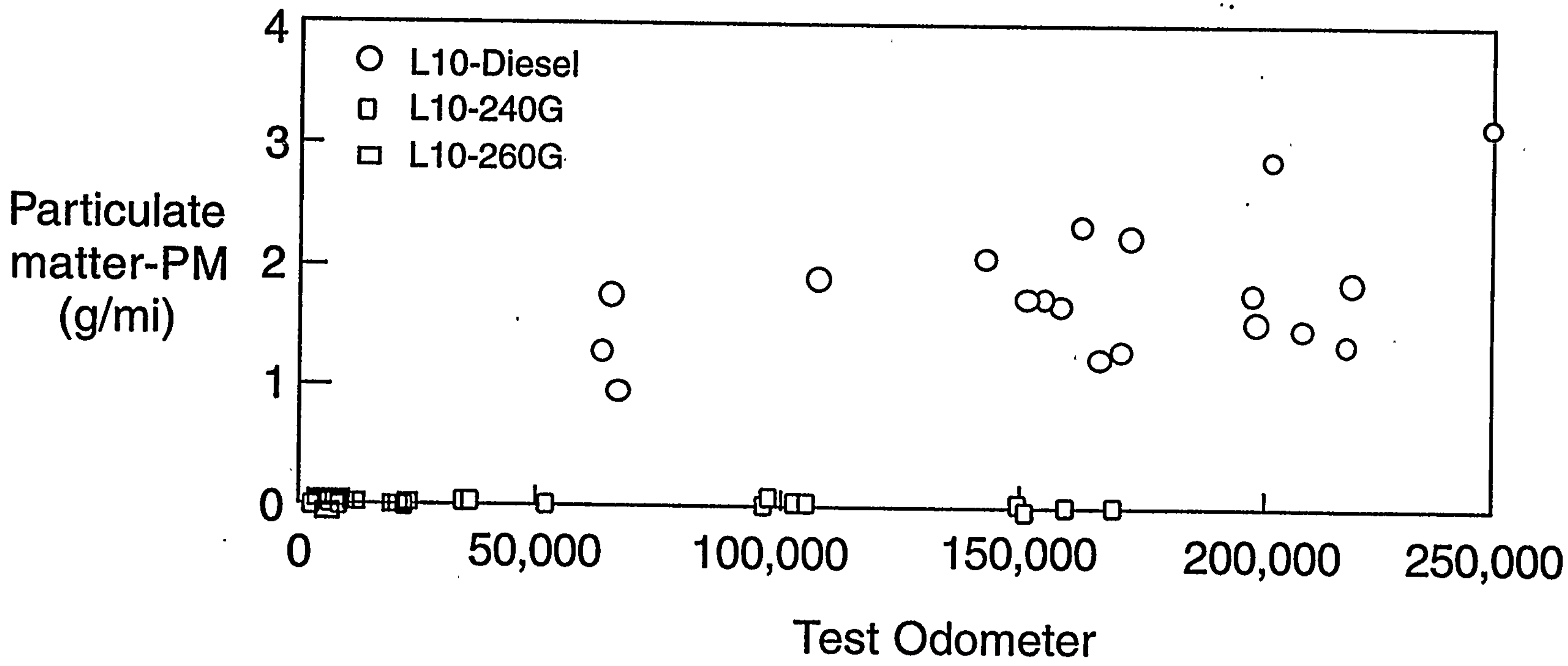
# Sample Emissions Results—
## Carbon Monoxide from CNG and Diesel Buses



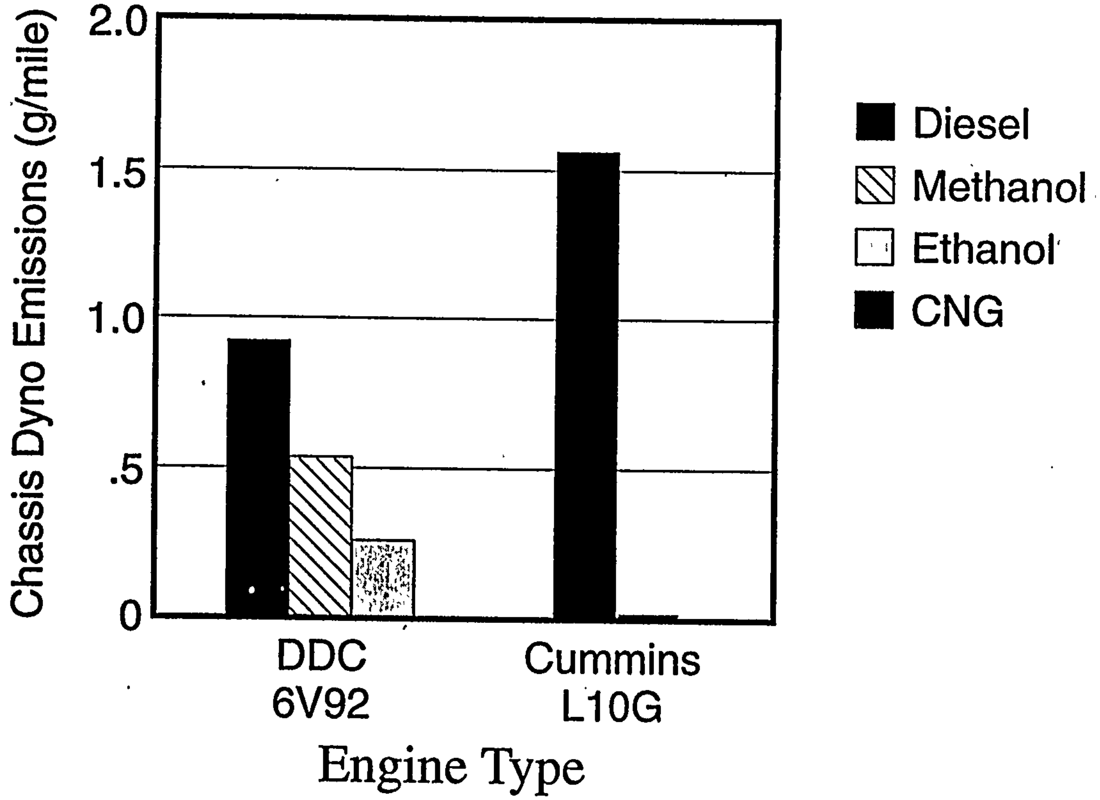
SQP4-B119325

*Center for Transportation Technologies and Systems*

# Sample Emissions Results—
## Particulate Matter from CNG and Diesel Buses



# Average Particulate Matter Emissions



SQP4-B119326

*Center for Transportation Technologies and Systems*

# Emissions Test Results—Conclusions

- Particulate matter emissions lower than diesel
- Alternative fuels have the potential to reduce other exhaust emissions
- Other factors are also very important
  - Technology level
  - Vehicle maintenance

# Some Program Conclusions

- Bus reliability (road calls) generally comparable with diesel except for LNG sites
- Bus operating costs are driven by fuel costs
  - Operating costs comparable for CNG
  - Operating costs high for alcohols
- Bus capital costs high for alcohols
  - High for CNG, low for alcohols
- Particulate matter emissions are lower than diesel
- More work needed on emissions

# Future Plans

- Wrap up current sites by July 1996
- Produce Final Report
- Produce more detailed case studies of some sites
- Begin new study with the next generation of technology in 1997

# More Information

- SAE Paper has more results than this presentation
- Final Report expected this summer
  - Call the National Alternative Fuels Hotline
    ***1-800-423-1DOE***
- Visit our Web Site
  ***http://www.afdc.doe.gov***

# Troubleshooting High Emissions from In-Service Alternative Fueled Buses

Nigel N. Clark, Wenguang Wang, Donald W. Lyons, Mridul Gautam, and Reda M. Bata
Department of Mechanical and Aerospace Engineering
West Virginia University
Morgantown, WV 26506-6106
USA
Telephone No. (304)-293-3111
Fax No. (304)-293-2582

## ABSTRACT

The West Virginia University Transportable Heavy Duty Emissions Testing Laboratory has gathered emissions data from transit bus fleets operating on alternative and conventional fuels, through funding from the U.S. Department of Energy. Historically, data have shown that transit bus emissions, measured using the Central Business District cycle on the chassis dynamometer, are more variable for alternative fuels than for conventional fuels. For example, buses with Cummins L-10 natural gas engines of various model years show $NO_x$ to have a range of 7 to 50 g/mile, CO from 0.01 to 68 g/mile and HC of 0.02 to 105 g/mile, whereas their diesel counterparts have $NO_x$ values of 18 to 50 g/mile, CO of 0.01 to 40 g/mile and total HC of 0.01 to 5 g/mile. Such emissions variations have been caused primarily by wandering fuel/air ratios, and also by dysfunctional spark systems and catalysts. A fleet of natural gas buses in Tacoma, Washington was tested, then subjected to appropriate fuel/air ratio adjustment and then re-tested. As an example, a Cummins L-10 powered natural gas bus as received for testing had high CO (40.7 g/mile) and $NO_x$ (46.1 g/mile) emissions, and these were not changed significantly by a re-setting of the boost and a setting of exhaust oxygen content at idle and stall. However, after replacing the mixer and regulators, and re-setting the boost and fueling, CO was reduced to 1.4 g/mile and $NO_x$ to 25.3 g/mile. A second bus had a similar repair and re-test history. Similarly, ethanol fueled Detroit Diesel 6V92 buses in Peoria, Illinois were subject to a test, repair and re-test program, which included replacement of injectors and catalytic converters. In the case of two buses in Peoria, installation of new catalytic converters decreased CO and HC emissions significantly, but raised $NO_x$ emissions, although $NO_x$ remained well below typical diesel values. Replacing injectors served only to decrease hydrocarbon emissions on one bus. A broad conclusion is that alternative fuels are able to offer emissions advantages over diesel, but only if the engines are properly maintained.

## Introduction

Major cities find themselves under pressure to reduce mobile source emissions to comply with Clean Air Act requirements. In consequence many transit buses are now being operated with alternative fuel engines which are seen to offer emissions reduction potential. Working with the United States Department of Energy, Office of Transportation Technologies, West Virginia University has designed, constructed and now operates two Transportable Heavy Duty Vehicle Emissions Testing Laboratories, which gather emissions data from alternative fuel trucks and buses, together with diesel control vehicles, across the nation. Details of these activities have been presented by Chandler et al. (1996).

Data from the first two years of operation have shown that the variation in emissions from alternative fuel vehicles is greater than that for diesel vehicles, as illustrated in Figure 1 (from Clark et al., 1995a) which shows that the range of emissions from full size transit buses powered by Cummins L-10 natural gas lean burn spark ignited engines and conventional Cummins L-10 diesel engines. Maintenance and adjustment issues arose as a concern for alternative fuel engines and in consequence West Virginia University embarked on a "test, maintain and re-test" compaign on natural gas powered buses in Tacoma, Washington and on ethanol powered Detroit Diesel 6V92 buses in Peoria, Illinois.

## The Transportable Laboratories

The Transportable Laboratories were constructed to satisfy the need to gather data on emissions from heavy duty vehicles without the need to remove engines from the vehicles for testing. The laboratories are transportable to permit testing at the site of bus operation and to ensure that tested vehicles were out of service for as short a time as possible. Several papers (Wang et al., 1993; Bata et al., 1996 and Clark et al., 1995b) have already presented the design of the first of the two laboratories as well as data from testing vehicles fueled by natural gas, methanol and diesel.

The laboratory facility arrives on the test site pulled on two trailers, one being a box trailer containing equipment for emissions measurement, data acquisition and control, and the other, a flat bed semi-trailer carrying the power absorber unit. The flat bed is lowered to the ground to provide a chassis dynamometer platform.

The vehicle to be tested is driven onto the flat bed and the wheels of the vehicle are positioned on rollers, set in the bed. The outer wheels of the dual wheel set on each side of the vehicle are connected to the drive shafts of the dynamometer units located on each side of the vehicle. Each dynamometer unit consists of speed increasing gearboxes with a power absorber and a flywheel set. The flywheel sets consist of a series of selectable discs to allow simulation of vehicle inertia. During the test cycle, torque cells and speed transducers in the power absorber drive train measure the actual vehicle load and speed. The buses tested in this program were exercised through the Central Business District speed versus time cycle, described by SAE recommended practice J1376. Bus test weights represented curb weight plus the weight of the driver and a half of the passenger load.

The full exhaust from the tail pipe of the test vehicle was ducted to a 45 cm diameter dilution tunnel on top of the emissions trailer. The exhaust was mixed with dilution air and the flow was controlled using a blower with critical flow venturis. Sampling probes sent diluted exhaust to a number of different gas analysis instruments, via heated lines. Levels of carbon dioxide ($CO_2$), carbon monoxide (CO), oxides of nitrogen ($NO_x$) and hydrocarbons (HC) were measured continuously. A bulk measurement of particulate matter (PM) was obtained using 70 mm filters and levels of alcohol and aldehydes were determined using impingers and cartridges respectively.

## Engine Details

The vehicles tested were all full-size transit buses, as shown in Table 1. A brief discussion of the Cummins natural gas and Detroit Diesel ethanol engines follows.

The natural gas powered Cummins 10 liter engines were spark ignited, turbocharged and intercooled with a compression ratio of 10.5 and were equipped with catalytic converters. Air/fuel ratio on these engines is controlled by a low-pressure mechanical mixer. Early versions of this engine (until August 1992), designated by part number CPL-1379, operated under less lean burn conditions, with about 7.6% oxygen in the exhaust at the rated power, but were preset to operate only slightly lean at idle. These engines were rated at 240 hp and 750 ft-lb of torque. These early engines were not required to be certified for emissions and were produced to demonstrate the practicability of operating lean-burn, heavy duty natural gas engines rather that achieve optimally low emissions levels. Later versions (CPL-1653 and CPL-1654) were rated at 240 hp/850 ft-lb (August 1992-July 1994) and operated at leaner conditions with more boost (8.5% exhaust oxygen at rated power, 2.5% at idle). More recently engines rated at 260 hp with electronic wastegate control have been produced (CPL-1858 and CPL-1937). Ignition timing was also changed between early and late models. The later units were all certified to California Air Resources Board standards. The three engines used in this study were CPL-1379. Experience has shown that CO emissions on CPL-1379 engines may be reduced through adjustment of idle exhaust gas oxygen content in tuning the engine.

Resistance to auto-ignition and high heat of vaporization make alcohol fuels difficult for compression ignition applications. In addition, the low heating value of alcohol fuels demands that a greater volume of fuel must be injected into the cylinder in each cycle than for diesel. Other problems that must be addressed are related to poor fuel lubricity, the changed heat release rates relative to diesel and the presence of corrosive products of combustion in the cylinder. Despite these obstacles, Detroit Diesel Corporation (DDC) has manufactured an ethanol compression ignition engine based on the 6V92 diesel engine. The design uses the two stroke cycle, with exhaust valves in the head and is supercharged and turbocharged. Injection is managed electronically and the bus engines are rated at 253 hp. After treatment catalytic converters are used to oxidize emissions.

Early versions of the engines operating on methanol had a compression ratio of 19 with glow plug support at light load, while models currently in use employ a compression ratio of 23 and do not need ignition support during normal operation. Use of DDEC electronic engine control unit permits software changes to injection timing, fueling and boost pressure through bypass control. Review of previous alcohol fueled heavy duty vehicle chassis data has been provided by Clark et al. (1996).

## Natural Gas Buses

Figures 2, 3 and 4 show the emissions measured and actions taken on three buses in Tacoma, Washington. It is evident from the work reported by Sharp et al. (1993) and from prior laboratory data (Clark et al., 1995a) that a cause of high CO emissions was either mixer wear or mixer maladjustment, since replacement of the mixer unit or re-shimming was required. The results offered a dramatic reduction of CO.

Three natural gas fueled buses have been considered in this paper. The first, PT-478, (see Figure 2) had been found to have high CO emissions (30.7 and 40.9 g/mile averages) in two tests the previous year, and had exhibited $NO_x$ emissions of 28.3 and 25.3 g/mile and total hydrocarbon emissions (both methane and higher hydrocarbons) of 9.7 and 8.7 g/mile at that time. When re-tested as a part of this study a year later, CO had dropped to 22.8 g/mile but $NO_x$ had risen to 44.3 g/mile (well above that expected for a diesel engine), whereas HC remained the same. Such variations may be due to fuel composition changes, interim adjustments or mixer wear. On this particular bus, a comprehensive adjustment of boost and richness reduced CO by a factor of 20, but did not affect $NO_x$ or HC, as shown in figure 2. This implies that idle richness was corrected, but that operation at load was still insufficiently lean, thus producing high $NO_x$.

On bus PT-480, as received (see figure 3), both CO and $NO_x$ were high. In this case adjustments to boost and exhaust oxygen failed to produce acceptable levels of CO and $NO_x$. However, replacement of the mixer unit brought emissions to a very low level of CO and a $NO_x$ level that ranked with diesel Cummins L-10 buses (Clark et al., 1995a).

For a third bus PT-481, as received (see figure 4), CO and $NO_x$ were also high, and a new mixer was fitted without attempting adjustment of the old mixer. CO and $NO_x$ levels were again substantially reduced. Figure 5 shows the continuous $NO_x$ emissions from bus PT-481. Such $NO_x$ emissions follow the power curve of the CBD cycle closely, and the reduction in emissions after the new mixer was fitted is obvious. CO emissions (see figure 6) are generally not positively correlated with power in CNG engines, but the decrease in emissions after mixer replacement is clear.

One may conclude that mixer wear is a factor that contributes to raised emissions in the Cummins L-10 powered CPL-1379 engines after milage accumulation. Also, it is essential to control idle air/fuel ratio precisely through maintenance to limit CO production and to control the air-fuel ratio and boost under load to limit $NO_x$ production. New engine designs employing lean oxygen sensors and feedback control will obviate some of these maintenance requirements.

## Ethanol Buses

In Peoria, Ill., two ethanol buses, GPT-1507E and GPT-1508E were tested. Figures 7 and 8 show the procedures followed and the emissions recorded. Tables 2, 3 and 4 show the boost settings discussed in Figures 7 and 8. Changes and modifications were implemented by Detroit Diesel personnel. Conclusions on GPT-1507E were as follows.

implemented by Detroit Diesel personnel. Conclusions on GPT-1507E were as follows. The bus as received, after 117,000 miles of use, had high CO emissions (38.3 g/mile) which were similar to values found in the previous year of testing (40.8 g/mile after 63,000 miles of use). Emissions of $NO_x$, at 13.9 g/mile, were below those typical of diesel 6V92 buses. Hydrocarbons, expressed as Organic Material Hydrocarbon Equivalent mass, were at 6.47 g/mile. Following the installation of a new catalytic converter, but not refitting the muffler, emissions of CO were reduced by a factor of 7, hydrocarbon levels were more than halved and particulate levels were reduced, but $NO_x$ was raised by 14 %. Refitting the muffler did not increase CO due to the increased back pressure, as might be expected, but rather reduced all emissions slightly. The vehicle was also operated with increased boost pressures as shown in Table 3, and this served to reduce particulate slightly but to raise $NO_x$ at the same time.

Vehicle 1508E as received had higher CO and hydrocarbons than 1507E, but lower $NO_x$. Before replacing the catalytic converter, 1508E was fitted with new titanium alloy fuel injectors, which served to reduce CO and hydrocarbons to lower levels, though still higher than values expected with a well functioning catalyst. Then boost values were changed on this vehicle (see table 3) as they had been on 1507E, and CO was reduced a little while $NO_x$ was raised. An intermediate boost (see table 4) was also used and, as expected, intermediate values of CO and $NO_x$ arose. The catalytic converter was then replaced and showed dramatic reductions in CO and hydrocarbons.

One may conclude in the case of these ethanol buses that a well-functioning catalytic converter is essential if CO is to be maintained below 10 g/mile and hydrocarbons below 5 g/mile. While there were modest effects on $NO_x$ and PM during the maintenance and re-setting, these values were already significantly below levels expected of diesel-fueled counterparts (Clark et al., 1996).

Of particular interest is the selective nature of the new catalyst. Emitted hydrocarbons consist of unburned ethanol, unburned petroleum adulterant, formaldehyde, acetaldehyde and some lighter lubricant derivatives. Analysis for formaldehyde, acetaldehyde and alcohol was performed on all tests. Before the catalyst was replaced, unburned ethanol constituted a third to a half of the hydrocarbon emissions, but after a new catalyst was installed, this value was about 10 %. Table 5 provides examples of this phenomenon. Similar selectivity for aldehydes was not observed. Formaldehyde emissions were decreased no more significantly than were the total hydrocarbon emissions by the new catalyst and acetaldehyde values varied too much from run to run to reach a confident opinion on the disposition of this species. Emission rates in table 5 are given in g/mile and represent the average of 2 to 5 runs on each bus configuration.

Hydrocarbon emissions are fuel dependent and some of the components of the emissions, such as formaldehyde and acetaldehyde, for alcohol fuels, do not register significantly with the Flame Ionization Detector (FID). Hence a more complete representation of the hydrocarbon emissions, for alcohol fuels, is made using the "Organic Material Hydrocarbon Equivalent" (OMHCE), which has been used in reporting ethanol vehicle exhaust hydrocarbons above.

$$\mathrm{OMHCE} = (\mathrm{FIDHC}) - 0.768(C_2H_5OH) + 0.4621(HCHO) + 0.6298(CH_3CHO) + 0.6023(C_2H_5OH)$$

This formula corrects for species and excludes weight of oxygen in the species. In essence, the FID reading is corrected for the calibration with respect to ethanol ($C_2H_5OH$) which is independently measured using impingers and which has a lower FID response per unit mass than the propane used for FID calibration, OMHCE also accounts for the level of formaldehyde (HCHO) and acetaldehyde ($CH_3CHO$) measured using cartridges. RHC is the FID hydrocarbon reading with the contribution of the alcohol emissions subtracted from that reading.

## Repeatability of Data

Regulated emissions data obtained by the laboratories are repeatable from run-to-run, as shown in tables 6 and 7. However, in the case of alcohol buses, formaldehyde had significant variation and acetaldehyde had variation in this study that was too severe to permit quantitative use.

## Conclusions

Tests on three natural gas buses in Tacoma, Wa., revealed high CO and $NO_x$ emissions, which may be attributed to inappropriate air/fuel ratio control. Replacement of the mixers on two buses produced low CO and reduced $NO_x$, while adjustment on the third reduced CO but did not appreciably affect $NO_x$. Also, two ethanol powered buses in Peoria, Ill. were tested for emissions as received, then had catalysts replaced, and were re-tested. Improved emissions of CO and HC with the new catalysts was evident and the new catalysts showed themselves to be very selective in reducing ethanol. One may conclude that careful maintenance and monitoring of alternative fuel vehicles is desirable to maintain low emissions.

## Acknowledgments

This research was supported by the US Dept. of Energy, Office of Transportation Technologies. The authors are grateful to Byron Rapp and the staff of the Transportable Heavy Duty Vehicle Emissions Testing Laboratory and to Kenneth Kelly, Robert Motta and Charles White of the National Renewable Laboratories, Golden, Colorado. Clarence Gadapati is thanked for his assistance in the preparation of this paper.

## References

Bata, R., Lyons, D., Clark, N., Gautam, G. and Wang, W. (1996), "Vehicle Performance and Exhaust Gas Emissions of In-use Methanol Fueled Transit Buses", Eleventh International Symposium on Alcohol Fuels, April 1996, Sun City, South Africa, Vol. 3, pp. 809-820.

Chandler, K., Malcosky, N., Motta, R., Norton, P., Kelly, K., Schumacher, L. and Lyons, D. W., "Alternative Fuel Transit Bus Evaluation Program Results", SAE paper 961082, 1996.

Clark, N. N., Gadapati, C. J., Kelly, K., White, C. L., Lyons, D. W., Wang, W., Gautam, M. and Bata, R., "Comparative Emissions from Natural Gas and Diesel Buses", SAE Paper 952746, 1995a.

Clark, N. N., Gautam, M., Bata, R. M., and Lyons, D. W. (1995b), "Design and Operation of a New Transportable Laboratory for Emissions Testing of Heavy Duty Trucks and Buses", Int. Journal of Vehicle Design: Heavy Vehicle Systems, Vol. 2, Nos. 3/4, pp. 285-299.

Clark, N. N., Wang, W. G., Bata, R. M., Gautam, M., Gadapati C. J., Lyons, D. W., Kelly, K. and White, C. L., (1996), "Emissions from Heavy Duty Trucks and Buses Operating on Ethanol Based Fuels", Eleventh International Symposium on Alcohol Fuels, April 1996, Sun City, South Africa, Vol. 3, pp. 821-836.

Sharp, C., Ullman, T., and Stamper, K., "Transient Emissions from Two Natural Gas-Fueled Heavy Duty Engines", SAE Paper 932819, 1993.

Wang, W., Gautam, M., Sun, X., Bata, R., Clark, N., Palmer, M. and Lyons, D., "Emissions Comparisons of Twenty-Six Heavy Duty Vehicles Operated on Conventional and Alternative Fuels", SAE Paper 932952, 1993.

## Table 1: Details of Buses Tested

| Bus # & Location | Manufacturer & Year | Transmission Type | Engine Make | Milage (miles) | Test Weight (lb) | Power (hp) |
|---|---|---|---|---|---|---|
| 1507 E<br>Peoria, Ill. | TMC<br>1992 | Allison VR-731. 3-spd. | DDC 6V-92 TA. DDEC II | 117,680 | 31,361 | 253 |
| 1508E<br>Peoria, Ill. | TMC<br>1992 | Allison VR-731. 3-spd. | DDC 6V-92 TA. DDEC II | 103,959 | 31,361 | 253 |
| PT-478<br>Tacoma, Wa. | BIA<br>1992 | ZF-4HP590<br>4-spd | Cummins<br>L-10 240G | - | 35,652 | 240 |
| PT-480<br>Tacoma, Wa. | BIA<br>1992 | ZF-4HP590<br>4-spd | Cummins<br>L-10 240G | - | 35,652 | 240 |
| PT-481<br>Tacoma, Wa. | BIA<br>1992 | ZF-4HP590<br>4-spd | Cummins<br>L-10 240G | - | 35,652 | 240 |

## Table 2: Original DDEC Settings

(Detroit Diesel Electronic Control Settings, Lookup Tables for Blower Bypass Valve)

| Desired Boost | | Torque (% max. torque) | | |
|---|---|---|---|---|
| | | 0.0 | 12.5 | 25 |
| Engine Speed (rpm) | 600 | 123 | 122 | 137 |
| | 900 | 123 | 122 | 138 |
| | 1200 | 120 | 134 | 148 |

## Table 3: 10% Increase Settings

(Detroit Diesel Electronic Control Settings, Lookup Tables for Blower Bypass Valve)

| Desired Boost | | Torque (% max. torque) | | |
|---|---|---|---|---|
| | | 0.0 | 12.5 | 25 |
| Engine Speed (rpm) | 600 | 135 | 134 | 150 |
| | 900 | 135 | 134 | 151 |
| | 1200 | 132 | 138 | 162 |

## Table 4: 5% Increase Settings
(Detroit Diesel Electronic Control Settings, Lookup Tables for Blower Bypass Valve)

| Desired Boost | | Torque (% max. torque) | | |
|---|---|---|---|---|
| | | 0.0 | 12.5 | 25 |
| Engine Speed (rpm) | 600 | 129 | 128 | 144 |
| | 900 | 129 | 128 | 145 |
| | 1200 | 126 | 140 | 155 |

## Table 5: Breakdown of Hydrocarbon Emissions in g/mile Before and After Fitting of New Catalyst to Ethanol Buses.

| | RHC Residual Hydrocarbon | OMHCE | HCHO Formaldehyde | $C_2H_5OH$ Ethanol | $CH_3CHO$ Acetaldehyde |
|---|---|---|---|---|---|
| Bus 1507E Before new catalyst | 4.40 | 6.47 | 0.25 | 2.86 | 0.37 |
| Bus 1507E After new catalyst | 2.19 | 2.55 | 0.17 | 0.35 | 0.11 |
| Bus 1508E Before new catalyst | 5.03 | 6.97 | 0.16 | 2.66 | 0.25 |
| Bus 1508E After new catalyst | 2.84 | 3.05 | 0.08 | 0.23 | 0.05 |

## Table 6: Reproducibility of Data for a Natural Gas Bus Tested in Tacoma, Wa.

**Emissions Results (g/mile)**

| Run Seq. No. | CO | $NO_x$ | FIDHC | PM |
|---|---|---|---|---|
| 549-1 | 28.8 | 38.5 | 17.16 | 0.00 |
| 549-2 | 27.6 | 38.8 | 17.96 | 0.01 |
| 549-3 | 28.3 | 38.6 | 16.70 | 0.01 |
| 549-4 | 28.3 | 39.2 | 15.69 | 0.00 |
| | | | | |
| 549 Average | 28.3 | 38.8 | 16.88 | 0.00 |
| Std. Dev. | 0.5 | 0.3 | 0.95 | 0.00 |
| CV% | 1.8 | 0.7 | 5.6 | - |

## Table 7: Reproducibility of Data for an Ethanol Bus Tested in Peoria, Ill.

**Emissions Results (g/mile)**

| Run Seq. No. | RHC | FIDHC | OMHCE | HCHO | $C_2H_5OH$ | $CH_3CHO$ |
|---|---|---|---|---|---|---|
| 619-1 | 4.54 | 8.42 | 6.70 | 0.27 | 2.82 | 0.53 |
| 619-2 | 4.63 | 8.36 | 6.29 | 0.15 | 2.60 | 0.04 |
| 619-3 | 4.50 | 8.32 | 6.48 | 0.23 | 2.99 | 0.11 |
| 619-4 | 3.93 | 7.57 | 6.42 | 0.35 | 3.02 | 0.81 |
| | | | | | | |
| 619 Average | 4.40 | 8.17 | 6.47 | 0.25 | 2.86 | 0.37 |
| Std. Dev. | 0.32 | 0.40 | 0.17 | 0.08 | 0.19 | 0.36 |
| CV% | 7.3 | 4.9 | 2.7 | 33.8 | 6.8 | 97.5 |

Figure 1: Distribution of Emissions from Buses with Cummins Engines Operating on Diesel and CNG. The CNG Engines Consisted of 48 CPL-1379 Engines and 4 CPL-1653 Engines. (Clark et al. 1995a).

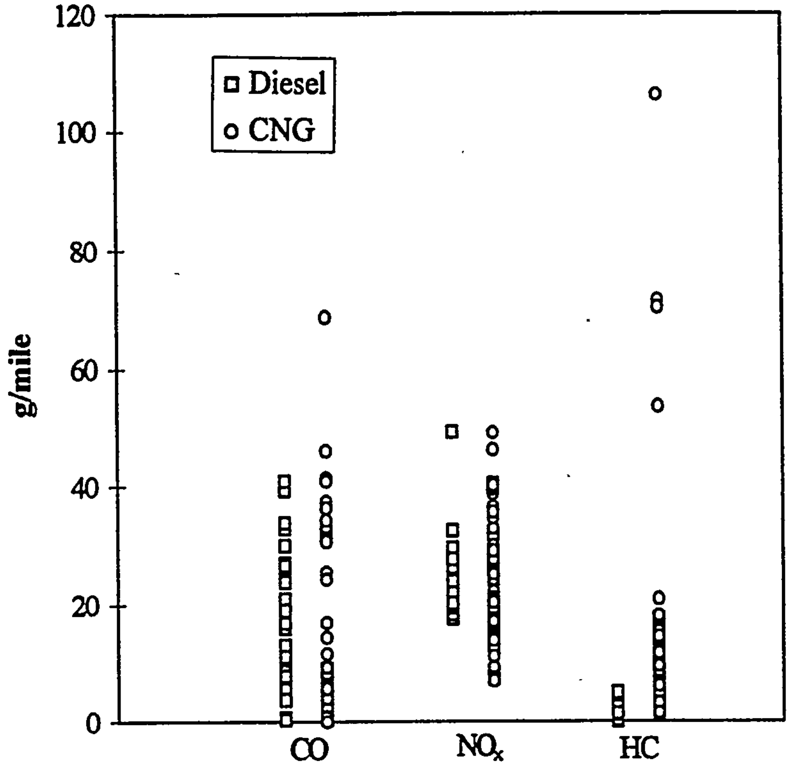


Figure 2: Testing of Bus PT-478 at Tacoma, Wa.

Test # 546: Vehicle was tested as received, no adjustments to engine parameters were made.

**Emissions Results (g/mile)**

| Run Seq. No. 546 | CO | $NO_x$ | Total HC |
|---|---|---|---|
| Average | 22.8 | 44.3 | 8.83 |
| CV% | 2.9 | 2.2 | 1.6 |

Test # 563: Engine was tuned to the following specifications:

(1) Exhaust $O_2$ at idle was set at 2.5 %.

(2) Exhaust $O_2$ at 1670 rpm stall speed was set at 6.5 %.

(3) Turbo boost at 1670 rpm stall speed was set at 11.5 psig.

Additional shims were installed on Impco mixer in order to achieve desired $O_2$ levels.

**Emissions Results (g/mile)**

| Run Seq. No. 563 | CO | $NO_x$ | Total HC |
|---|---|---|---|
| Average | 1.0 | 44.6 | 8.70 |
| CV% | 31.5 | 1.9 | 8.2 |

## Figure 3: Testing of Bus PT-480 at Tacoma , Wa.

Test # 548: Vehicle was tested as received. No adjustments were made.

**Emissions Results (g/mile)**

| Run Seq. No. 548 | CO | $NO_x$ | Total HC |
|---|---|---|---|
| Average | 40.7 | 46.1 | 10.47 |
| CV% | 2.1 | 3.8 | 1.1 |

Test # 554: Vehicle was re-tested to compare with test # 548 and determine the effects of minor air/fuel ratio adjustments on emissions results. Noted, scored bullet valve in mixer. Installed additional shims on mixer. Engine was tuned to the following specifications:

(1) Exhaust $O_2$ at idle was set at 2.5 %.
(2) Exhaust $O_2$ at 1670 rpm stall speed was set at 6.5 %.
(3) Turbo boost at 1670 rpm stall speed was set at 11.5 psig.

**Emissions Results (g/mile)**

| Run Seq. No. 554 | CO | $NO_x$ | Total HC |
|---|---|---|---|
| Average | 46.6 | 43.7 | 12.57 |
| CV% | 33.6 | 14.4 | 31.4 |

Test # 556: Test performed to compare with results from tests 548 and 554 and to determine the effects of major air/fuel ratio adjustments with new components on emissions results. New mixer (with additional shims), new high and low pressure regulators were installed.

Engine was tuned to the following specifications:

(1) Exhaust $O_2$ at idle was set at 2.5 %.
(2) Exhaust $O_2$ at 1670 rpm stall speed was set at 6.5 %.
(3) Turbo boost at 1670 rpm stall speed was set at 11.5 psig.

**Emissions Results (g/mile)**

| Run Seq. No. 556 | CO | $NO_x$ | Total HC |
|---|---|---|---|
| Average | 1.4 | 25.3 | 11.62 |
| CV% | 9.7 | 5.7 | 1.4 |

## Figure 4: Testing of Bus PT-481 at Tacoma, Wa.

Test # 549: Vehicle was tested as received. Engine was running rich at idle.
Turbo boost was 13 psig at 1670 rpm stall speed.

**Emissions Results (g/mile)**

| Run Seq. No. 549 | CO | $NO_x$ | Total HC |
|---|---|---|---|
| Average | 28.3 | 38.8 | 16.88 |
| CV% | 1.8 | 0.7 | 5.6 |

Test # 559: Test was performed for comparison with results from previous test # 549, to determine the effects of major air/fuel ratio adjustments with new components on emissions results.
New mixer (with additional shims) was installed.
Engine was tuned to the following specifications:
(1) Exhaust $O_2$ at idle was set at 2.5 %.
(2) Exhaust $O_2$ at 1670 rpm stall speed was set at 6.5 %.
(3) Turbo boost at 1670 rpm stall speed was set at 11.5 psig.

**Emissions Results (g/mile)**

| Run Seq. No. 559 | CO | $NO_x$ | Total HC |
|---|---|---|---|
| Average | 3.7 | 20.7 | 9.66 |
| CV% | 9.1 | 1.4 | 1.8 |

Figure 5: Comparison Between Continuous $NO_x$ Emissions for a Cummins L-10 Powered Natural Gas Bus (PT-481), First Tested As-received and then with Adjustments.

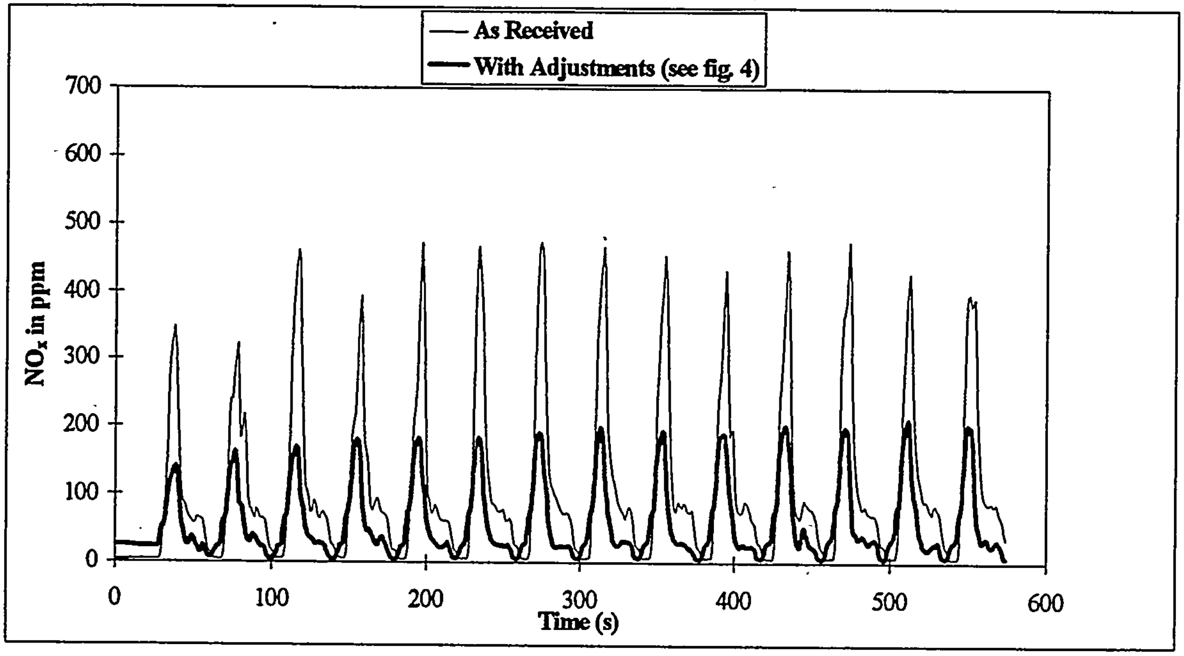
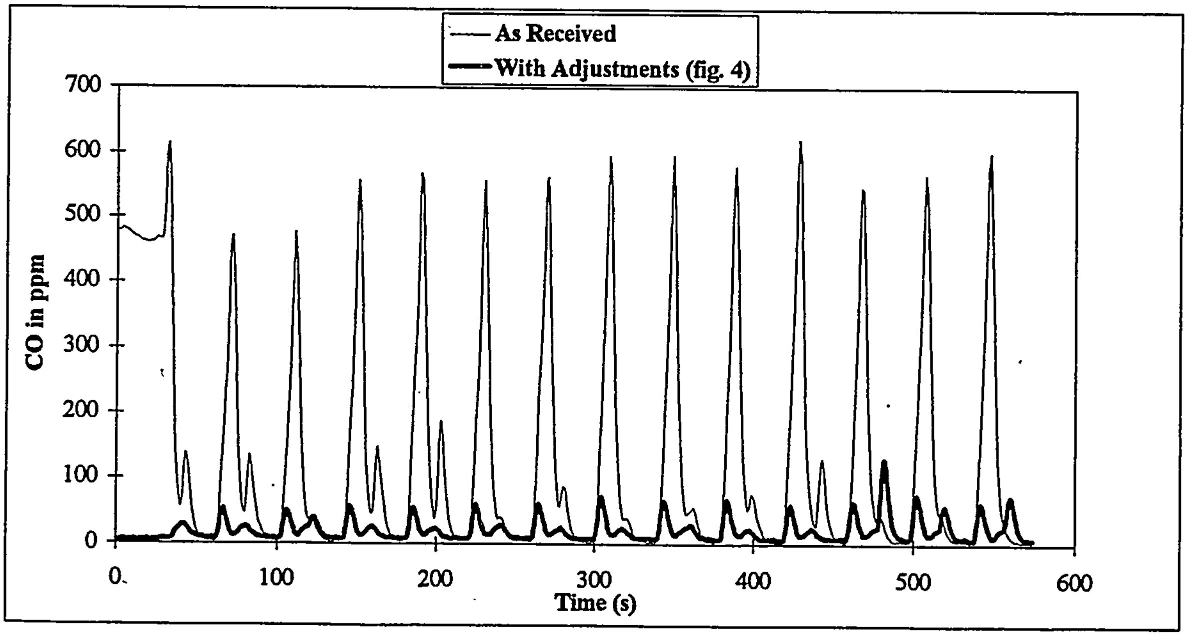


Figure 6: Comparison Between Continuous CO Emissions for a Cummins L-10 Powered Natural Gas Bus (PT-481), First Tested As-received and then with Adjustments.



## Figure 7: Testing of Bus 1507E at Peoria, Ill.

Test # 619: Baseline test for vehicle 1507E. A set of data established by this test will be used for comparison with results obtained after engine modifications. A pre-test check was undertaken before commencing this run, involving a visual inspection and a diagnostic check using the engine's electronic control module. Also, the air filter was replaced.

**Emissions Results (g/mile)**

| Run Seq. No. 619 | CO | $NO_x$ | OMHCE | PM |
|---|---|---|---|---|
| Average | 38.3 | 13.9 | 6.47 | 0.67 |
| CV% | 2.5 | 0.5 | 2.7 | 5.6 |

Test # 621: New catalytic converter was installed. The muffler was not connected to the catalytic converter. Emissions were measured directly from the converter.

**Emissions Results (g/mile)**

| Run Seq. No. 621 | CO | $NO_x$ | OMHCE | PM |
|---|---|---|---|---|
| Average | 5.9 | 16.0 | 2.55 | 0.42 |
| CV% | 26.9 | 5.4 | 6.7 | 8.7 |

Test # 622: The original exhaust system, including the muffler, was attached to the new catalytic converter, to determine the effect of the muffler on emissions.

**Emissions Results (g/mile)**

| Run Seq. No. 622 | CO | $NO_x$ | OMHCE | PM |
|---|---|---|---|---|
| Average | 4.6 | 13.9 | 2.01 | 0.40 |
| CV% | 16.8 | 2.3 | 4.6 | 3.4 |

Test # 623: Modifications to the Detroit Diesel Electronic Control unit were made. New values were given to the lookup table of the Blower Bypass Valve settings in the ECM (Electronic Control Module) for nine different setpoints, which were mapped to engine speed and torque. These were done for the 0, 12.5 and 25 percent maximum torque settings at 600, 900 and 1200 rpm. The original values at these points (Table 2) were increased by 10% (Table 3). These modifications caused the blower valve to open less, thus forcing more air into the intake and creating a leaner air/fuel mixture. In addition, the Bypass Overall Gain was increased from 1.0 to a value of 2.0. This modification increased the sensitivity of the bypass valve controller and provided a smoother transition from running speed to idle speed.

**Emissions Results (g/mile)**

| Run Seq. No. 623 | CO | $NO_x$ | OMHCE | PM |
|---|---|---|---|---|
| Average | 4.4 | 16.2 | 2.00 | 0.34 |
| CV% | 11.7 | 3.7 | 4.8 | 5.8 |

## Figure 8: Testing of Bus 1508E at Peoria, Ill.

Test # 620: Baseline test for vehicle 1508E. A set of data established by this test will be used for comparison with results obtained after engine modifications. A pre-test check was undertaken before commencing this run, involving a visual inspection and a diagnostic check using the engine's electronic control module. Also, the air filter was replaced.

**Emissions Results (g/mile)**

| Run Seq. No. 620 | CO | $NO_x$ | OMHCE | PM |
|---|---|---|---|---|
| Average | 47.0 | 8.0 | 10.06 | 0.63 |
| CV% | 2.1 | 2.4 | 2.7 | 1.9 |

Test # 624: The vehicle's original set of fuel injectors was replaced with a new set of titanium alloy fuel injectors. The vehicle was then tuned and run for several test cycles to ensure that the new injectors were functioning properly and were seated correctly.

**Emissions Results (g/mile)**

| Run Seq. No. 624 | CO | $NO_x$ | OMHCE | PM |
|---|---|---|---|---|
| Average | 32.5 | 9.3 | 6.64 | 0.45 |
| CV% | 0.8 | 1.3 | 2.8 | 1.9 |

Test # 625: The same modifications that were made to the Detroit Diesel Electronic Control unit on vehicle 1507E (Test # 623, given above) were made to this vehicle.

**Emissions Results (g/mile)**

| Run Seq. No. 625 | CO | $NO_x$ | OMHCE | PM |
|---|---|---|---|---|
| Average | 26.9 | 11.6 | 6.74 | 0.49 |
| CV% | 3.8 | 2.1 | 2.9 | 16.8 |

Test # 626: During the previous test, knocking was noticed and it was decided that in combination with the new fuel injectors, the DDEC settings were not appropriate. To rectify the same the Blower Bypass Valve settings were changed to the values shown in Table 4, which were decreased 5% from Table 3 or increased 5% from Table 2. The Bypass Overall Gain was left at a setting of 2.0 as in the previous set of tests, since the transition from full power to idling was smooth.

**Emissions Results (g/mile)**

| Run Seq. No. 626 | CO | $NO_x$ | OMHCE | PM |
|---|---|---|---|---|
| Average | 31.4 | 10.1 | 6.97 | 0.49 |
| CV% | 2.6 | 1.1 | 4.4 | 4.3 |

Test # 627: The new catalytic converter that was used on vehicle 1507E was installed according to manufacturer's specifications, along with the muffler. The bus was run on the dynamometer for several test runs before data was taken to ensure that any impurities from handling were burned.

**Emissions Results (g/mile)**

| Run Seq. No. 627 | CO | $NO_x$ | OMHCE | PM |
|---|---|---|---|---|
| Average | 7.2 | 10.3 | 3.05 | 0.36 |
| CV% | 8.5 | 1.4 | 2.6 | 8.9 |

# 1996 WINDSOR WORKSHOP ON ALTERNATIVE FUELS

## POSTER SESSION

# 1996 WINDSOR WORKSHOP ON ALTERNATIVE FUELS

## POSTER SESSION

# Natural Gas Geo Metro

**M. Sulatisky, S. Hill, J. Lychak, Saskatchewan Research Council**

(Poster unavailable at time of publication)

# Comparative Emissions from Chassis Tests of Trucks using Diesel No. 2 and Biodiesel Blend

Nigel N. Clark, Donald W. Lyons
Department of Mechanical and Aerospace Engineering
West Virginia University
Morgantown, WV 26506-6106
Fax # 304-293-6689

Biodiesel, usually as a blend with petroleum diesel, offers great potential as an alternative fuel because it requires no modification to compression ignition engines for its use. With a higher cetane rating than diesel, it is argued that biodiesel serves to reduce particulate matter emissions, perhaps at the expense of increased oxide of nitrogen emissions. Eight over-the-road tractors were tested for regulated emissions using the West Virginia University Transportable Heavy Duty Emissions Testing Laboratory, which incorporates a chassis dynamometer, full scale dilution tunnel and conventional emissions bench. Two trucks were powered by 1989 Mack 350 hp engines, three by 1989 Cummins 315 hp engines, and three by recent model Detroit Diesel Series 60 350 hp engines. The trucks were tested at 42,000 lb inertia simulation, using a road load equation and the WVU 5 peak truck cycle speed-time schedule. The vehicles were operated on No 2 diesel fuel (D2) and on a 35% soy diesel / 65% petroleum diesel blend (BD). Data was calculated in units of grams per mile. Unexpectedly, both Mack trucks showed higher particulate emissions on BD, but values were reduced for the remaining six units. Overall the emissions of oxides of nitrogen increased slightly, but trends were mixed. One Mack truck showed increased hydrocarbon readings, as measured by flame ionization detection of an analyzer calibrated on propane, but the other seven units all showed hydrocarbon reductions. The other Mack truck showed an increase in carbon monoxide emissions while the remaining seven trucks showed a decrease. From this data one must conclude that the emissions differences between BD and D2, though discernible, are slight.

U.S. Department of Energy
Office of Transportation Technologies

West Virginia University
Mechanical and Aerospace Engineering

# TRANSPORTABLE HEAVY-DUTY VEHICLE EMISSIONS TESTING LABORATORY

*West Virginia University, working with the U.S. Department of Energy Office of Transportation Technologies, has designed and constructed two Transportable Vehicle Emissions Testing Laboratories to monitor engine performance and to measure the emissions from heavy-duty vehicles operating on conventional and alternative fuels. The laboratories can be moved easily from site to site so that vehicles can be tested where they are housed, thus minimizing their time out of service.*

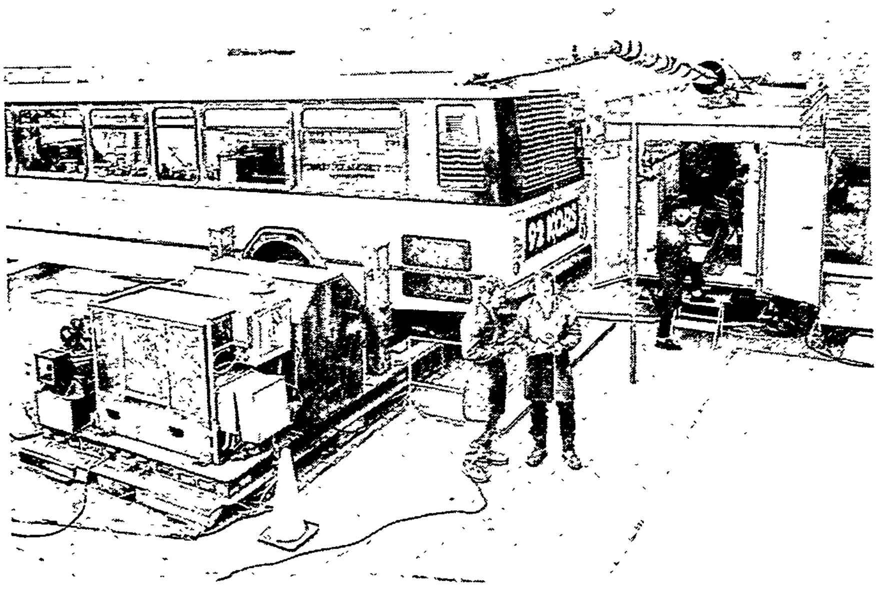
## LABORATORY CAPABILITIES

**The Transportable Heavy-Duty Vehicle Emissions Testing Laboratories are able to:**

- perform transient and steady state chassis dynamometer emissions tests on vehicles in the field, at or near their home base or maintenance facility;
- simulate a range of urban and highway driving cycles to provide performance data for medium and heavy-duty vehicles;
- measure the emissions from heavy-duty trucks and busses operating on conventional and alternative fuels;
- provide emissions data for CO, $CO_2$, $NO_X$, HC, $CH_4$, $CH_3OH$, HCHO, particulate matter, and other exhaust constituents;
- simulate road load, aerodynamic drag, and vehicle inertia; and
- provide a complete computer record and a hard copy log of time-varying speed, torque, and emissions.

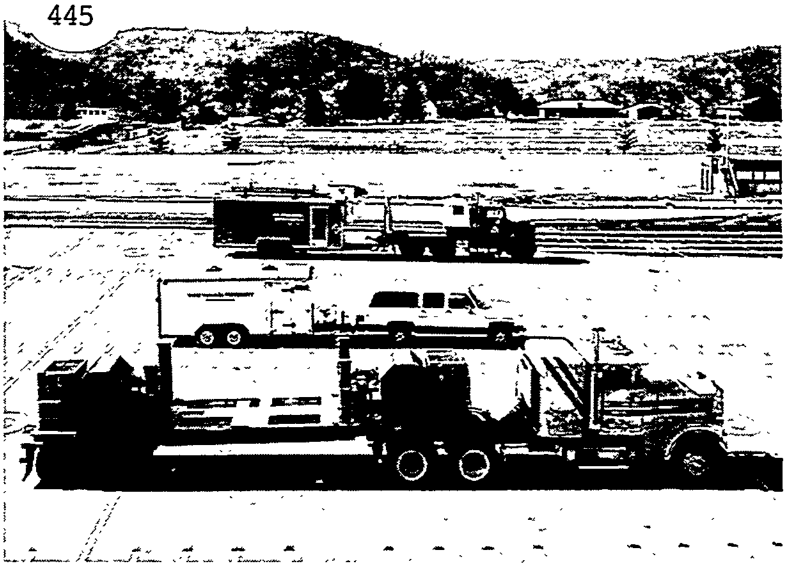
**The Chassis Dynamometer incorporates:**

- fast-response, computer-controlled eddy current power absorbers;
- flywheels that can be adjusted to simulate the inertia of a vehicle in 250-pound increments over the range of 15,000 to 60,000 pounds;
- direct mechanical coupling between the drive axle and the dynamometer power train using wheel hub adapters. This coupling method eliminates problems associated with tire slippage and over-heating, which are common for systems with tire-to-roller coupling;
- on-line continuous torque and speed measurement;
- a computer monitor for the driver which provides a visual display of the selected driving cycle;
- a full exhaust dilution tunnel and a secondary dilution tunnel for particulate sampling; and
- emissions analysis instrumentation and calibration gases as required for both continuous and bag sampling measurement of the major constituents of the exhaust. The measurement procedures follow closely the Federal Test Procedure for certification of heavy-duty engines.



## LABORATORY OPERATIONS

This photograph shows the laboratory in operation at a test site. The vehicle to be tested is placed on the flat bed chassis dynamometer and the exhaust from the vehicle is collected, diluted, and sampled and analyzed to measure the levels of the constituents of the exhaust.



The Transportable Vehicle Emissions Testing Laboratories are each moved by one tool and two equipment trailers to the site of the vehicles to be tested.

## LABORATORY DESIGN

The laboratory facility is transported to the test site by two trailers, a box trailer containing equipment for emissions measurement, data acquisition, and control; and a flatbed carrying the chassis dynamometer unit. Once on the site, the flatbed is lowered to the ground using built-in hydraulic jacks.

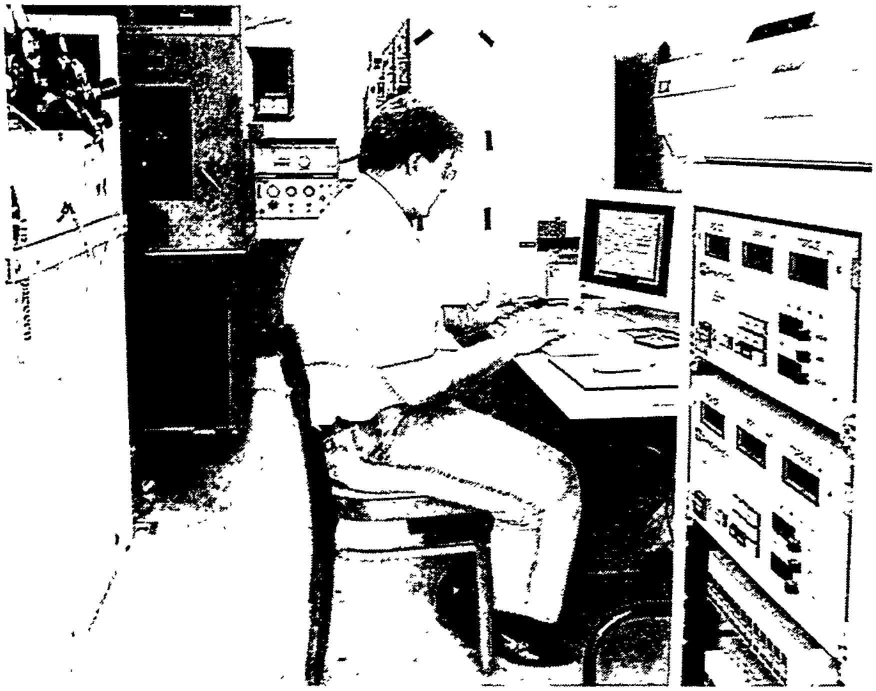
The vehicle to be tested is driven onto the flatbed and positioned so that the drive axle of the vehicle is over the center section of the test bed and is perpendicular to the length of the test bed. The wheels of the vehicle are positioned on free-turning rollers. The outer wheels of the dual-wheel set on each side of the vehicle are removed, and special hub adapters are mounted to the drive axle. The drive shafts of the dynamometer units located on each side of the vehicle are connected to the hub adapters. Each drive shaft is coupled through gearboxes to a power absorber and a set of flywheels. Each flywheel set consists of a series of selectable discs allowing simulation of an inertia load equal to a gross vehicle weight.

During the test, torque cells and speed transducers in the dynamometer drive train measure the actual vehicle load and speed. The vehicle can be driven through various standard test cycles to simulate either dynamic or steady state vehicle driving conditions. A computer system contains a program description of the driving cycles and sends a signal to a video display screen mounted next to the driver's compartment. The display screen shows the driver the desired and actual vehicle speeds during the test.

The full exhaust from the tail pipe of the test vehicle is ducted to a dilution tunnel located on the top of the emissions trailer. A centrifugal fan draws the exhaust and dilution air into the tunnel and a critical flow venturi is used to maintain and measure the rate of air flow. Sampling probes route diluted exhaust through heated sampling lines to the gas analysis instruments. Calibration certified gasses are used to calibrate the emissions measurement equipment before and after each test.

The laboratories have been used throughout the United States to conduct emissions testing of more than 500 vehicles, operating on a wide range of conventional and alternative fuels. Test results are accurate, repeatable, and traceable. The test results are normally provided to the Alternative Fuels Database maintained by the National Renewable Energy Laboratory for the USDOE

*For more information contact*
*Dr. Donald Lyons, Department of Mechanical and Aerospace Engineering, West Virginia University, Morgantown WV 26506-6106; telephone (304) 293-3111 ext. 360 or Mr. John Garbak, Program Manager, Office of Alternative Fuels, U.S. Department of Energy, 1000 Independence Avenue S.W., Washington DC 20585; telephone (202) 586-1723.*



The data acquisition system and exhaust gas analysis instrumentation are contained in the enclosed instrument trailer.

# EXAMPLES OF ACTUAL EMISSIONS DATA SHOWING REPRODUCIBILITY (APP-25386, KENWORTH WITH DETROIT DIESEL SERIES 60) TRUCK DATA

| | |
|---|---|
| Fleet Owner Full Name | AG Processing, Inc. |
| Fleet Address | 804 Second Ave., P.O.Box 220 |
| Fleet Address (City, State, Zip) | Sheldon, IA 51201 |
| | |
| Vehicle Type | Tractor |
| Vehicle ID Number (VIN) | 2HSFHDPR9RSO90633 |
| Vehicle Manufacturer | INTL |
| Vehicle Model Year | 1993 |
| Gross Vehicle Weight (GVW) (lb) | 80000 |
| Vehicle Total curb Weight (lb) | 14167 |
| Vehicle Simulated Weight (lb) | 42071 |
| Odometer Reading (mile) | 86348 |
| Transmission Type | Manual |
| Transmission Configuration | Fuller 9-Spd |
| Number of Axles | 3 |
| | |
| Engine Type | DDC Series 60 DDEC III |
| Engine ID Number | 06R0153408 |
| Engine Displacement in Liters | 11.1 |
| Number of Cylinders | 6 |
| Engine Rated Power (hp) | 350 |
| | |
| Primary Fuel | BD |
| Primary Fuel ID | 95-07 |
| | |
| Test Cycle | WVU-Truck |

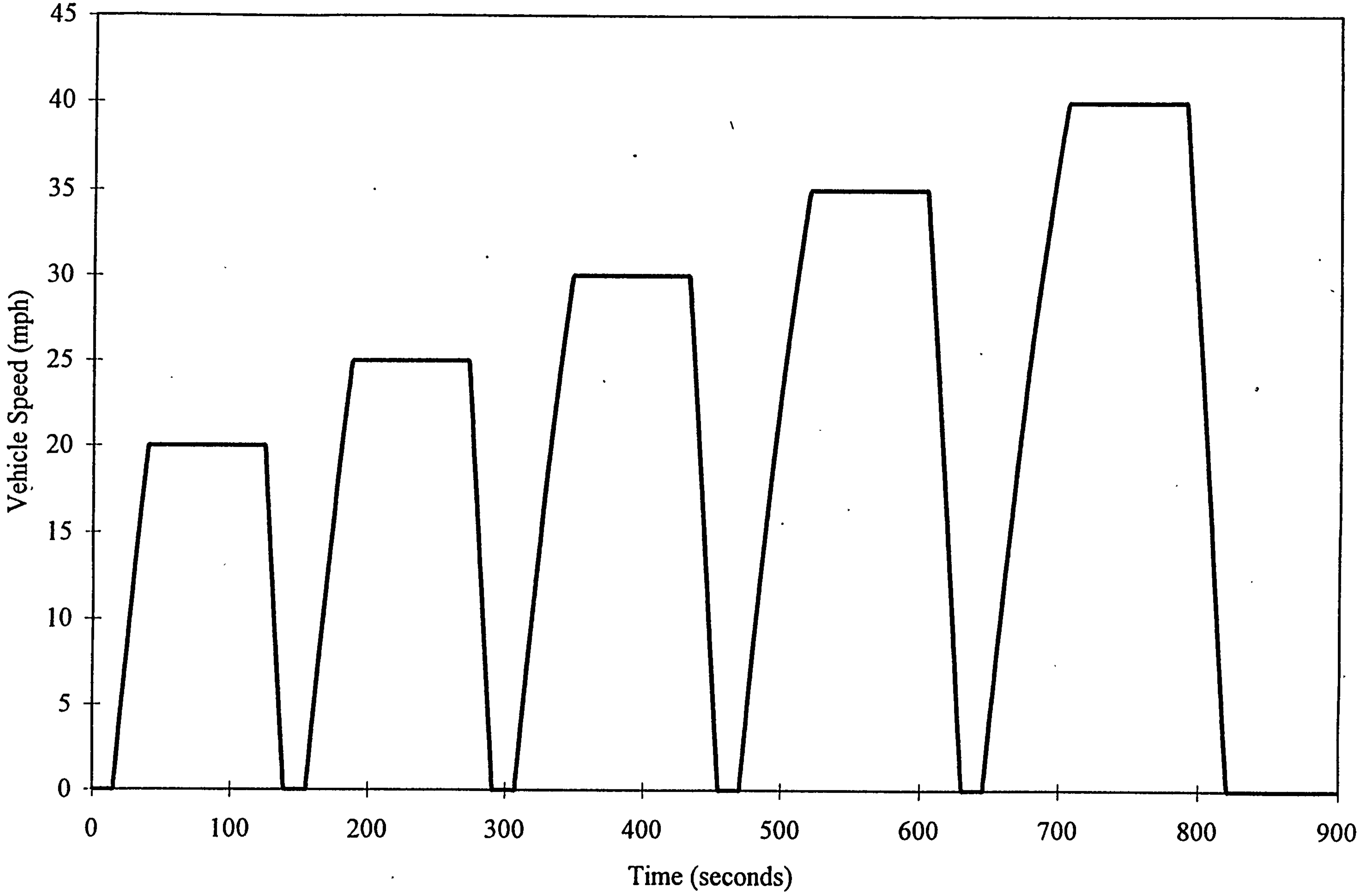
**BIODIESEL EMISSIONS RESULTS (g/mile)**

| Run Seq. No. | CO | NOx | FIDHC | PM |
|---|---|---|---|---|
| 466-1 | 3.4 | 17.6 | 0.24 | 0.29 |
| 466-2 | 3.8 | 16.9 | 0.25 | 0.25 |
| 466-3 | 3.0 | 16.9 | 0.25 | 0.25 |
| 466-4 | 3.8 | 17.4 | 0.22 | 0.22 |
| | | | | |
| 466 Average | 3.5 | 17.2 | 0.24 | 0.25 |
| Std. Dev. | 0.24 | 17.2 | 0.24 | 0.25 |
| CV% | 11.4 | 2.1 | 5.2 | 10.3 |

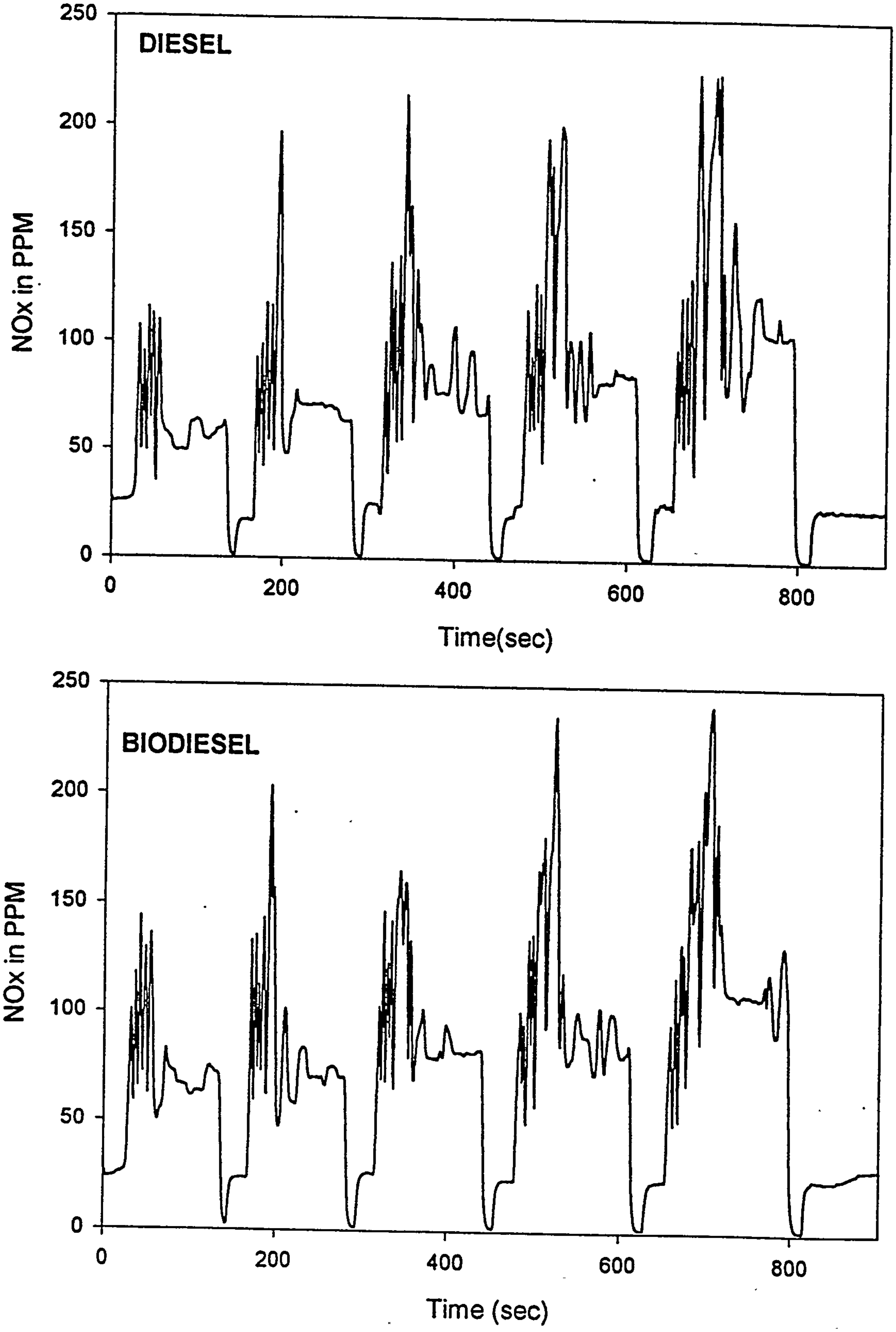
**DIESEL EMISSIONS RESULTS (g/mile)**

| Run Seq. No. | CO | NOx | FIDHC | PM |
|---|---|---|---|---|
| 481-1 | 3.8 | 16.9 | 0.29 | 0.26 |
| 481-2 | 3.8 | 16.9 | 0.25 | 0.25 |
| 481-3 | 4.1 | 17.2 | 0.30 | 0.26 |
| | | | | |
| 481 Average | 4.4 | 17.2 | 0.28 | 0.28 |
| Std. Dev. | 0.8 | 0.4 | 0.02 | 0.04 |
| CV% | 17.8 | 2.1 | 6.9 | 12.9 |

WVU 5 Peak Truck Cycle for testing
Heavy Duty Class 8 Vehicles



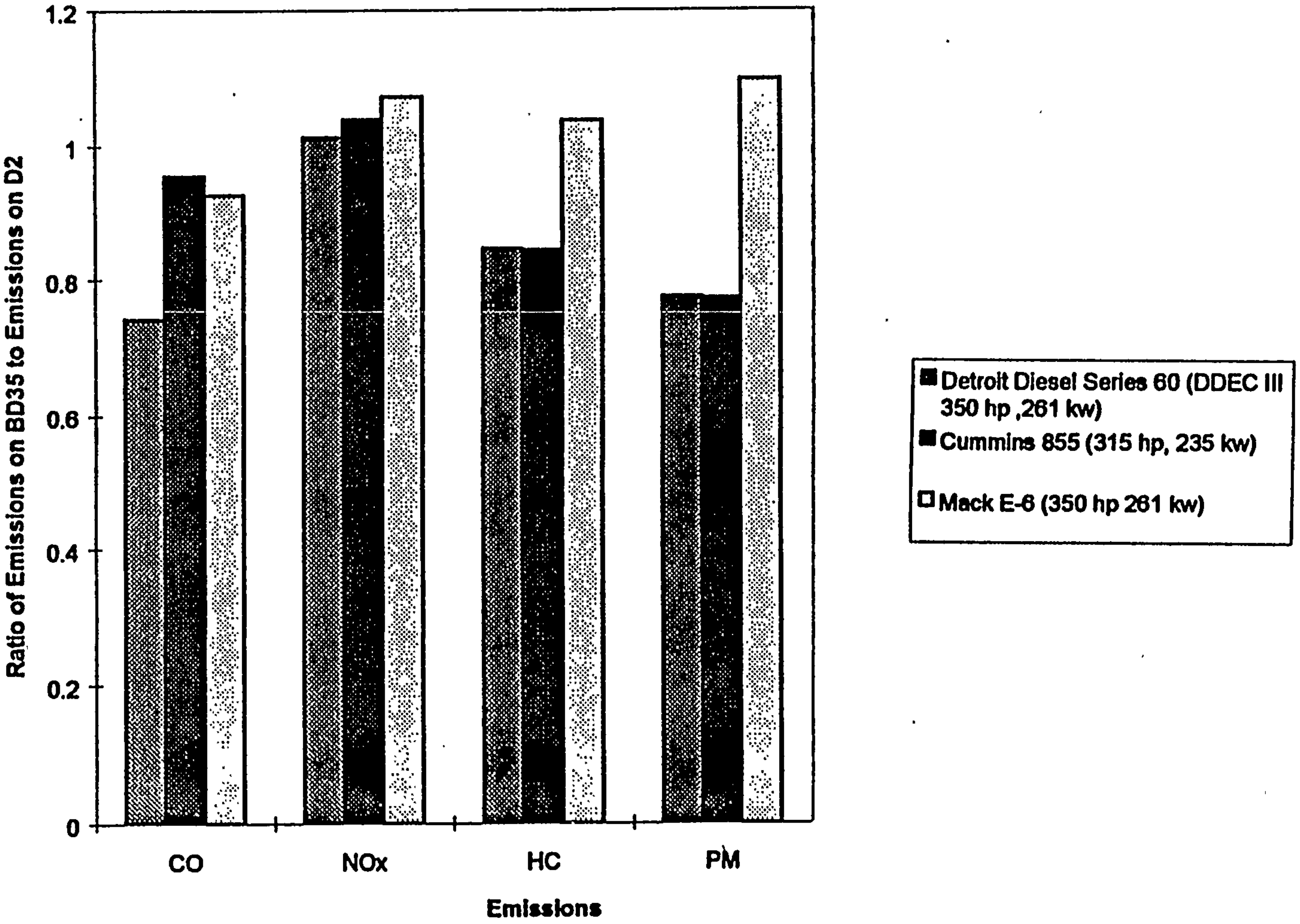
# CONTINUOUS NOx
# 5 PEAK EMISSIONS FROM AGP-25386
# KENWORTH WITH DETROIT DIESEL SERIES 60



Demographics of tractors tested in Sheldon, Iowa, each on conventional No. 2 Diesel and on biodiesel (a blend of soy-derived ester (35%) and #2 diesel (65%)).

| Year | ID Number | Model | Engine | Transmission | Odometer |
|---|---|---|---|---|---|
| 1994 | AGP-25386 | Kenworth | DDC Series 60 (DDEC III) - 350 hp | Fuller 9-Speed | 851580 |
| 1994 | AGP-25387 | Kenworth | DDC Series 60 (DDEC III) - 350 hp | Fuller 9-Speed | 857260 |
| 1993 | AGP-25389 | International | DDC Series 60 (DDEC III) - 350 hp | Fuller 9-Speed | 863480 |
| 1992 | AGP-21068 | Freightliner | Cummins 855 - 315 hp | Fuller 9-Speed | 695405 |
| 1989 | AGP-21069 | Freightliner | Cummins 855 - 315 hp | Fuller 9-Speed | 654852 |
| 1989 | AGP-21070 | Freightliner | Cummins 855 - 315 hp | Fuller 9-Speed | 649851 |
| 1989 | AGP-21018 | Mack | Mack E-6 - 350 hp | Mack 9-Speed | 520425 |
| 1989 | AGP-21022 | Mack | Mack E-6 - 350 hp | Mack 9-Speed | 495582 |

# RATIO OF BIODIESEL TO DIESEL EMISSIONS ON 8 TRUCKS

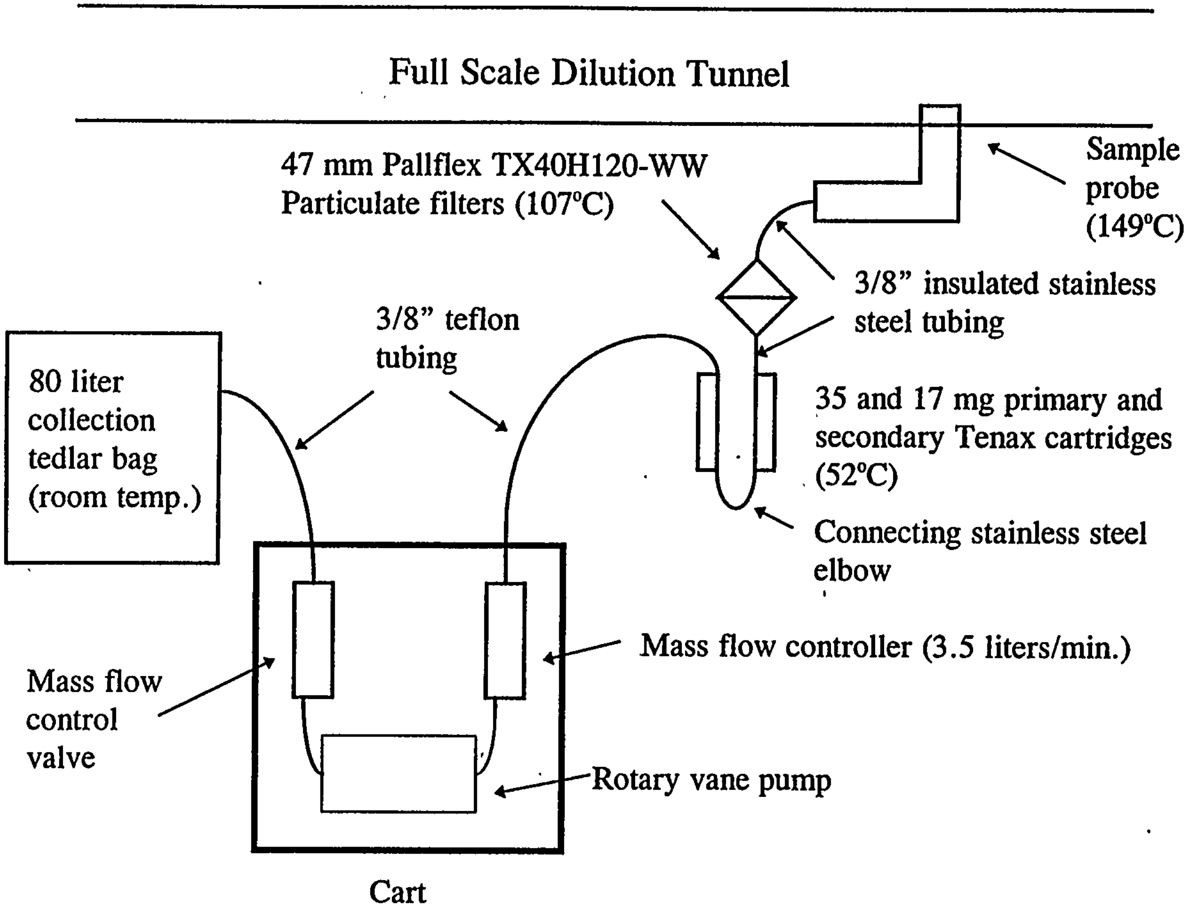


# Speciation of Reactive Components of Lean Burn CNG Exhaust Emissions

Ralph D. Nine, Nigel N. Clark, Christopher M. Atkinson, Gregory E. Mott, Brian E. Mace
Mechanical and Aerospace Engineering
West Virginia University

An effort is underway at West Virginia University to identify and quantify the specific hydrocarbon components present in heavy duty exhaust emissions. Hydrocarbon emissions are a source of particular concern due to their ground level ozone forming potential in the presence of sunlight and their harmful respiratory health effects. Samples were drawn from a full scale dilution tunnel through a dedicated hydrocarbon sampling train. Recently, a Hercules GTA 3.7 liter medium duty (93 kW at 2800 rpm; 441 Nm at 1600 rpm) CNG engine was operated at 1600 rpm and 217 Nm using three fuels (local supply CNG gas of 91% methane, 99.3% methane gas, and 86% propane) at a desired lean air/fuel ratio (lambda=1.32). The engine was then operated under the same conditions using the supply CNG gas while the lambda value was varied from a rich $NO_X$ limit (1.10) to a lean misfire limit (1.47). Similarly, the engine was operated using the target lambda at 1600 rpm and loads of 22 and 109 Nm. The lighter load tests as well as the lean operation tests showed an increase in the hydrocarbon emissions as a result of unburnt fuel passing through the engine. Although there was an appreciable increase in $NO_X$ production during the rich operation test, the total hydrocarbon emissions were reduced as the lambda value approached its stoichiometric value. Total hydrocarbon emissions increased by approximately 15% in the propane tests when compared to the equivalent power CNG tests. Approximately 15 hydrocarbon compounds were identified in each of the tests performed. For the supply gas (91% methane), the methane fraction of the exhaust hydrocarbons was unaffected by engine load. For the propane fuel tests as expected, propane dominated the hydrocarbon emissions.

# *Speciation Sampling Train Layout*



Full Scale Dilution Tunnel

Sample
probe
(149°C)

47 mm Pallflex TX40H120-WW
Particulate filters (107°C)

3/8" insulated stainless
steel tubing

35 and 17 mg primary and
secondary Tenax cartridges
(52°C)

Connecting stainless steel
elbow

3/8" teflon
tubing

80 liter
collection
tedlar bag
(room temp.)

Mass flow controller (3.5 liters/min.)

Mass flow
control
valve

Rotary vane pump

Cart

* Particulate filters and Tenax cartridges used for fuels other than CNG

# Test Fuel Composition

| | |
|---|---|
| *CNG* | methane 91.0%; ethane 6.45%; propane 1.08%; i-butane 0.159%; n-butane 0.216%; i-pentane 0.071%; n-pentane 0.049%; hexane 0.064%; $N_2$ 0.903% |
| *Methane* | methane 99.2%; ethane 0.060%; propane 0.167%; $N_2$ 0.376%; $CO_2$ 0.181% |
| *Propane* | methane 1.76%; ethane 10.5%; propane 85.6%; i-butane 0.859%; n-butane 0.081%; $N_2$ 1.12%; $CO_2$ 0.061% |

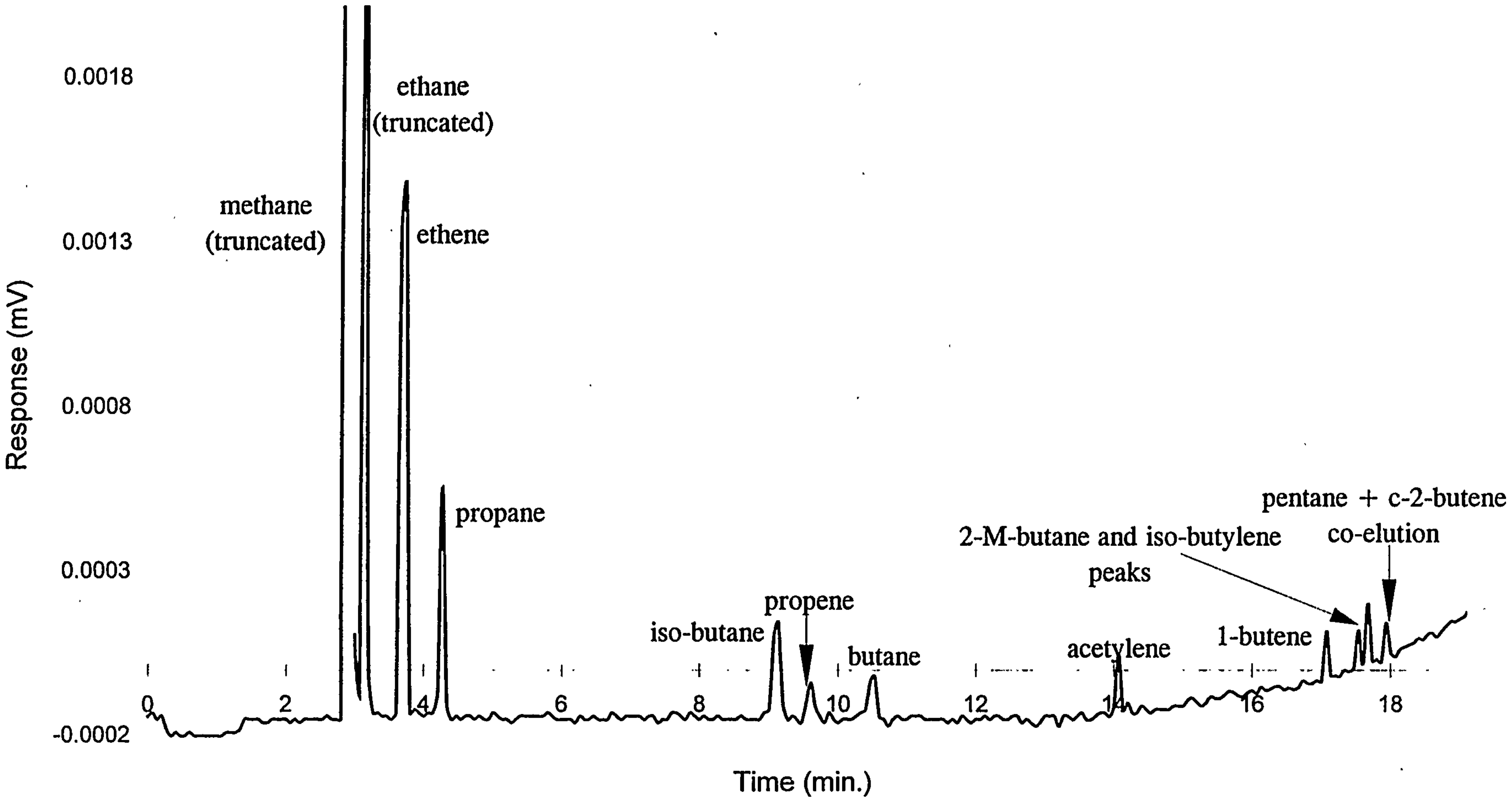
*(% by volume)*

# Speciated Hydrocarbons Present in the Exhaust

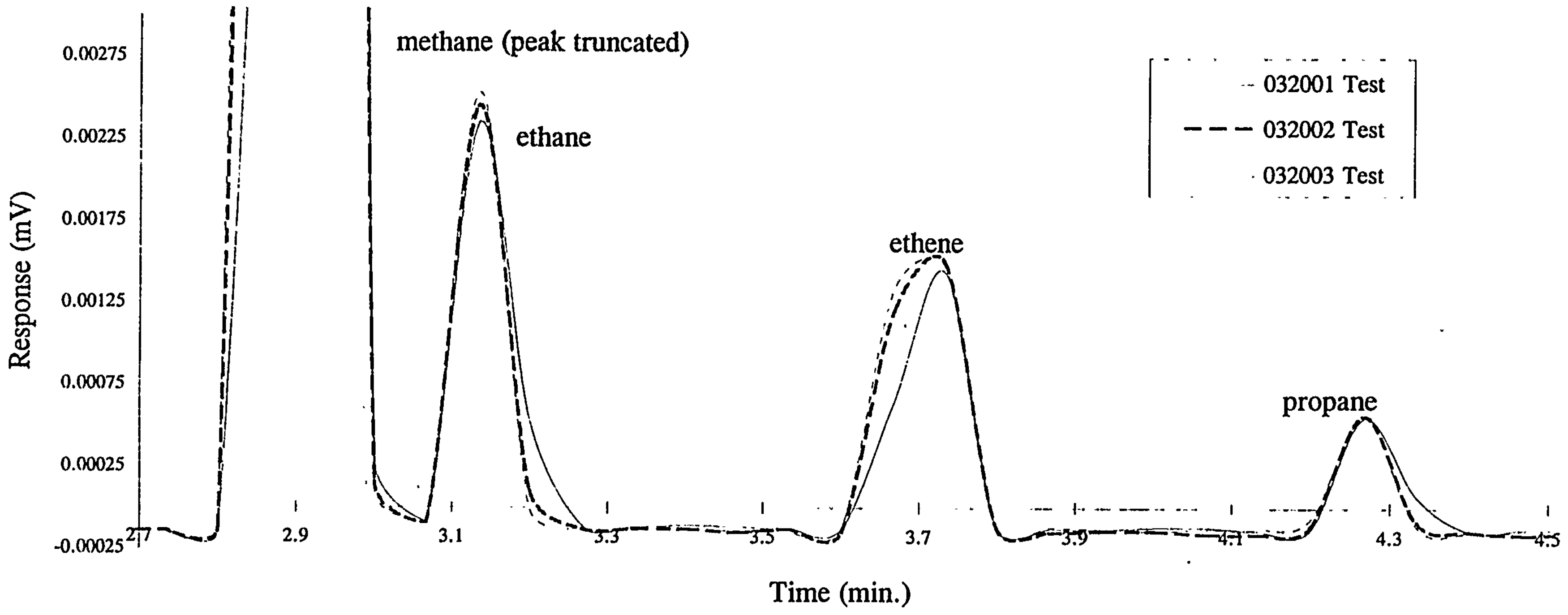
| **Test number** | **Test 1** | **Test 2** | **Test 3** | **Test 4** | **Test 5** | **Test 6** | **Test 7** | **Test 8** | **Test 9** | **Test 10** | **Test 11** | **Test 12** | **Test 13** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Fuel** | **CNG** | **CNG** | **CNG** | **CNG** | **CNG** | **CNG** | **CNG** | **Methane** | **Methane** | **Methane** | **Propane** | **Propane** | **Propane** |
| **Test Mode** | **I50** | **I50** | **I50** | **I25** | **I5** | **I50** | **I50** | **I50** | **I50** | **I50** | **I50** | **I50** | **I50** |
| **Speed (rpm)** | **1600** | **1600** | **1600** | **1600** | **1600** | **1600** | **1600** | **1600** | **1600** | **1600** | **1600** | **1600** | **1600** |
| **Load (Nm)** | **217** | **217** | **217** | **109** | **22** | **217** | **217** | **217** | **217** | **217** | **217** | **217** | **217** |
| **Lambda (λ)** | **1.32** | **1.32** | **1.32** | **1.32** | **1.32** | **1.10** | **1.47** | **1.32** | **1.32** | **1.32** | **1.32** | **1.32** | **1.32** |
| **A/F ratio** | **17.03** | **17.03** | **17.03** | **17.03** | **17.03** | **17.03** | **17.03** | **17.13** | **17.13** | **17.13** | **15.64** | **15.64** | **15.64** |
| **units** | **g/bhp-hr** | **g/bhp-hr** | **g/bhp-hr** | **g/bhp-hr** | **g/bhp-hr** | **g/bhp-hr** | **g/bhp-hr** | **g/bhp-hr** | **g/bhp-hr** | **g/bhp-hr** | **g/bhp-hr** | **g/bhp-hr** | **g/bhp-hr** |
| methane | 1.117 | 1.125 | 1.170 | 1.728 | 14.714 | 0.944 | 4.081 | 1.351 | 1.391 | 1.423 | 0.148 | 0.103 | 0.094 |
| ethane | 0.115 | 0.118 | 0.122 | 0.169 | 1.807 | 0.098 | 0.475 | 0.013 | 0.008 | 0.007 | 0.085 | 0.083 | 0.087 |
| ethene | 0.070 | 0.074 | 0.076 | 0.157 | 0.708 | 0.068 | 0.259 | 0.036 | 0.037 | 0.036 | 0.192 | 0.200 | 0.214 |
| propane | 0.030 | 0.032 | 0.032 | 0.039 | 0.463 | 0.026 | 0.108 | 0.003 | * | * | 0.942 | 0.943 | 1.004 |
| iso-butane | 0.018 | 0.020 | 0.019 | 0.031 | 0.181 | 0.018 | 0.051 | 0.010 | 0.010 | 0.009 | 0.110 | 0.113 | 0.122 |
| propene | 0.005 | 0.007 | 0.005 | 0.001 | 0.094 | 0.001 | 0.022 | | | | 0.013 | 0.013 | 0.013 |
| butane | 0.008 | 0.010 | 0.009 | 0.002 | 0.125 | 0.007 | 0.026 | | | | | | |
| ethyne | 0.006 | 0.006 | 0.006 | 0.010 | 0.039 | 0.011 | 0.012 | 0.004 | 0.004 | 0.004 | 0.012 | 0.012 | 0.013 |
| 1-butene | 0.003 | 0.003 | 0.005 | 0.006 | 0.039 | 0.004 | 0.008 | 0.002 | 0.002 | 0.002 | 0.004 | 0.003 | 0.003 |
| 2-m-butane | 0.010 | 0.005 | 0.005 | 0.010 | 0.052 | 0.007 | 0.010 | 0.005 | 0.004 | 0.003 | 0.005 | 0.004 | 0.003 |
| isobutylene | 0.005 | 0.004 | 0.006 | 0.007 | 0.071 | 0.004 | 0.014 | | | | | | |
| pentane + c-2-butene | 0.004 | 0.003 | 0.003 | 0.004 | 0.044 | 0.003 | 0.009 | | | | | | |
| 1,3-butadiene | | | | 0.002 | 0.039 | | 0.003 | | | | | | |
| Total: | 1.392 | 1.406 | 1.459 | 2.164 | 18.376 | 1.191 | 5.080 | 1.423 | 1.458 | 1.486 | 1.512 | 1.474 | 1.553 |

* small response detected

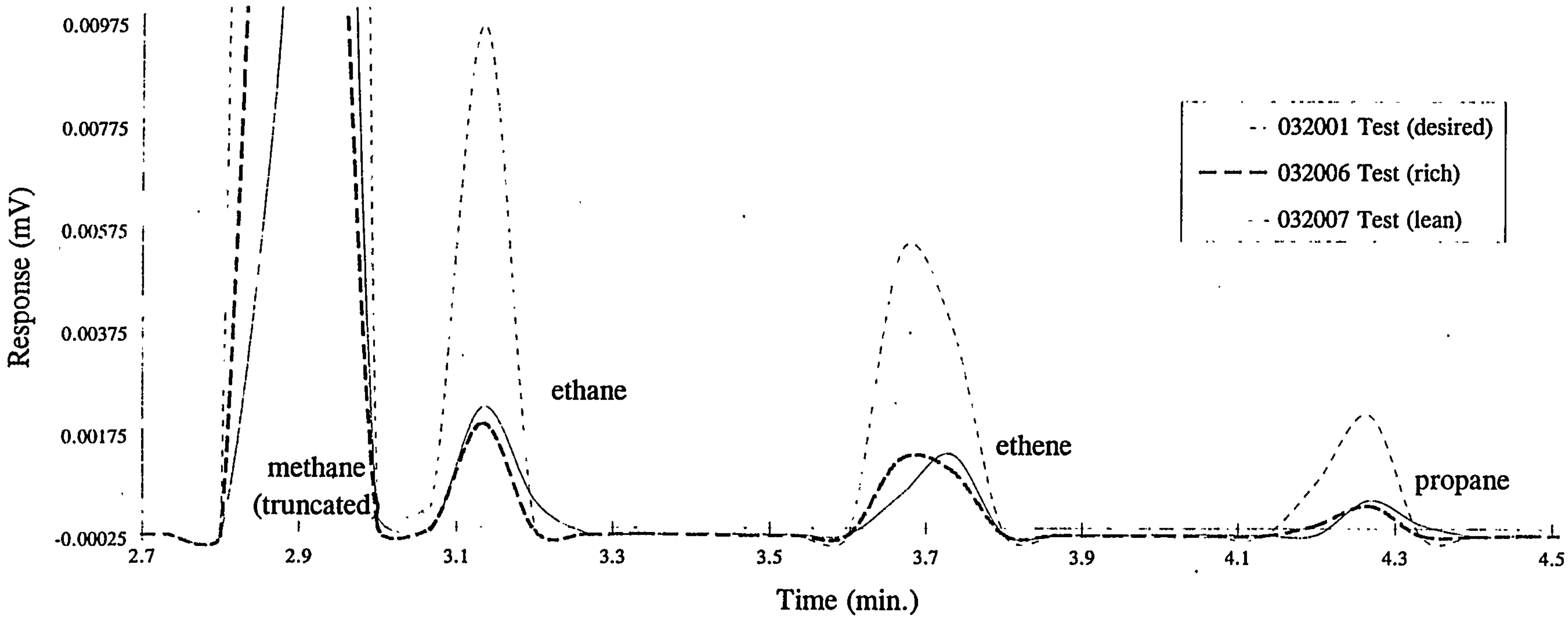
Complete Chromatograph of CNG Exhaust (test 3)



## Repeatability of Tests using One Fuel and One Mode
## (CNG; 1600 rpm at 209 Nm)



**Desired, Rich and Lean Lambda Operating Conditions**
**(CNG; 1600 rpm at 209 Nm)**



# Conclusions

* Speciated hydrocarbon emissions from heavy load conditions and from rich operation show little difference in the production of hydrocarbon species although regulated gases such as $NO_X$ and CO can be greatly affected.

* Light load conditions and lean operation resulting in misfire and hence produced an increase in ethene.

* Propane tests produced higher order compounds such as ethene and propene which have high maximum incremental reactivity values (MIR) (7.28 and 9.39 respectively).

* The fraction of the exhaust hydrocarbons that is methane is lower than the methane fraction in the fuel hydrocarbons.

* Exhaust NMOG versus methane content cannot be judged unambiguously from fuel gas composition.

* More research is required on the effects of mal-adjustment and misfire on HC species during CNG operation.

# West Virginia University

## Department of Mechanical and Aerospace Engineering

## Closed Loop Fueling Control for a Lean Burn Natural Gas Engine

Windsor Workshop on Alternative Fuels
June 3-5, 1996

# Closed Loop Fueling Control for a Lean Burn Natural Gas Engine

| Principal Investigators | Research Staff |
|---|---|
| Dr. Nigel N. Clark | Gregory E. Mott, Engineering Scientist |
| Dr. Christopher M. Atkinson | Richard J. Atkinson, Instrumentation Engineer |
| Dr. Donald W. Lyons | Remco J. deJong, Graduate Research Assistant |
|  | Timo E. Latvakoski, Graduate Research Assistant |

In a project funded by the U.S. Department of Energy, West Virginia University is developing a closed loop fueling control strategy for a lean burn natural gas engine. The integration of a wide-range exhaust gas oxygen (EGO) sensor with the existing open-loop control system will allow continuous equivalence ratio control to maintain the reduced emissions output of a typical lean burn engine. Fueling variations and engine component wear can be compensated for over the life of the engine eliminating any need for engine controller calibration changes or periodic recalibration. By implementing a system that can maintain various air-fuel ratios, excessive production of oxides of nitrogen (NOx) and hydrocarbons (HC) can be avoided by always operating the engine at an optimal equivalence ratio. Such a system can also guard against internal engine damage due to overheating and/or engine knock. Other advantages such as better cold start reliability, increased fuel economy and lower maintenance costs would be realized after implementation of a closed-loop control system.

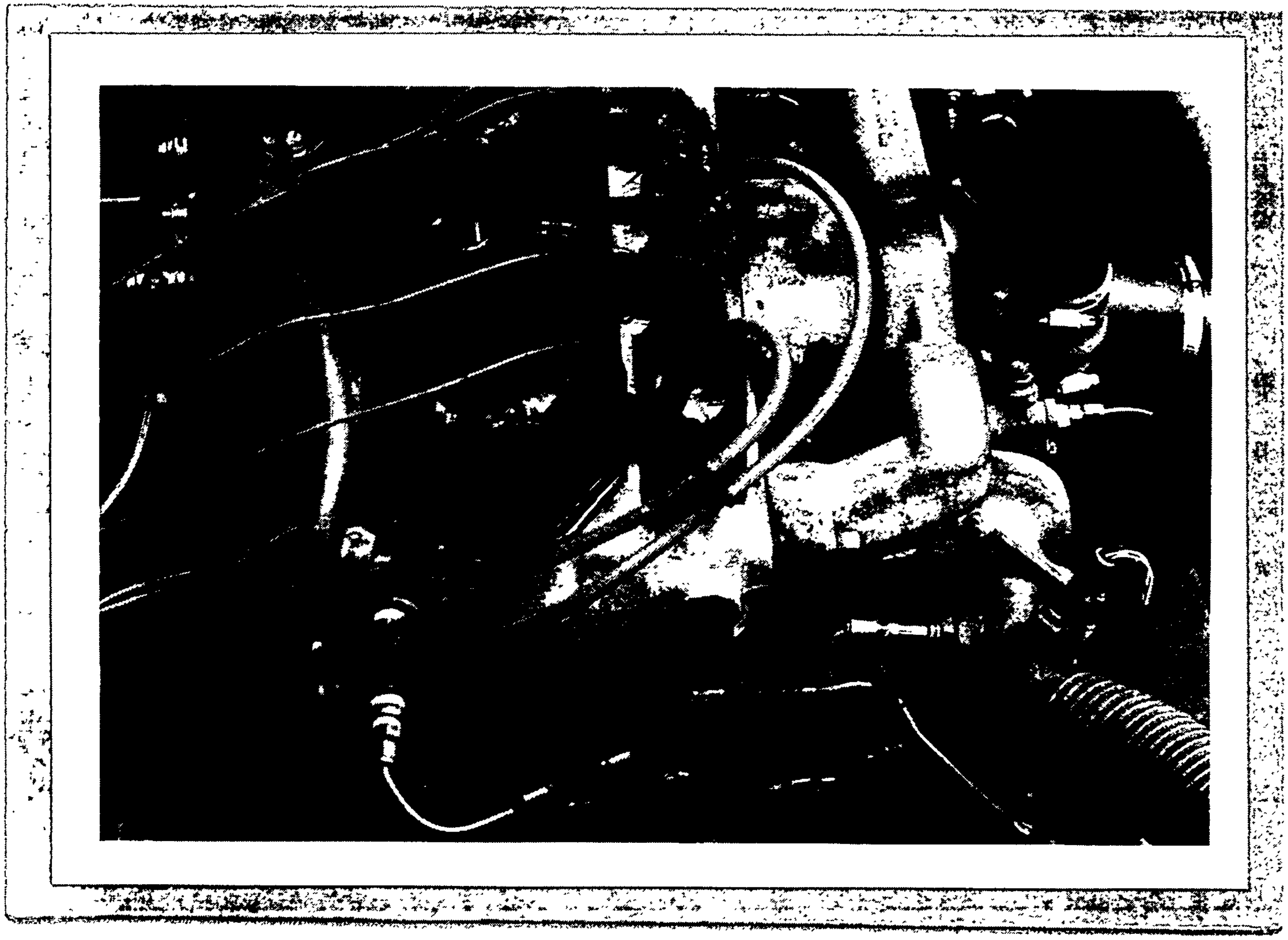
A Hercules turbocharged lean burn natural gas engine fitted with a GFI Compuvalve and an Altronics spark ignition system are being used as a test bed for the research. Closed loop fueling control is accomplished by means of feedback to the Compuvalve from a wide range EGO sensor. Two types of EGO sensor, the NGK Universal Exhaust Gas Oxygen (UEGO) sensor and the Bosch LSM11 wide-range oxygen sensor, have been used in the feedback control. Exhaust gas oxygen sensor longevity is being studied in conjunction with Hercules Engine Company to determine sensor variations relevant to in-field usage for both the NGK UEGO and the Bosch LSM11. Preliminary results from reliability and calibration tests will be presented.

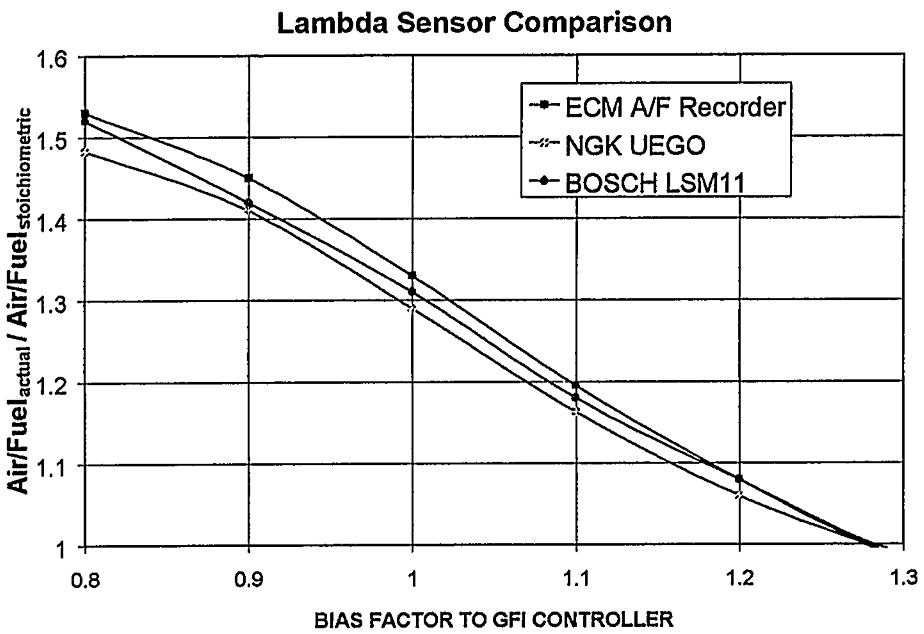
Effects of fuel composition on engine operation was investigated by operating the engine on four different fuel compositions in both open and closed loop modes and at fixed operating setpoints. The fuels varied widely in composition from pure methane to pure propane but retained similar heating values. Results from the sampled data showed small deviations in the in-cylinder pressures with only slight deviations in the engine-out emissions. Due to the fact that natural gas suppliers sell the fuel on the basis of energy content and not composition, engine operation is not significantly affected.

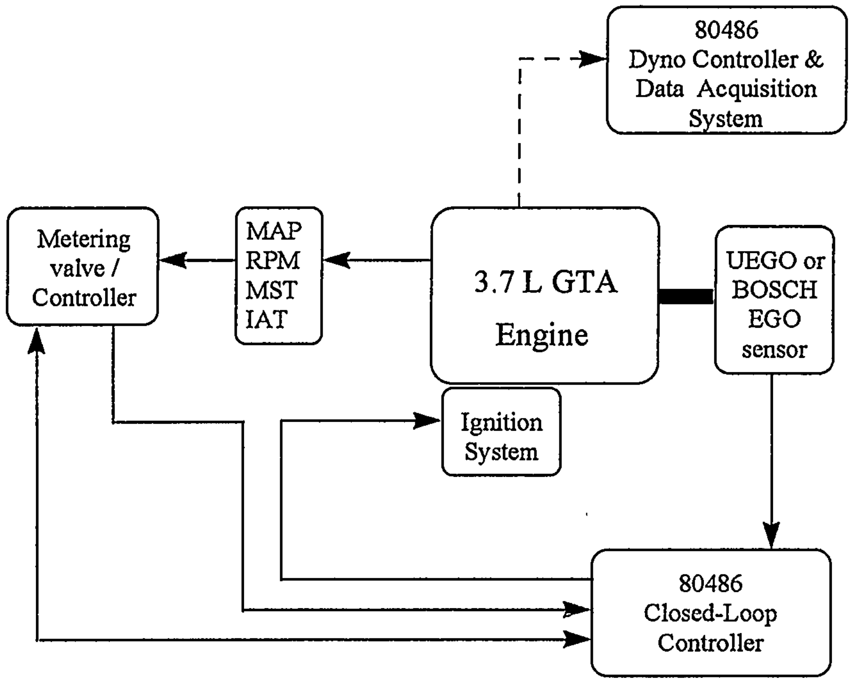
Engine knock detection is being addressed as a means of engine protection. Block resonance has been determined with and without engine knock using accelerometers and non-resonant sensors while the onset of knock has been verified with in-cylinder pressure traces. The dependence of block resonant frequency on engine speed has been established to allow noise from other engine components to be filtered out. Either ignition timing or fueling changes or both will be used to prohibit engine knock. Closed-loop ignition control using direct in-cylinder pressure measurement will be used to minimize regulated emissions and maximize efficiency at each engine load and speed setpoint.

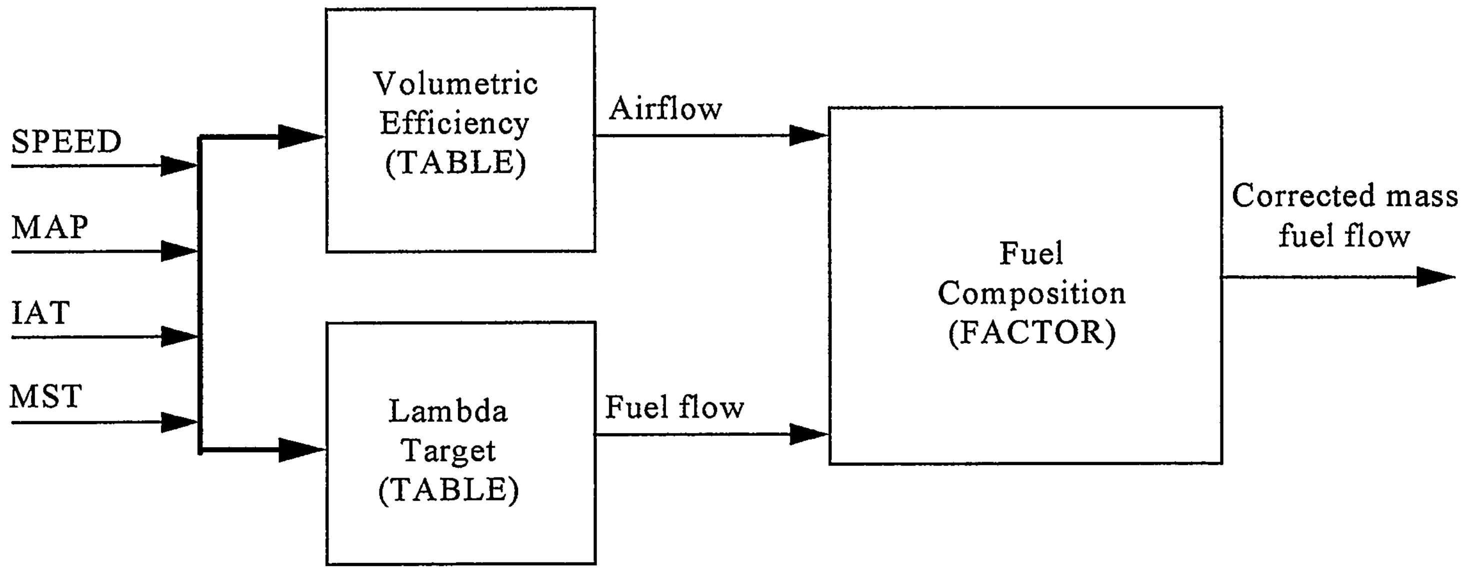
A study is currently underway to improve engine operation by the addition of exhaust gas recirculation (EGR). EGR will be investigated as a means of oxides of nitrogen (NOx) reduction by introducing different amounts of exhaust gases into the turbocharger intake. Exhaust gas has a lower oxygen concentration and will help to reduce NOx production. Initial data has been captured to evaluate the method by which the exhaust gases are being introduced to the intake airstream.

Electronic turbocharger wastegate control will be investigated as a means to allow variable boost levels at different operating conditions. Not only will the maximum boost levels be controlled, but part load efficiency will be increased by eliminating throttling losses.

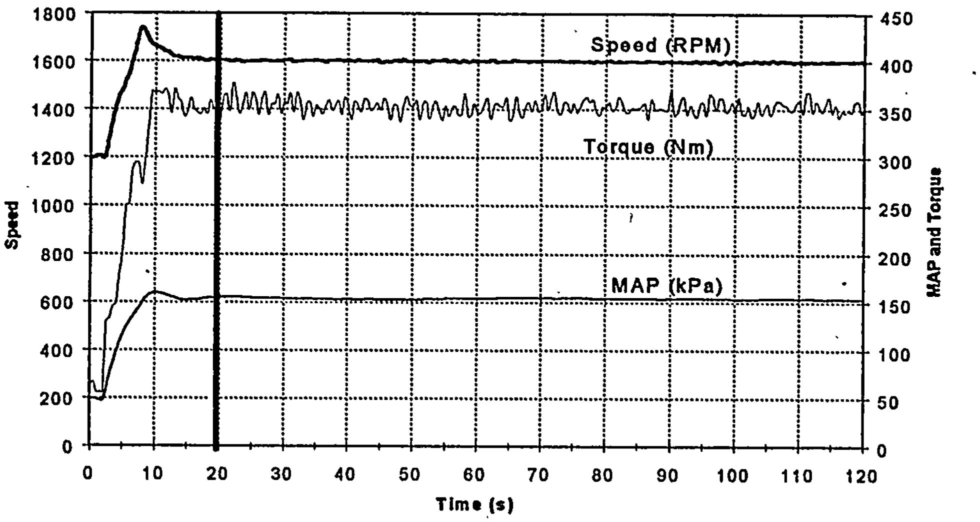


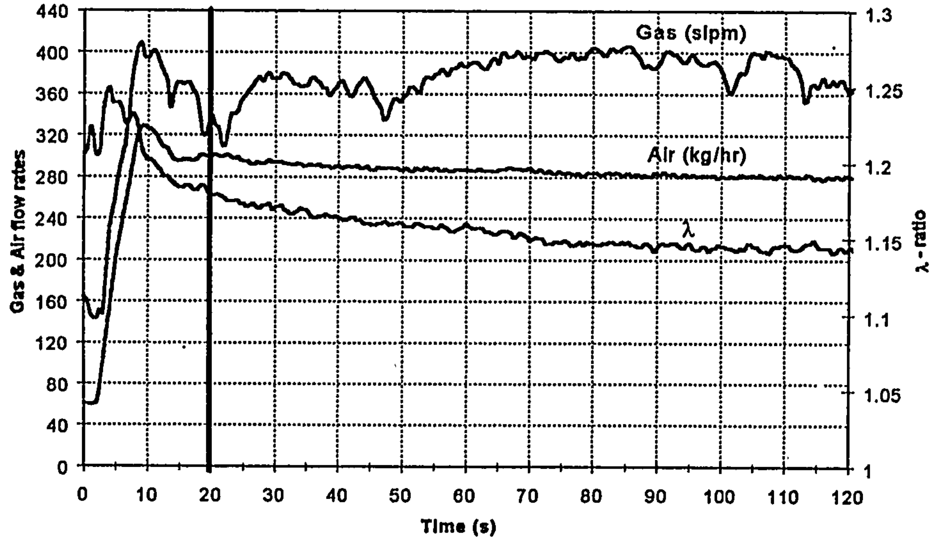

Lambda Sensor Comparison
Air/Fuel$_{actual}$ / Air/Fuel$_{stoichiometric}$
1.6
1.5
1.4
1.3
1.2
1.1
1
0.8
0.9
1
1.1
1.2
1.3
BIAS FACTOR TO GFI CONTROLLER
ECM A/F Recorder
NGK UEGO
BOSCH LSM11


80486
Dyno Controller &
Data Acquisition
System
Metering
valve /
Controller
MAP
RPM
MST
IAT
3.7 L GTA
Engine
UEGO or
BOSCH
EGO
sensor
Ignition
System
80486
Closed-Loop
Controller

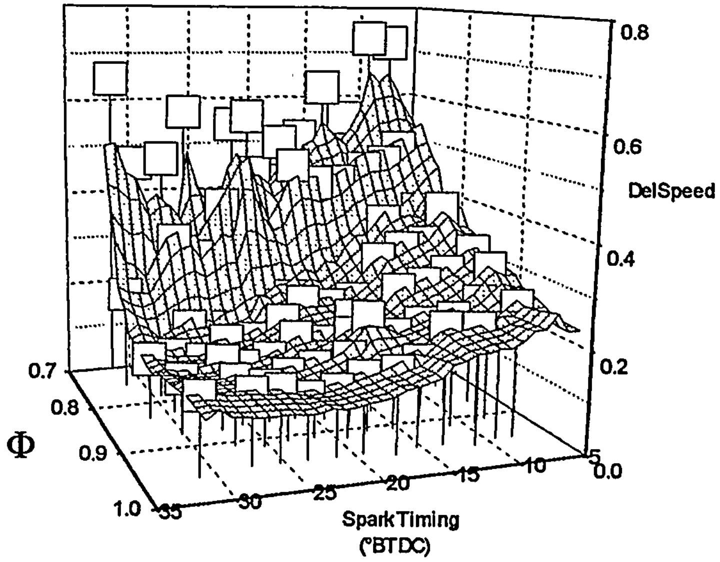

SPEED
MAP
IAT
MST
Volumetric
Efficiency
(TABLE)
Lambda
Target
(TABLE)
Airflow
Fuel flow
Fuel
Composition
(FACTOR)
Corrected mass
fuel flow

# Volumetric Efficiency Deviation

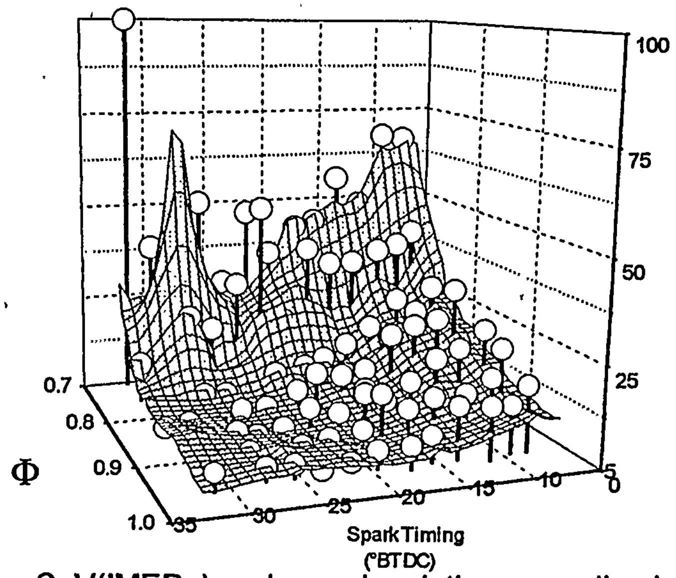




# Lean Limit of Combustion

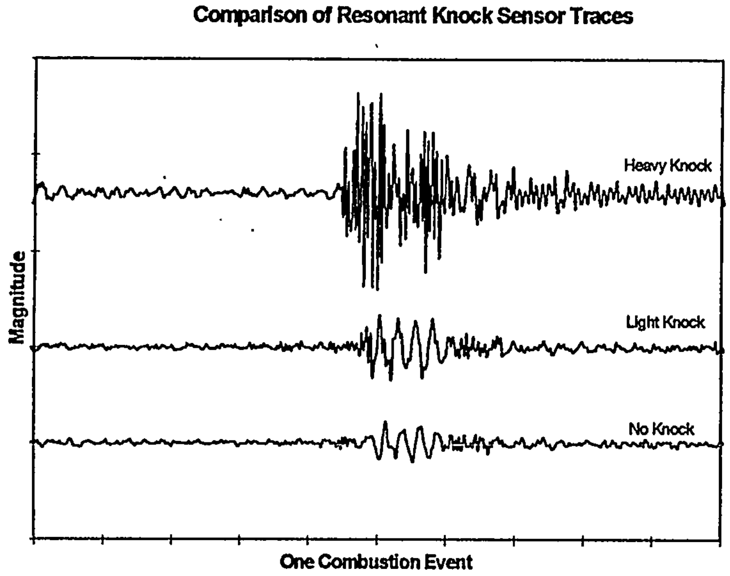


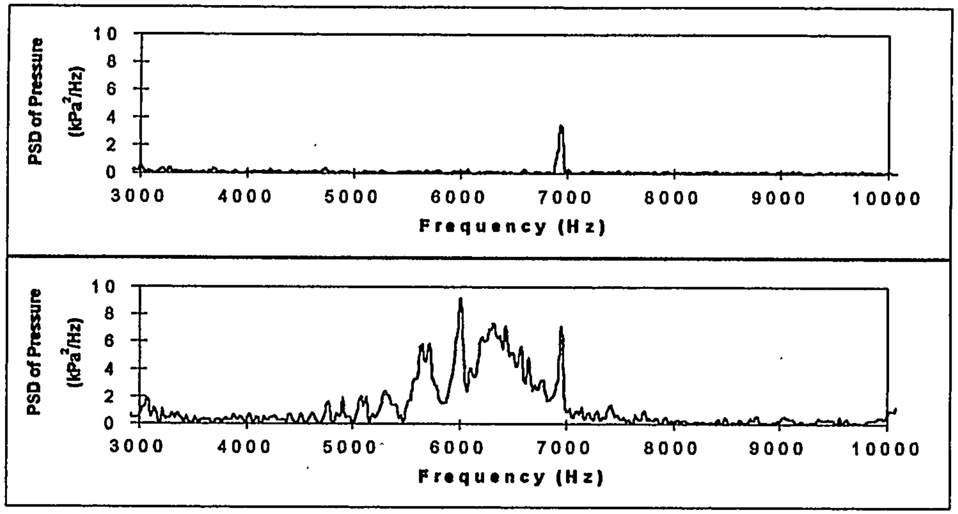
Crankshaft speed variation



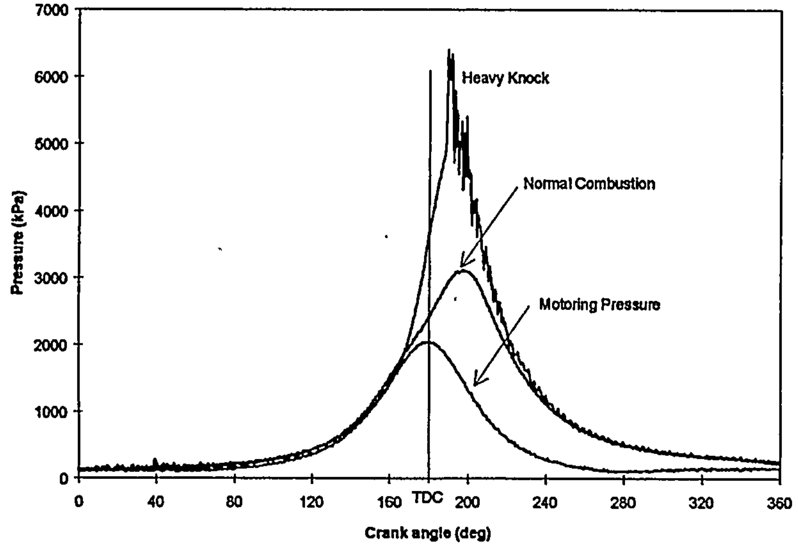
CoV(IMEPg) and speed variation normalized

# Knock Detection


Comparison of Resonant Knock Sensor Traces



PSD of in-cylinder pressure 1800 RPM, 135 Nm



In-cylinder pressure traces

| Method or Sensor | Knock Indicator |
|---|---|
| PCB Resonant Accelerometer | 50 g |
| Bosch Knock Evaluation Circuit | 2.2 volts |
| Delco Resonant Accelerometer | 0.8 to 4 volts |
| Maximum Band Pass Pressure | 50 kPa |
| RMS of Band Pass Pressure | 25 kPa |
| Avg. Abs. Value of Band Pass Pressure | 25 kPa |
| PSD of Band Pass Pressure | 30 $kPa^2/Hz$ |
| Maximum First Derivative | 50 kPa/deg |
| Maximum Second Derivative | 6 $kPa/deg^2$ |
| Minimum Third Derivative | -40 $kPa/deg^3$ |

# Selected Test Results

| CONFIGURATION | FUEL | FTP | CODE | HC (g/BhpHr) | CO (g/BhpHr) | $CO_2$ (g/BhpHr) | $NO_x$ (g/BhpHr) | WORK (Bhp Hr) | BSFC (lb/HpHr) | VALID |
|---|---|---|---|---|---|---|---|---|---|---|
| STOCK | A | COLD | 0325_t1 | 5.786 | 2.445 | 621.66 | 4.782 | 7.82 | 0.515 | Y |
| STOCK | A | HOT | 0322_t8 | 4.488 | 2.125 | 573.93 | 5.831 | 8.2 | 0.474 | Y |
| | | | | | | | | | | |
| CLOSED LOOP | A | COLD | 0402_t2 | 5.352 | 2.389 | 598.2 | 5.051 | 7.24 | 0.495 | Y |
| CLOSED LOOP | A | HOT | 0402_t4 | 5.36 | 2.259 | 568 | 5.187 | 7.32 | 0.471 | Y |
| | | | | | | | | | | |
| STOCK | B | COLD | 0410_t1 | 7.164 | 2.643 | 605.78 | 2.599 | 7.71 | 0.506 | Y |
| STOCK | B | HOT | 0410_t2 | 5.071 | 2.224 | 573.4 | 3.221 | 8.09 | 0.475 | Y |
| | | | | | | | | | | |
| CLOSED LOOP | B | COLD | 0409_t1 | 6.996 | 2.54 | 622.65 | 4.706 | 7.17 | 0.519 | Y |
| CLOSED LOOP | B | HOT | 0403_t2 | 5.356 | 2.152 | 580.54 | 4.489 | 7.84 | 0.481 | Y |
| | | | | | | | | | | |
| STOCK | C | HOT | 0411_t2 | 4.306 | 2.674 | 606.51 | 5.722 | 9.07 | 0.5 | N |
| | | | | | | | | | | |
| CLOSED LOOP | C | HOT | 0411_t1 | 4.075 | 2.339 | 589.96 | 7.779 | 9.39 | 0.486 | N |
| | | | | | | | | | | |
| CLOSED LOOP 3% RICH | A | HOT | 0417_t2 | 4.375 | 2.163 | 566.6 | 7.163 | 8.44 | 0.468 | Y |
| CLOSED LOOP 3% LEAN | A | HOT | 0417_t3 | 6.245 | 2.475 | 569.79 | 3.101 | 7.82 | 0.475 | Y |
| | | | | | | | | | | |
| CLOSED LOOP (PARTIAL EGR) | A | HOT | 0418_t1 | 6.209 | 2.615 | 601.3 | 3.375 | 7.49 | 0.5 | Y |
| CLOSED LOOP (FULL EGR) | A | HOT | 0418_t2 | 9.663 | 3.215 | 657.132 | 1.563 | 6.62 | 0.553 | N |

| | FUEL | | |
|---|---|---|---|
| Constituent | A | B | C |
| METHANE % | 91.82 | 99.9 | 45.8 |
| ETHANE % | 5.33 | | 13.3 |
| PROPANE % | 1.217 | | 23.7 |
| N-BUTANE % | 0.245 | | 2.1 |
| CO2 % | 0.142 | | |
| NITROGEN % | 0.814 | | 15.1 |
| | | | |
| Wobbe# (MJ/$m^3$) | 46.14 | 45.6 | 48.1 |
| Motor Octane Number | 133 | 140 | 107 |

# EVALUATION OF DIFFERENT NATURAL GAS FUELLING STRATEGIES DURING THROTTLE TRANSIENTS

John G. Crawford, Hannu E. Jääskeläinen and James S. Wallace
Department of Mechanical & Industrial Engineering
University of Toronto

Throttle tip-in and tip-out tests were conducted on a 2.0 litre passenger car engine to determine the transient response characteristics of four different natural gas fueling systems:

- Air-valve (variable restriction) mixer
- Venturi-type mixer
- Central fuel injection
- Port fuel injection

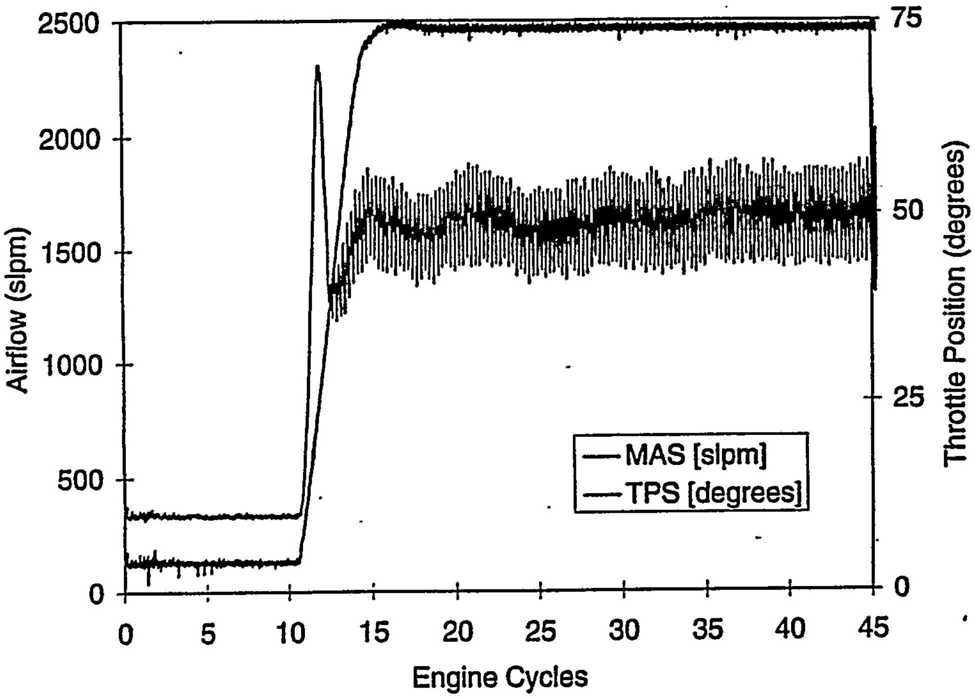
The transient response of each system was characterized by measuring the in-cylinder fuel-air equivalence ratio, $\phi$, each engine cycle using a fast flame ionization detector sampling about 7 mm from the spark plug gap.

The torque response and fuel-air equivalence ratio in the exhaust port were also measured. A wide range oxygen (UEGO) sensor was used for the exhaust port $\phi$ measurements.

All tests were conducted at 2000 rpm with the following throttle transients:

- Throttle tip-in - A throttle step from 35 N-m to WOT in 100 ms.
- Throttle tip-out - A throttle step from WOT to 35 N-m in 100 ms.

Air flow at the throttle plate during the transients showed essentially the same behaviour for all four fueling systems. Figure 1 shows the inrush of air to fill the intake manifold part way through the throttle tip-in.

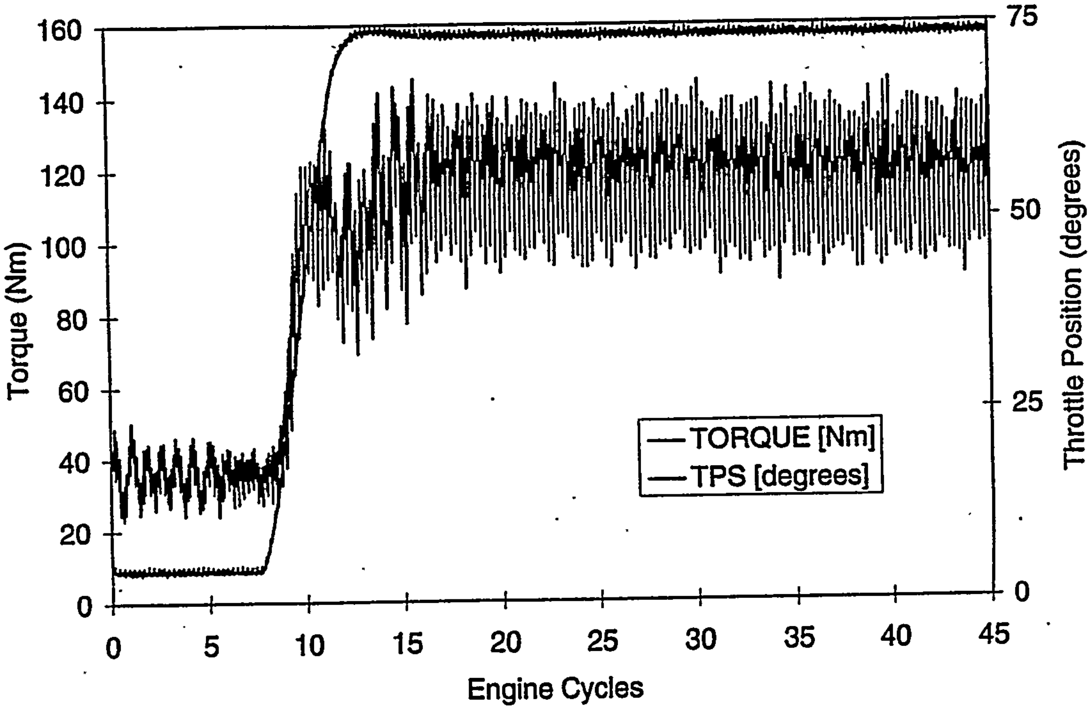


## REPRESENTATIVE TEST RESULTS

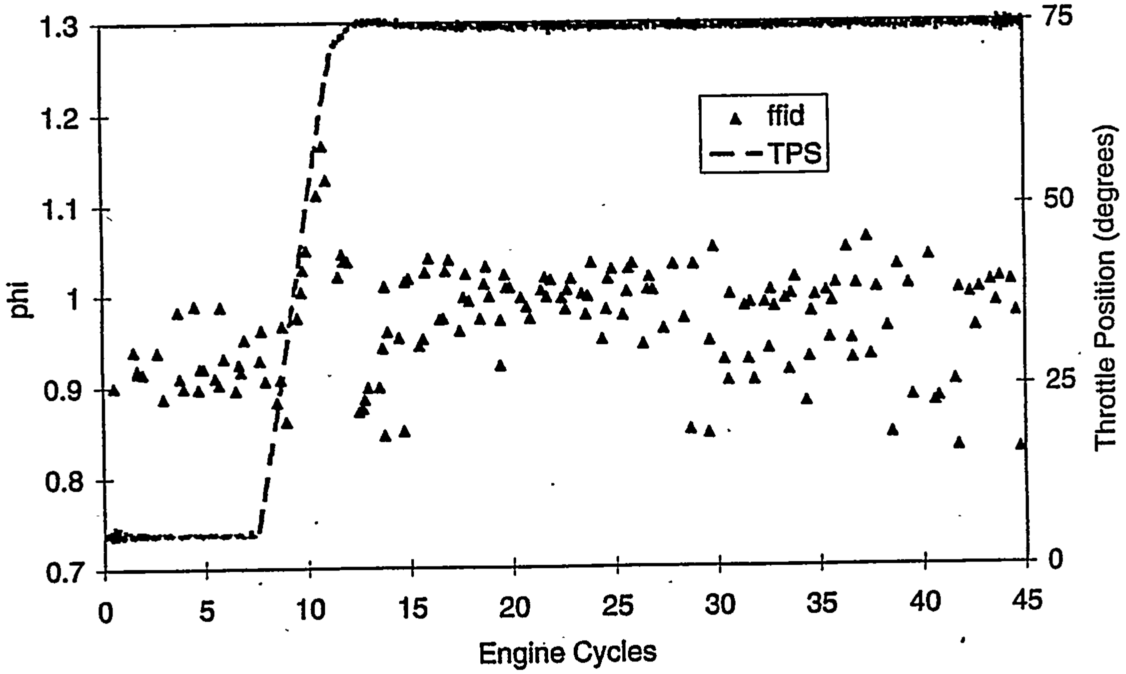
Due to space limitations, only data for the variable restriction mixer will be presented here.

### Throttle tip-in

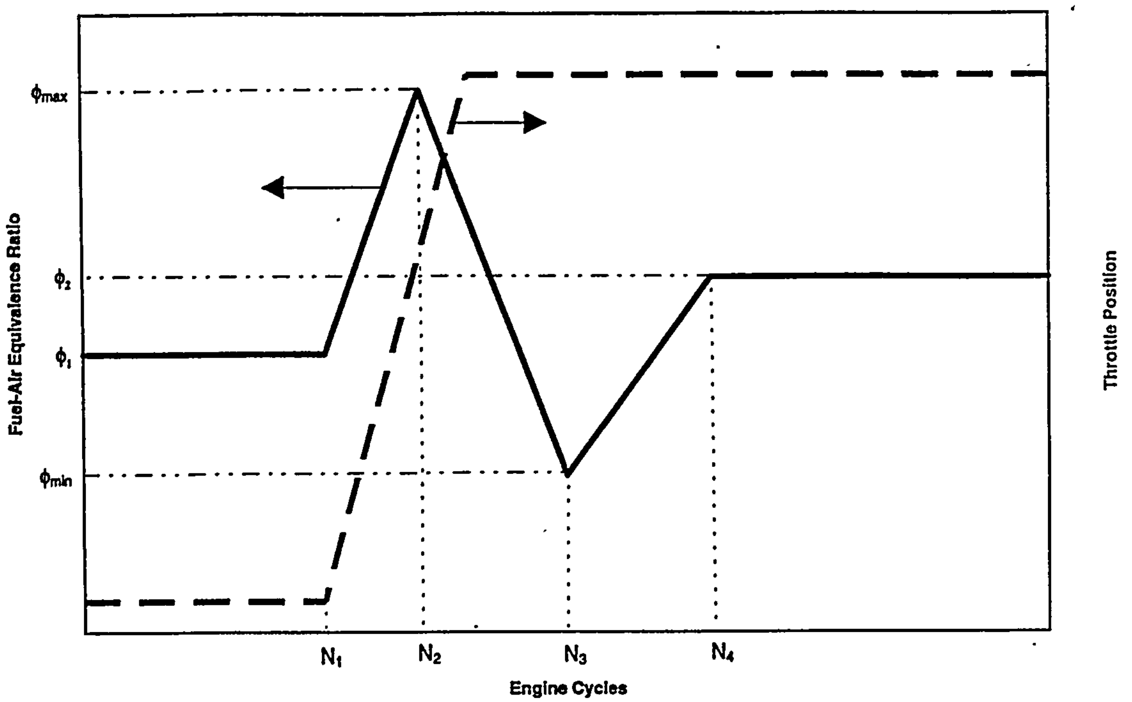
The torque response of this system is quite good, with a quick torque rise from about 35 N-m to 110 N-m, a brief stumble, and then a slower rise to the final torque of 120 N-m.



The figure below shows a sample of the actual in-cylinder ϕ measurements.



The figure below shows the general response trend of the in-cylinder $\phi$ measurements.



A rich excursion begins at the time the throttle has started its movement. It is then followed by a lean excursion after which the effect of the transient on the fuel-air ratio disappears and the in-cylinder $\phi$ rises to its final steady-state value. The effect of the transient lasts a total of 7 or 8 engine cycles.

The table below shows the values of the parameters identified on the plot of the general response trend for each of the individual cylinders. In addition, the cycle-to-cycle variations, as quantified by the standard deviation of the initial and final values of equivalence ratio $\phi_1$ and $\phi_2$, seem to be much more significant in some cylinders than others.

| Cylinder | $\phi_1$ | STD $\phi_1$ | NTK $\phi_1$ | $\phi_{max}$ | STD $\phi_{max}$ | $\phi_{min}$ | STD $\phi_{min}$ | $\phi_2$ | STD $\phi_2$ | $N_1$ | $N_2$ | $N_3$ | N |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.03 | 0.064 | 1.04 | 1.19 | 0.052 | 0.93 | 0.026 | 1.05 | 0.046 | - | 3 | 5 | |
| 2 | 1.00 | 0.054 | 1.04 | 1.27 | 0.051 | 0.89 | 0.12 | 1.06 | 0.046 | - | 2 | 5 | |
| 3 | 1.02 | 0.028 | 1.00 | 1.11 | 0.021 | 0.87 | 0.010 | 1.00 | 0.036 | - | 2 | 4 | |
| 4 | 0.93 | 0.030 | 0.93 | 1.11 | 0.049 | 0.88 | 0.012 | 0.97 | 0.089 | - | 2 | 4 | |
| Average | 1.00 | | 1.00 | 1.17 | | 0.89 | | 1.02 | | | | | |
| STD | 0.045 | | 0.052 | 0.077 | | 0.026 | | 0.042 | | | | | |

TABLE 1. Variable restriction type fuel system parameters for the throttle tip-in.

## PERFORMANCE RATINGS

In order to quantify the performance of the different fuel systems, each one is rated according to several categories, including:

- Torque response, characterized by how quickly and smoothly torque output changes from the intial to the final value.
- Steady-state fuel distribution, characterized according to the variation of the time-averaged fuel-air equivalence ratio among cylinders before and after the throttle transient.
- Transient fuel-air equivalence ratio response, characterized by the limits of the maximum rich excursion and the minimum lean excursion that occured due to the throttle transient (the smaller this difference, the better).

The ratings are given as the letters A through D, with A being the highest rating and D being the lowest. The performance ratings are summarized in the table below.

| *System* | *Tip-in/Tip-out* | *Torque* | *Fuel Distribution* | | *Transient $\phi$* |
|---|---|---|---|---|---|
| | | | *pre-transient* | *post-transient* | |
| **variable restriction** | in | B | C | D | B |
| | out | A | C | C | A |
| **venturi** | in | C | B | C | A |
| | out | C | D | A | C |
| **port injection** | in | A | D | B | C |
| | out | A | B | D | B |
| **central injection** | in | D | A | A | D |
| | out | D | A | B | D |

The table shows that although one particular system may perform well in a given category, it may also perform extremely poorly in another category. The same view can be gained from the list of best performance in each category:

- The port injection system gave the best throttle tip-in torque response.
- The port injection system and the variable restriction mixer both gave excellent throttle tip-out torque response.
- The central fuel injection system gave the least cylinder-to-cylinder maldistribution
- The venturi mixer gave the best throttle tip-in $\phi$ response (only marginally better than the variable restriction mixer).
- The variable restriction mixer gave the best throttle tip-out $\phi$ response.

Note that the overall performance of a particular fuel system depends very strongly on the details of its design. Thus, the performance of the four specific systems evaluated in the present tests should not be extrapolated to other systems of the same general type.

## CONCLUSIONS

The results showed that none of the four systems tested outperformed the others in every rating criterion. Simply bolting on components employing more advanced technology is no guarantee of improved performance. Fueling components, the fuel control system and the control strategy must be carefully integrated to achieve better performance than conventional mixer-based systems.

## ACKNOWLEDGEMENTS

The authors gratefully acknowledge financial support for the project from Nissan Canada and from the Ontario University Research Incentive Fund. We also appreciate helpful discussions with Dr. Shizuo Ishizawa and Mitsunori Ishii of the Environment and Energy Research Laboratory at the Nissan Research Centre in Yokosuka, Japan.

## FURTHER INFORMATION

A full paper is being prepared for the SAE Fall Fuels and Lubricants Meeting. Copies can be requested from:

Professor James S. Wallace
Department of Mechanical & Industrial Engineering
University of Toronto
5 King's College Road
Toronto, Ontario  M5S 3G8

Telephone (416) 978-5736
Fax (416) 978-7753
e-mail: wallace@me.utoronto.ca

# A CASE FOR BIOFUELS IN AVIATION

M. E. Shauck *, M. G. Zanin
Renewable Aviation Fuels Development Center
Baylor University (817-755-3563)
PO Box 97413
Waco, Texas 76798-7413

In the last 15 years, the technical and the economic feasibility of biomass based fuels for general aviation piston engines has been proven. Exhaustive ground and flight tests performed at the Renewable Aviation Fuels Development Center (RAFDC) using ethanol, ethanol/methanol blends, and ETBE have proven these fuels to be superior to aviation gasoline (avgas) in all aspects of performance except range.

Mandates of the Clean Air Act Amendments of 1990 banning lead from all motor fuels, have prompted an effort to find an unleaded alternative to the existing aviation fuel. Avgas is today the single largest contributor of lead in the atmosphere in the U.S. As a result of environmental regulations mandating special handling requirements for avgas and because of its low sales volume, it is predicted that the oil companies will eventually quit its production. For this reason, pilot organizations, the Federal Aviation Administration (FAA), engine manufacturers, and some of the producing companies, are all searching for a replacement aviation fuel.

The main difficulty in manufacturing an unleaded gasoline for aviation is the high octane needed by many aircraft engines. Thus, the current consensus among the organizations involved in the research is to settle for a fuel of between 96 to 98 octane. The development of a fuel with a lower than 100 octane rating could satisfy the requirements of about 70% of the general aviation aircraft in the U.S. fleet. However, the remaining 30% of the fleet requires 100 octane fuel, and it uses 80 % of the aviation fuel sold in this country (1).

General aviation is facing a serious problem. Ethanol can be the solution. RAFDC has obtained FAA certifications for two series of aircraft engines and certification of a training aircraft and an agricultural aircraft are expected to be completed shortly. One series of aircraft engines certified is fuel injected while the other is carburated. Thus, FAA approval has been received for engines whose delivery systems cover the range of those in use. This experience will considerably simplify and shorten the process in pursuing further engine certifications.

The piston engine fleet in the United States uses 305 million gallon of avgas per year. This is a market for which ethanol has distinct performance advantages and is competitive at today's ethanol prices. With the demise of 100LL avgas on the horizon, and the competitive economic position of ethanol versus aviation fuel, the potential success of this program is unquestionable. Gaining the aviation market could, in addition to providing a substantial expansion in the ethanol industry, contribute to a public acceptance of ethanol as a general transportation fuel.

1. D.Macnair, (AOPA), Presentation to the "First International Conference on Alternative Aviation Fuels", Waco, Texas, November 1995.

# ETBE AS AN AVIATION FUEL

G. D. Maben, M.E. Shauck, M.G. Zanin
Department of Aviation Sciences
Baylor University
Waco, TX 76798

## Abstract

This paper discusses the preliminary flight testing of an aircraft using neat burning ethyl-tertiary-butyl-ether (ETBE) as a fuel.

No additional changes were made to the fuel delivery systems which had previously been modified to provide the higher fuel flow rates required to operate the engine on neat ethanol. Air-fuel ratios were manually adjusted with the mixture control. This system allows the pilot to adjust the mixture to compensate for changes in air density caused by altitude, pressure and temperature. The engine was instrumented to measure exhaust gas temperatures (EGT), cylinder head temperatures (CHT) and fuel flows, while the standard aircraft instruments were used to collect aircraft performance data. Baseline engine data for ETBE and Avgas are compared.

Preliminary data indicates the technical and economic feasibility of using ETBE as an aviation fuel for the piston engine fleet. Furthermore, the energy density of ETBE qualifies it as a candidate for a turbine engine fuel of which 16.2 billion gallons are used in the U.S. each year.

# ETBE AS AN AVIATION FUEL

## Introduction

In an effort to clean up the air, programs such as the phase-out of leaded gasoline and the use of cleaner fuels are being required in the United States. Mandates in the Clean Air Act Amendments of 1990, banning leaded fuels and requiring reformulated oxygenated fuels, are a major cause of turmoil in the aviation industry since 100 Low Lead (100 LL) is the only high octane aviation gasoline currently available.

Although aviation fuel is only a small fraction of the gasoline sold in this country, as a result of reducing lead in other fuels, 100 LL aviation gasoline (Avgas), is now the single largest source of lead in the atmosphere. At the current consumption level of around 300 million gallons of aviation gasoline a year, 0.45 million grams of lead are released annually into the air (Nussbaum, 1991).

The U.S. requirements for oxygenated fuels for automobiles are providing the opportunity to introduce fuels that can replace leaded aviation gasoline, providing not only environmental benefits but technical advantages as well.

## Avgas Situation

Due to the difficulty of producing an unleaded alternative to 100 LL, the Environmental Protection Agency (EPA) has granted aviation gasoline a temporary waiver to the ban on leaded fuels. However, it is expected that within two years there will be no more leaded fuels. The urgency for the oil industry to find an alternative fuel is going to be dictated by economic considerations because the requirements for handling leaded fuels are going to be more restrictive. Some of the companies producing or delivering 100 LL have already quit its production and/or distribution, while most of the companies still producing it have already switched to dedicated distribution systems. This means high costs, as the pipes and trucks used to deliver leaded fuels cannot be used for the delivery of unleaded gasolines. Under these conditions, the aviation fuel market, which is very small when compared to the auto-gasoline market, provides narrow profit margins for the petroleum industry.

Besides the economic consideration of the producing companies, there are other costs involved with the continued use of leaded fuel.

Environmental regulations are going to affect the disposal of the oil used in the engines burning leaded fuel. The oil will contain too much lead to be burned in incinerators and will probably have to be treated as a toxic waste at a great expense due to high disposal fees.

Also, increased use of alkylates in the new automotive reformulated fuel will cause the price to increase and could result in supply shortages for their use in Avgas production.

Additionally, the Montreal Protocol requires elimination of all use of Ethyl-Di-Bromide, a lead scavenger without which 100 LL cannot be used.

## Search for Alternatives

For these reasons, the search for an alternative fuel to aviation gasoline is underway. The American Society for Testing Materials (ASTM) formed the Committee D.2 Section J, and Subcommittee J Section J.2 to consider the problems involved in the development of an alternative fuel for aviation and to examine the proposed alternatives. In response to demands advanced during ASTM meetings by various fuel producers, the General Aviation Manufacture Association (GAMA) distributed suggested guidelines to fuel producer organizations. This general description of the proposed fuel characteristics called for a lead free high octane gasoline suitable for use in powerplants approved for 100 LL/130 Avgas. According to GAMA, the fuel should require only minimum, or preferably no, engine modifications and have minimal impact on operational procedures (GAMA 1991).

Guidelines were created in an effort to somewhat ease the current standards for aviation gasolines, which were, in part, established fifty years ago to meet the needs of large displacement radial engines. Since few of these engines are currently operating, the suggested new standards should be able to meet the requirements of most of the horizontally opposed General Aviation engines in use today.

Fuel formulations complying with GAMA's suggestions have been produced in laboratories and results have been presented at ASTM meetings. However, as of today, few of the gasoline producing companies or engine manufactures are involved in actual field testing of the proposed fuel blends.

The Federal Aviation Administration (FAA) Technical Center in Atlantic City, New Jersey, has been testing different fuels containing variable concentrations of ethers and other additives intended to improve the octane rating of the fuel.

The Center is currently testing octane number requirements in certain commonly used engines in order to determine if a lower octane number would be technically acceptable. An octane number of 98 has been proposed for aviation gasoline. This lower octane would facilitate the production of the new fuel and lower its cost.

The decision to adopt a fuel with a lower octane number will negatively affect 30 percent of the current General Aviation flying fleet, which will not be able to fly with the new fuel. The problem is that this group of aircraft burns about 80 percent of the total fuel used today (Mac Nair, 1995).

The FAA Technical Center is currently testing blends of unleaded gasoline with 5 to 30 percent MTBE (methyl tertiary butyl ether). Blends of unleaded gasoline and ETBE (ethyl tertiary butyl ether) are also being tested.

The Renewable Aviation Fuels Development Center (RAFDC) at Baylor University in Waco, Texas, has been working on research and certification of renewable fuels for aviation for the past 15 years. The Center has been testing ethanol, methanol, and various blends of the two in reciprocating engines and has certified two series of Lycoming engines on pure ethanol. As part of the search for an alternative to 100LL, RAFDC has received a grant from the FAA Technical Center to test the non-petroleum alternatives to aviation fuel and improve the efficiencies of the engines using these fuels.

One of the most promising fuels to be tested under this research project is ETBE. In April of 1995, the first flight tests ever on pure ETBE were performed by RAFDC. The results of the preliminary testing were so satisfactory that RAFDC flew a Pitts Special S2B aerobatic biplane, on ETBE at the Paris airshow (the largest aviation event in the world), in June 1995.

## ETBE Characteristics

The technical characteristics that make ETBE an attractive fuel for aviation are numerous.

ETBE is made from domestically produced materials: ethanol, a renewable liquid fuel (43 percent by volume); and Isobutylene, produced from domestic natural gas liquids or obtained as a co-product in domestic oil refining and petrochemical production. It is an oxygenated fuel with an oxygen content of 15.7 percent by weight.

ETBE has a neat Reid Vapor Pressure (RVP) of 4.0. Its energy density is 96,000 BTU /gallon.

ETBE's high octane number, 110 (R+M/2), allows the use of a higher compression ratio in the engine, improving fuel efficiency. It should be noted that a six octane number increase in gasoline can allow the increase of engine compression ratio by two numbers. This translates into a 10 percent increase in fuel efficiency.

2

## Flight Test Data

All data was taken in a Pitts Special S2-B powered by an Avco-Lycoming AEIO-540-D4A5. This is an air-cooled, fuel injected engine rated at 260 horsepower at 2700 RPM. The aircraft was equipped with the following instrumentation:

Oil Temperature
Oil Pressure
Fuel Flow (turbine type)
Fuel Pressure
Manifold Pressure (MAP)
Tachometer
Exhaust Gas Temperatures (all cylinders)
Cylinder Head Temperatures (all cylinders)
Airspeed
Altimeter (set to 29.92 Inches Hg.)
Outside Air Temperature (OAT)

All testing was done at 2000 feet pressure altitude. This means the altimeter was set to 29.92 Inches Hg. As reference, the ICAO standard atmosphere at 2000 feet has a temperature of 51.87 degrees F..

## Range and Power Comparison Between Avgas and ETBE

Figure 1 and 2 depict data collected at 24 In. MAP and 2400 RPM on Avgas and ETBE. The OAT for the data on ETBE was 61 degrees F. and for Avgas it was 60 degrees F., thus the conditions were essentially identical for the two tests.

The maximum specific range for ETBE was 9.75 miles per gallon (mpg) at 14 gallons per hour (gph) and 140 miles per hour (mph). (Fig. 1)

The maximum specific range for Avgas was 11.5 mpg at 13 gph and 140 mph. (Fig 2)

Energy density for Avgas is approximately 125,000 BTU's per gallon. It is 96,000 BTU's per gallon for ETBE. Thus, the energy density of ETBE is approximately 23 percent less than Avgas. However, the range reduction on ETBE compared to Avgas was only 15 percent according to the measurements taken on the two flights. On both flights the airplane was operating at very close to the same RPM and airspeed, so the propeller efficiency was essentially constant. This implies that the engine combustion efficiency is greater on ETBE.

The maximum airspeed, hence maximum power available, are essentially the same at the power setting tested.

## Additional Flight Test Data on ETBE

Data was taken at 25 in. MAP and 2500 RPM. The OAT was 58 degrees F. (Fig. 3) The graph shows that a maximum of 165 mph at 19 gph was recorded at a specific range of 8.5 mpg. For this power setting, the maximum specific range was 9.2 mpg at 16.2 gph and 150 mph.

In figure 4, data collected at 23 inches MAP and 2300 RPM is shown. The OAT was 72 Degrees F. In this case a maximum specific range of 10.2 mpg at 140 gph and 145 mph was recorded.

## Comments

This flight data maps only a small portion of the performance of ETBE as an aviation fuel. For example, the range comparisons between Avgas and ETBE are given for only one power setting. Note that the specific range of ETBE increases from 9.75 mpg to 10.2 mpg at 23 in. MAP and 2300 RPM, while the airspeed actually increases at the lower power setting. Clearly, a caveat is necessary at this point. This data is taken in real world conditions and as such is subject to errors induced by updrafts, downdrafts and/or pilot induced errors such as incorrect instrument interpretation and imprecise aircraft control.

The initial results on ETBE (43 percent ethanol) are consistent with the extensive experience of RAFDC on neat ethanol as an aviation fuel.

A recently completed test stand facility equipped with a dynamometer will enable more precise data to be obtained.

## Economics and Market Potential

The cost of ETBE production is predicted to swing around \$ 0.75/ gallon. This calculation is made by assuming natural gas price at \$ 2.00/MCF; butanes at \$ 0.35/gallon; ethanol at \$ 1.04/gallon (before \$0.54/gallon credit).

The size of the aviation gasoline market represents an ideal niche for pure ETBE fuel. It is estimated that annual consumption of aviation gasoline varies between 300 and 350 million gallons. The most conservative figure given by the Aircraft Owners and Pilots Association (AOPA) for the year 1993 is 305 million gallons. Over the last ten years the consumption of aviation gasoline decreased abruptly from about one billion gallons in the early 80's to today's 300 million gallons. The reasons for this decrease are to be attributed to problems related to a down turn in general aviation largely because of product liability issues. A regulation to limit this product liability has been recently passed and there are predictions of a resurgence in general aviation with a consequent increase in aviation fuel consumption.

At today's projected prices, ETBE is already economic competitive with aviation gasoline (\$ 1.60 to \$ 2.30 per gallon). It is all the more so when considering that the price of ethanol is decreasing as new production technologies are developing and the feedstock base is expanding. On the other hand, the price of Avgas can only increase in the future since, as a general trend, petroleum prices can only rise as reserves are depleted, extraction costs increase, and the demand for energy grows.

## Environmental Benefits

The production and use of fossil fuels worldwide contribute 57 percent to all manmade greenhouse gas emissions. Fossil fuels constitute 85 percent of U.S. energy consumption. The transportation sector is responsible for almost one third of U.S. carbon dioxide emissions (NTIS, 1992) and it is 97 percent dependent on oil (Lynd, 1991).

Renewable fuels can decrease the net output of carbon dioxide by displacing fossil fuels. The use of biomass to produce ethanol and ETBE, will greatly reduce the nation's greenhouse gas emissions. Fossil fuels remove carbon that is stored underground and transfer it to the atmosphere. Biomass releases carbon dioxide as it burns but extracts it from the atmosphere as it grows, creating a closed carbon cycle. Indeed, substantial quantities of carbon can be captured in the soil through biomass root structure, creating a net carbon sink.

ETBE's high octane rating eliminates the need to use carcinogenic hydrocarbon based aromatic octane enhancers (such as benzene which is proven to cause cancer) and many of the environmentally less desirable gasoline components such as sulfur.

Since the ban on leaded fuels exists because of environmental concerns, emission testing of the new blends are an important aspect of this research. Emissions from new fuels need to be environmentally acceptable. Data collected on the engines tested by the FAA Technical Center shows a general trend: by increasing ether concentrations, emissions of hydrocarbons and carbon monoxide decrease while emissions of oxides of nitrogen and of carbon dioxide increase (Ferrara, 1994). RAFDC is in the process of acquiring all the equipment necessary to analyze the emissions of pure ETBE and other renewable fuels.

There are three basic issues involved in the debate over the formulation of the next generation of fuels; economics, energy independence, and environment. The environmental issue and the potential of the new fuels to reduce and possibly eliminate the adverse health effects of the current liquid transportation fuels is by far the most important of all these issues.

## Conclusions

Besides the environmental benefits, the economic advantages, and the superior performance, the adoption of a domestic renewable fuel will reduce the dependence on foreign oil, reduce the federal budget deficit, improve the balance of trade and national energy security, boost rural economy, and create jobs together with a major new American industry.

Today, the United States imports more than 50 percent of its petroleum. This situation presents an energy security problem and it is responsible for approximately $ 45 billion of the U.S. trade deficit. Furthermore, the military expense of maintaining access to the Persian Gulf oil exceeds $ 35 billion a year (U.S. DOE Alternative Fuels Hotline, 1996).

ETBE satisfies all of the requirements as an aviation fuel. The potential for ETBE production is enormous. ETBE combines the nation's two most abundant domestic clean burning fuels, natural gas and ethanol. It can be used in a reciprocating aircraft engine with minor modifications to its fuel injection system. Additionally, it has a great potential as a turbine fuel to improve emissions.

It is time for the real cost of oil to be taken into account. The promotion of biofuel programs cannot be postponed just because their prices are not competitive with the present artificially low cost of oil. Liquid biofuels development has to become a national priority. They will decrease our energy dependence and trade deficit while providing benefits to air quality and employment.

Although the potential market for ETBE (or ethanol) as an aviation fuel is a small percentage (0.5 percent) of total transportation fuel consumption in the US., its adoption will be an important step in the right direction.

The use of these fuels in aviation, where high performance is essential, will demonstrate the technical and economic feasibility of renewable fuels as high quality liquid transportation fuels.

## Acknowledgments

The authors would like to acknowledge the support of the following organizations:

ARCO Chemical Company
Aviation&Pilote (French Aviation Magazine)
Ecofuel S. p. A. (Italy)
Federal Aviation Administration (FAA)
Kiewit Fuels Inc.

## References

Ferrara, G. 1994. "Forum on Unleaded Aviation Fuel Program." *Presentation to Experimental Aircraft Association Fly-In.* Oshkosh, WI: Federal Aviation Administration.

GAMA, 1991. *GAMA Suggested Guidelines: Unleaded High Octane Aviation Gasoline Minimum Characteristics.* Ocean City, NJ: General Aviation Manufacturers Association.

Lynd, L.R, J.H Cushman, R.J. Nichols and C.E Wyman. 1991 "Fuel Ethanol from Cellulosic Biomass" *Science,* 251:1318-1323.

MacNair, D. 1995. "Current Search for Petroleum Alternatives to Av-Gas." *Presentation to The First International Conference on Alternative Aviation Fuels,* Waco, TX: Aircraft Owners & Pilots Association.

NTIS. 1992. *Biofuels Program Plan FY 1992 - FY 1995.* Springfield, VA: U.S. National Technical Information Service.

Nussbaum, B. 1991. *Communication with Authors.* Washington, D.C.: Field Operations and Support Division, Office of Mobile Sources, U.S. Environmental Protection Agency.

U.S. Department of Energy's Alternative Fuels Hotline. 1996. *Environmental and Energy Information.* Arlington, VA: Information Resources, Inc.

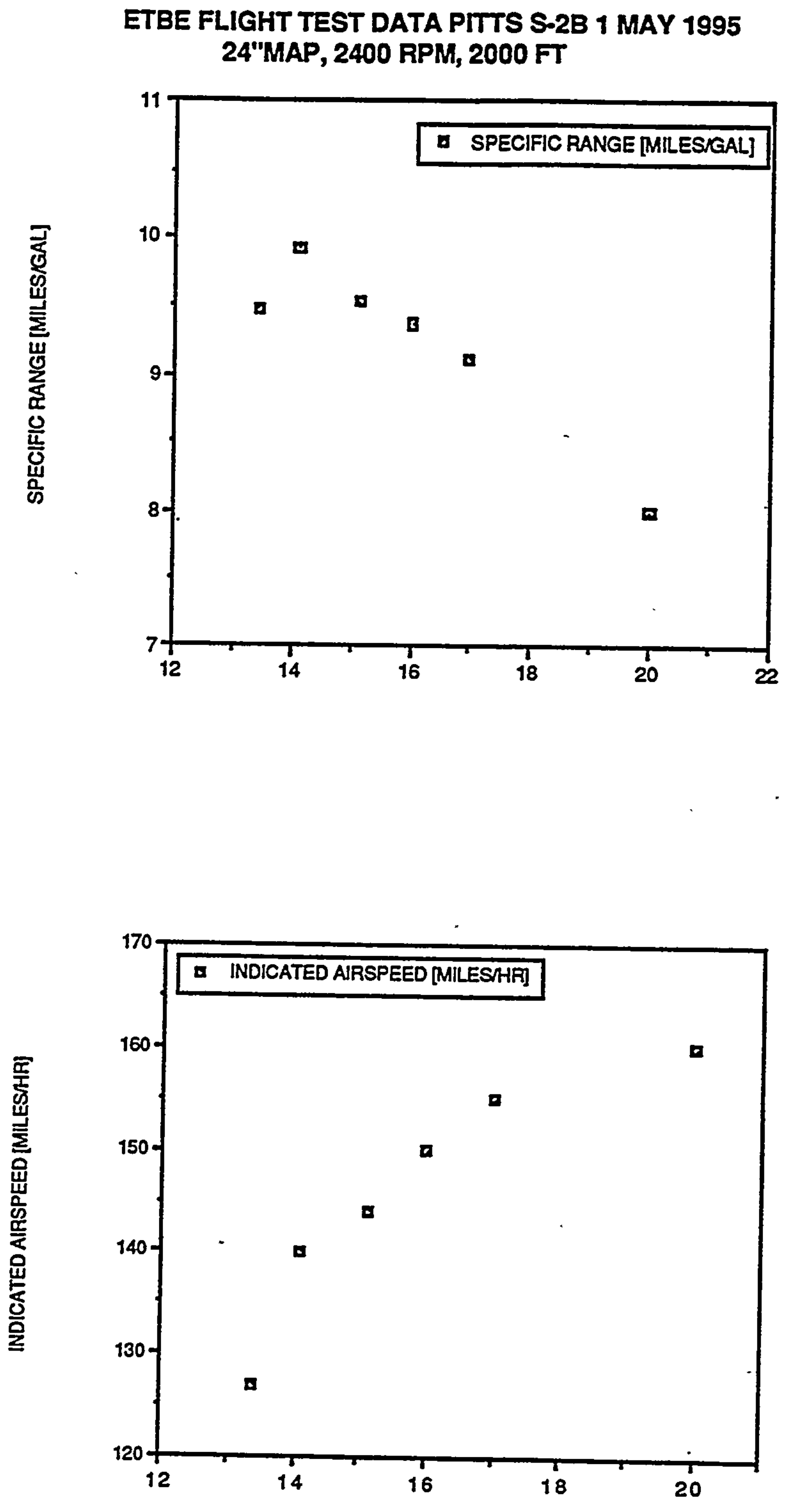
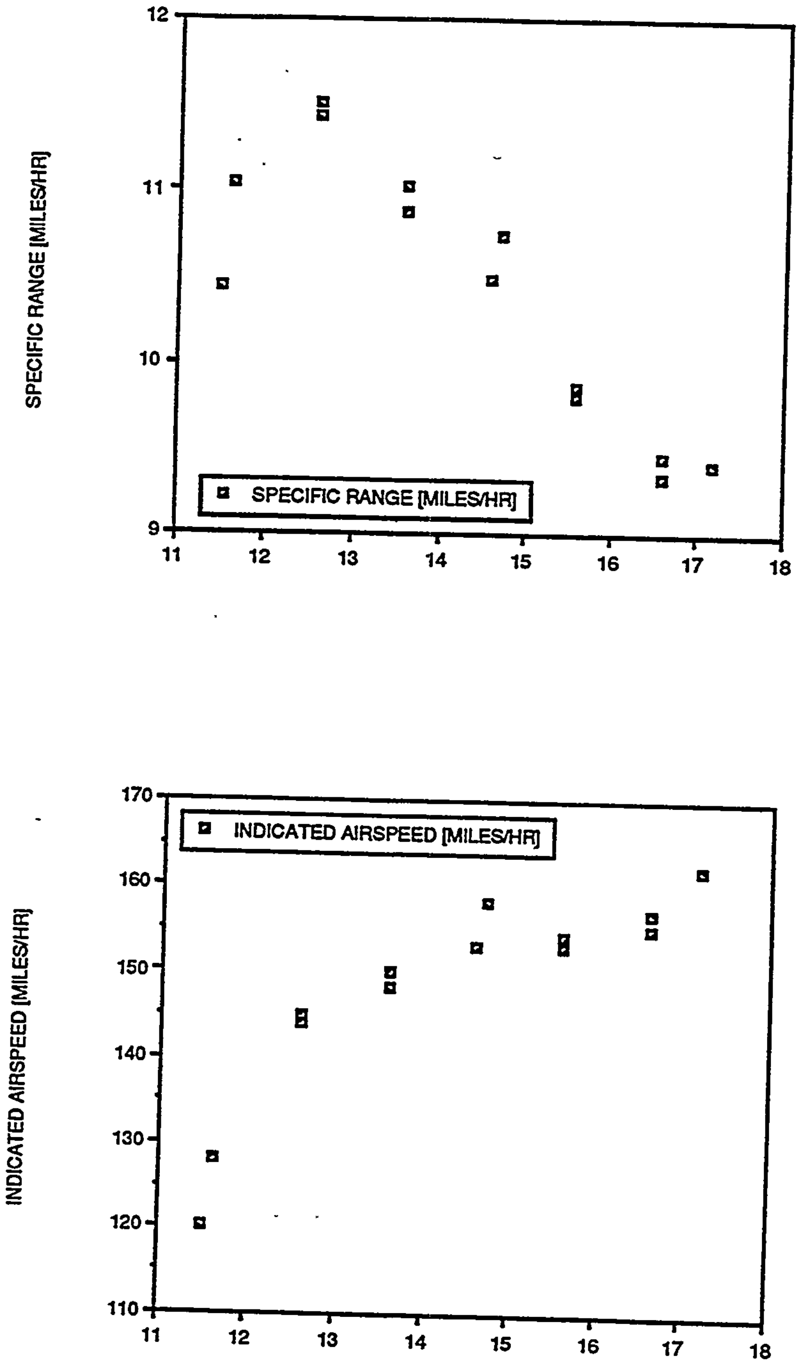
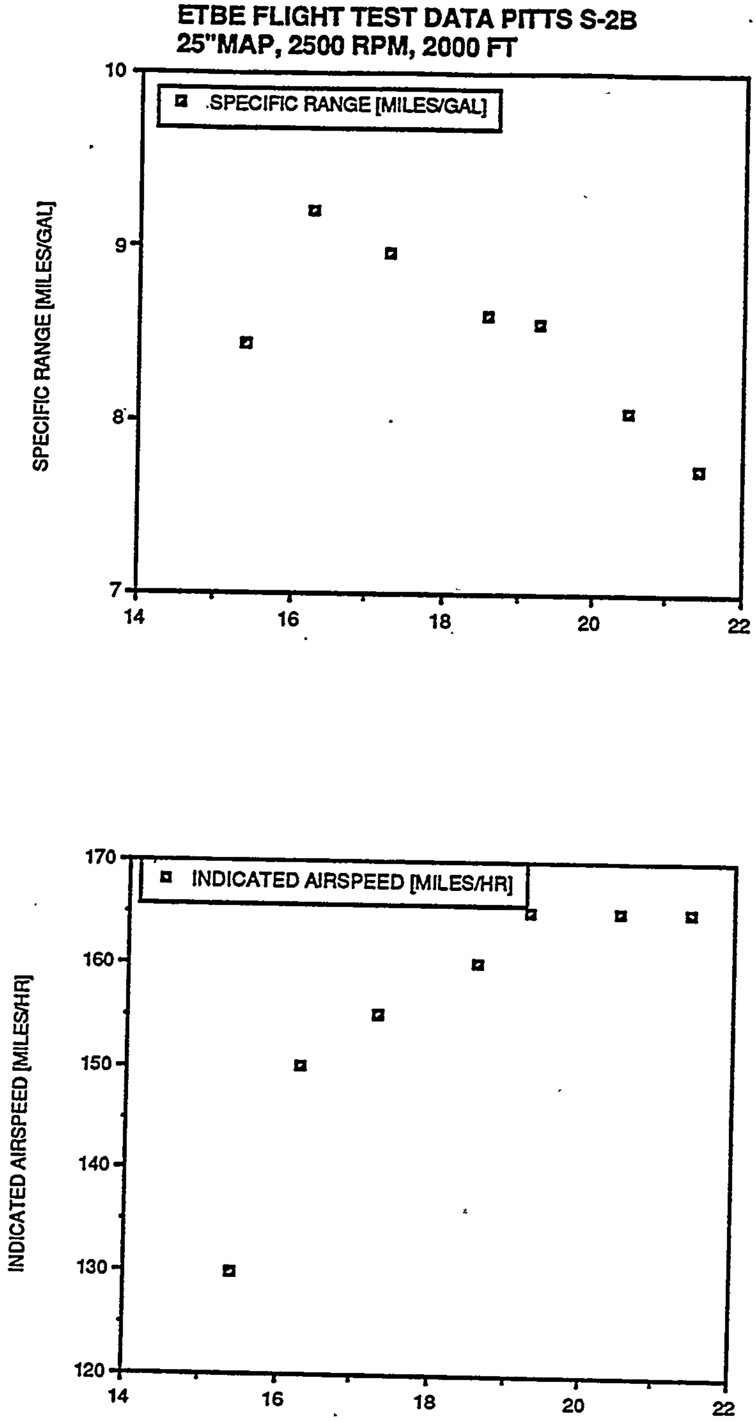

ETBE FLIGHT TEST DATA PITTS S-2B 1 MAY 1995
24"MAP, 2400 RPM, 2000 FT
SPECIFIC RANGE [MILES/GAL]
SPECIFIC RANGE [MILES/GAL]
11
10
9
8
7
12
14
16
18
20
22
INDICATED AIRSPEED [MILES/HR]
INDICATED AIRSPEED [MILES/HR]
170
160
150
140
130
120
12
14
16
18
20

Figure 1



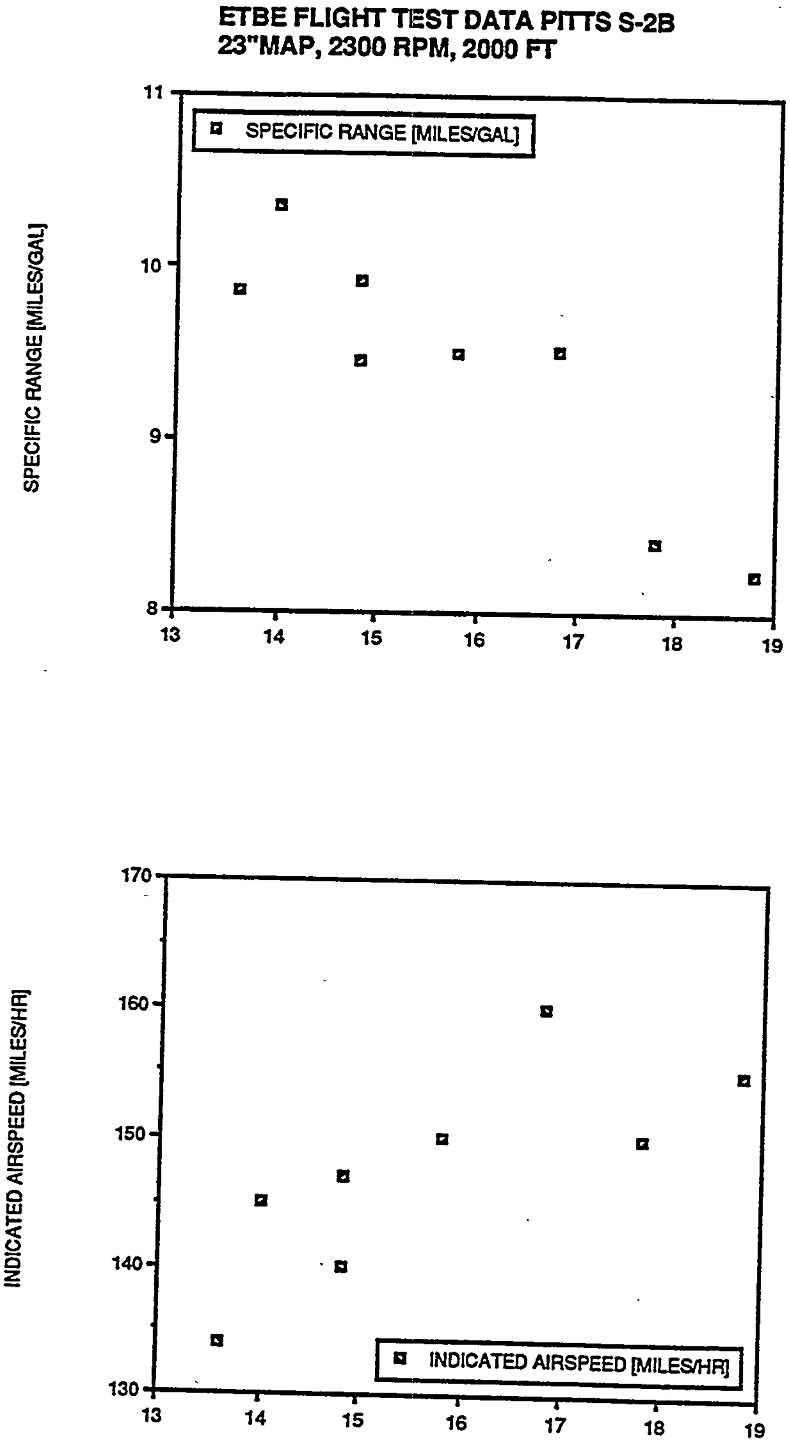
100LL FLIGHT TEST DATA
24"MAP, 2400 RPM, 2000 FT

Figure 2



ETBE FLIGHT TEST DATA PITTS S-2B
25"MAP, 2500 RPM, 2000 FT

Figure 3



ETBE FLIGHT TEST DATA PITTS S-2B
23"MAP, 2300 RPM, 2000 FT

Figure 4

| % HP | CORRECTED HORSEPOWER | AVGAS GPH | ETBE GPH | % FUEL CONSUMPTION CHANGE + = INC - = DEC | ETHANOL GPH | % FUEL CONSUMPTION CHANGE + = INC - = DEC |
|---|---|---|---|---|---|---|
| 60 | 180 | 20.4 | 22.5 | + 10 | 22.5 | + 10 |
| 70 | 210 | 19.3 | 22.5 | + 17 | 25.2 | + 18 |
| 75 | 225 | 20.6 | 19.5 | - 5 | 23.6 | + 15 |
| 80 | 238 | 21.8 | 21.8 | 0 | 24.2 | + 11 |
| 90 | 270 | 27.0 | 28.8 | + 7 | 31.5 | + 17 |
| 100 | 300 | 28.5 | 27.5 | - 4 | 34.0 | + 19 |

1. ENGINE TESTED: MODIFIED LYCOMING IO-540 D4A5 WITH 10:1 COMPRESSION RATIOS
2. GPH: GALLONS PER HOUR
3. MAX POWER AVAILABLE ON AVGAS: 300 HP
4. MAX POWER AVAILABLE ON ETBE: 304 HP
5. MAX POWER AVAILABLE ON ETHANOL: 316 HP

# ETHANOL AS AN AVIATION FUEL:
# AN OVERVIEW OF THE PROGRAM AT BAYLOR UNIVERSITY

M. E. Shauck, M. G. Zanin
Department of Aviation Sciences
Baylor University
Waco, TX 76798

## Abstract

Research and development of ethanol as an aviation fuel has been conducted at Baylor University for the past 13 years. Initially, the motivation was the possibility of fuel supply interruptions as a result of political instability in the Middle East. Modifications were developed to enable aircraft powered by reciprocating engines to use pure ethanol as fuel. Six different aircraft have been modified and flown on alcohol. Two series of aircraft engines have received Federal Aviation Administration (FAA) certification to use ethanol. Three aircraft are in the process of obtaining FAA certification to use ethanol as a fuel in commercial operations.

This paper will describe the Center's three areas of concentration: (1) certification of aircraft engines and airframes, (2) research and development to improve efficiency, performance and reliability of aircraft engines on alternative fuels, and, (3) educational programs to increase public awareness of alternative fuels in aviation.

## Introduction

The removal of lead from fuel, as mandated by the Clean Air Act, is a cause for great concern in the aviation industry. The industry standard, 100 octane, low-lead aviation gasoline will have to be replaced by an unleaded fuel with a minimum motor octane of 98 as recommended by the General Aviation Manufacturers Association. Different approaches have been taken in an attempt to manufacture a suitable fuel. As of now, none of the proposed solutions are acceptable due to inadequate octane, excessive emissions, or high cost.

The 13 year Baylor University project proved that 100% denatured ethanol is the ideal fuel to replace 100 octane, low-lead aviation gasoline.

## Project Background

When this project began in 1980, all of the activities engaged in by the project initiator were related to aviation. He was conducting air pollution research at Baylor University using an instrumented aircraft and flying aerobatic competition and airshows. The motivation for the research was the threat of fuel supply interruptions due to the unstable political climate of the Middle East. After considering a variety of fuels as possible candidates to replace aviation gasoline, ethanol was chosen because of its characteristics and availability. The Environmental Studies Institute at Baylor University was producing ethanol, using the waste stream from a local chocolate manufacturing company. A Texas oil man and environmentalist provided airplane and funds to initiate the project.

A Bellanca Decathlon, powered by a Lycoming IO-320, was converted to ethanol. Once the necessary engine modifications were determined and implemented, performance on ethanol was carefully recorded and analyzed. The immediately evident results were cooler engine temperatures and increased engine power. This aircraft flew over 600 hours on ethanol fuel. After the flight test phase, aerobatic demonstrations and airshows were flown including the EAA airshow in Oskosh. In 1982, this Decathlon made the first transcontinental flight on ethanol. Three additional Aeronautic Association records were established with this ethanol powered aircraft. The Decathlon was sold to an association of ethanol producers in Brazil and aerobatic demonstrations were performed in Sao Paulo and Rio de Janeiro.

Encouraged by the success of this aircraft, a second airplane was modified to run on ethanol. This was a Pitts Special S1S, a single engine, single seat aerobatic airplane used in competition flying and airshows. The compression ratio of the Lycoming IO-360 A4A power plant was increased from 8.5:1 to 10:1. Various fuel combinations were tested; among them, different percentages of ethanol and gasoline, and of ethanol and methanol. The resulting data was published in technical papers. All fuel wetted aircraft components were tested for compatibility with ethanol and those affected were either changed or treated. As a result of the higher compression, efficiency was improved. A considerable increase in available power was also recorded when flying on ethanol. This Pitts was flown in numerous airshows in the United States and Italy. A Pitts Special S1S was also modified in Paris, France, and flown to demonstrate ethanol performance.

Three more aircraft were converted to run on ethanol: a twin engine Piper Aztec, a Siae Marchetti SF 260, and a Velocity. The latter was purchased and modified for the sole purpose of crossing the Atlantic ocean on ethanol fuel in order to make an irrefutable public demonstration of the reliability of the fuel. This experimental category airplane, a canard type, was chosen because of its efficiency combined with a big cabin which accommodated large auxiliary fuel tanks. In the fall of 1989, the Velocity flew from Waco, Texas, to Paris, France, with refueling stops in the Azores Islands and Lisbon, Portugal. The flight was successful and proved the point.

The first ten years of research on ethanol as an aviation fuel and the record setting flights was carried out with very little financial support.

An important accomplishment of these years of activity has been the granting of a Supplemental Type Certificate by the FAA for the use of ethanol in a series of Lycoming engines. This certificate represented a significant achievement since it was the first official FAA recognition of the viability of ethanol as an airworthy alternative fuel.

As the mandates from the Clean Air Act stimulated the search for an alternative to leaded aviation gasoline, the project at Baylor University expanded its activities to respond more efficiently to the evolving situation and to assert the validity of ethanol as an aviation fuel.

At the beginning of 1991, the Center for the Research and Development of Ethanol as an Aviation Fuel was founded within the Aviation Sciences Department.

## Center Activities

The Center for the Research and Development of Ethanol as an Aviation Fuel was instituted to conduct research and development, engine and airframe certification, and reliability demonstrations related to the use of ethanol fuel for general aviation reciprocating engine aircraft. A program to be administered by the Department of Aviation Sciences in cooperation with Texas State Technical College was established with the following goals:

- Certificate a range of reciprocating aircraft engines using ethanol.

- Certificate a range of airplanes using the engines certified on ethanol fuel.

- Develop research and certification test facilities that meet current and projected FAA and environmental parameters.

- Conduct research and development testing to maximize efficiency, performance and economy.

- Conduct research and development testing to maximize the usable power potential with ethanol fuel and evaluate engine component wear, lubrication characteristics, etc.

- Develop public awareness for the use of ethanol as a renewable fuel by establishing seminars on the characteristics and use of ethanol and demonstrations using ethanol fuel in airplanes.

- Develop curriculum and training for teachers and instructors related to research and development and certification programs.

- Develop curriculum and initiate training of university and technical school students on research and development objectives and relevant FAA policy and certification procedures.

- Develop Advisory Circular documentation for FAA publication and disseminate information and procedures for certification of engines and airplanes using ethanol fuel.

This documentation should establish the minimum certification requirements based on results of the programs described above.

Research and testing proved that the efficiency of gasoline engines modified to run on ethanol could be considerably improved by such additional modifications as increasing the compression ratio or changing ignition timing. Additional research and development to implement these changes, or to manufacture a new engine ideal to run on ethanol, is needed. At the same time, to establish ethanol as a fuel, aircraft on ethanol must be proved in the market place as soon as possible and certification is a requisite for an aircraft to engage in commercial operations. Additionally, in order to insure acceptance of the new fuel, educational programs and demonstrations of the reliability of ethanol as an aviation fuel have to be conducted. These three main directions, research and development, certification of engines and airframes, and public education on the subject of ethanol as an aviation fuel, are to be pursued in parallel.

## Current Programs

Following establishment of the Center and determination of the desired goals, an active search for the necessary funds began.

In order to proceed, both short and long term goals of the program had to be identified. The need to integrate new modifications into existing engines to increase the efficiency, or to manufacture a complete new engine to take advantage of the characteristics of ethanol, had to be measured against the urgency to certify existing engines on ethanol fuel to prove its effectiveness in the market place. New concepts and major alterations always require extensive documentation prior to the official certification program.

A proposal to conduct research on the effects of increased compression on various cam geometrys and chances in ignition timing was presented to the Federal Aviation Administration Technical Research Center. Additionally, different types of oxygenated fuels other than ethanol were proposed for testing. The proposal was accepted and the project is under way.

To proceed with the certification of existing aircraft engines where most of the research had been conducted, a strategy had to be devised to assure implementation of the certified engines in the market place. Introductory problems, such as distribution of the fuel, had to be overcome. In order to minimize these initial difficulties, two important areas in aviation, flight training and agricultural aviation, were identified. In both areas, most of the flying is local; requiring only single fuel storage.

A grant from the Texas Higher Education Coordinating Board was obtained to certify a Cessna 152: the most common flight trainer in the United States. The aircraft was provided by Texas State Technical College. The engine of the Cessna 152, a Lycoming 0-235, has successfully completed the certification tests. This was the first carburated engine to be certified on ethanol. The airframe certification is currently underway. Upon certification, this aircraft will be placed in the flight training portion of the aviation sciences program, thus insuring utilization in a commercial operation.

A contract to certify an agricultural spray aircraft, a Piper Pawnee, was entered into between the Center at Baylor University and a consortium of organizations of corn producing states. The engine, a Lycoming IO-540, is already certified. The Piper Pawnee is currently flying on ethanol in order to satisfy the airframe certification requirements.

The airframe of a Pitts Special S2B is also being certified. This aircraft, utilizing ethanol, is used in airshows and demonstration flights. Once certification is obtained, this aircraft will also be used in the flight training portion of the Aviation Sciences program.

The certification tests on these engines has proved that ethanol burns cleaner and cooler and the engines run smoother because the limits of detonation are extended. These facts imply that the time between overhaul of ethanol powered engines can be safely extended; probably doubled.

A demonstration project funded by the Texas Governors' Energy Office was already successfully underway before the Center was established. Two ethanol powered airplanes, the Pitts Special and the Velocity, were taken to airshows and other aviation events for demonstration flights. Concurrently, talks with question & answer sessions were given, and informational material was distributed. This type of educational tour needed to be expanded from a state-wide to a nation-wide demonstration program. Proposals to raise funds were made to federal agencies and agricultural organizations.

During the summer of 1992, the South Dakota Corn Utilization Board sponsored a series of shows with the ethanol powered Pitts Special in the state of South Dakota. The Board contributed significantly to the success of the tour by organizing the publicity and notifying the media prior to the shows. Local radios, television stations, and newspapers carried stories about the ethanol program. Meetings were arranged and talks given to local pilots and organizations. As a result of a talk delivered to an Experimental Aircraft Association chapter in Sioux Falls, six airplanes were converted to ethanol. These aircraft are part of a team called the Vanguards which performs in shows and aviation events. Currently, the team, sponsored by the local Corn Growers Association, is involved in demonstration programs around the country.

A nation-wide demonstration program was proposed to the Governors' Ethanol Coalition, an organization comprised of 19 ethanol producing states. The proposal was accepted and the project is under way. A Pitts Special S2B, a two seat aerobatic aircraft powered by ethanol, will perform demonstration flights in the coalition states. The engine of this aircraft has already received FAA certification on ethanol. This aircraft can also be used to take members of the media for demonstration rides. The Baylor University Communications Department has installed a miniature video camera on the wing interplane strut which produces spectacular images of aerobatic maneuvers. This video will be available to local television stations to encourage them to carry stories about ethanol powered aircraft.

An ethanol powered van will be used in this program as a support vehicle: to carry the fuel and as a demonstration booth to exhibit and distribute the information about the program. During the lectures and demonstrations given over the past few years, people always ask if ethanol could be used as an automotive as well as an aviation fuel. This van will serve the dual purpose of support vehicle and as educational display in its own right. Seminars on ethanol as an aviation fuel will be given along the way, and a video will be shown. During this demonstration project, specific instructions on conversion of aircraft to ethanol and technical support will be provided. Many recent developments have contributed to make such conversions more attractive. Among them are the current precarious situation regarding aviation gasoline, the threat of a considerable increase in price, and a product that prevents the oxidation of aluminum parts, solving the main material compatibility problem.

During June 1993, the ethanol powered Pitts Special was shipped to Paris, France, to participate in the Paris airshow, the biggest aviation event in the world. The aircraft flew every day of the show in front of thousands of people. A lot of interest was generated in the audience and the media. National radio, television and newspapers carried the story of the event. The cover of the July issue of one of the most popular aviation magazines in France, *Aviation et Pilote*, was dedicated to the ethanol powered aircraft. This aviation magazine, in response to the success of the ethanol show and the interest generated, would like to take the lead in the promotion of ethanol as an aviation fuel in the European countries.

## Future Projects

Once certification of the three aircraft currently undergoing tests, the Cessna 152, the Piper Pawnee, and the Pitts Special, is completed, certification of different types of aircraft will begin. Performance of the certified aircraft during field operations will be recorded and analyzed on a regular basis. The economics of the use of ethanol versus aviation gasoline will be determined by taking into account not only the savings accrued from the lower cost per mile of ethanol versus aviation gasoline, but also the long range savings to be derived from the decreased wear and lack of detonation in the engines.

The long range objective of the Center is to certify a core of aviation engines and aircraft (including turbocharged engines) to establish common ranges of alterations that could apply to most engines and aircraft without a full range of testing. This program is designed to prove the concepts and light the fuse for entrepreneurial certification by other parties. As testing and certification questions are resolved, documentation will be provided that will serve as guidelines for the FAA and entrepreneurs for continued certification of the fleets of engines and airplanes.

Any progress achieved in the research and development phase of the project will be incorporated in the ongoing certifications. For example, there is enough evidence from the previous certification experiences to show that the time between overhaul of an ethanol powered engine can be considerably extended. Certification tests will be designed to prove this hypothesis. Eventually, an engine designed to take complete advantage of the ethanol characteristics will be manufactured.

Other renewable and oxygenated fuels will be tested, including ETBE, . in the search for the ideal fuel to replace jet fuel.

## Conclusion

Since its beginning, the goals set by the Center have been achieved on schedule, test results have met or exceeded expectations, and response, particularly among the general public in the aviation and agricultural communities, has been excellent. Despite the fact that current modifications have proven safe, reliable, superior in performance, and economically competitive, much remains to be accomplished in this area. However, the bureaucratic work of FAA certification must continue in order to insure that ethanol is proved in the final testing ground, the marketplace. A successful program of education directed at the grassroots level, officials in state and federal governments, and executives in private industry is a necessary component of this effort to gain acceptance for a domestically produced, high performance, economic fuel for general aviation.

*Windsor Workshop on Alternative Fuels, Toronto, June 3-5, 1996*

# ENERGY USE AND EFFICIENCY OF A HYBRID ELECTRIC VEHICLE IN COMMERCIAL SERVICE

Victor Yung and David Checkel

Mechanical Engineering, University of Alberta, Edmonton, Alberta, T6G 2G8
phone (403) 492-2340 (Checkel), fax (403) 492-2200
E-mail checkel@sneezy.mece.ualberta.ca

## ABSTRACT

Electric vehicles are attractive for their ability to reduce urban pollution. However, the limitations of current battery technology prevent dedicated electric vehicles from being attractive at the present time. Hybrid electric vehicles can operate as a zero-emission, battery-powered electric vehicle and also have a regular fuelled engine to extend range. This paper presents some results of a one-year in-use study on the energy consumption and efficiency of a hybrid electric vehicle operating in a commercial fleet. The vehicle was a modified Ford Escort station wagon with a hybrid powertrain developed for the university-based HEV Challenge. It was instrumented for continuous monitoring while being used as an electric meter service vehicle. Results of the study include driver impressions, gasoline/electric operating statistics, vehicle energy consumption, powertrain efficiency, battery charge efficiency, and battery capacity deterioration.

## THE HYBRID ELECTRIC VEHICLE

In 1992/93, the University of Alberta developed a Hybrid Electric Vehicle (HEV) in response to the HEV Challenge issued by Ford Motor Company. Based on a 1992 Ford Escort Wagon, this HEV was able to run about 35 km as a battery-powered, zero-emission electric vehicle (EV). It also had a small gasoline engine which allowed it to run extended distances. Designed to be a practical, usable, durable car, the University of Alberta HEV won the HEV Challenge in 1993. Figure 1 shows the general layout of the vehicle schematically. The hybrid powertrain used a "parallel" design which connected either the electric motor or the gasoline engine (or both) to the regular clutch on the 5 speed transmission. Electric power was provided by a Unique Mobility SR180 DC brushless motor and controller rated at 32 kW (continuous) and 63 kW (peak). The 1 Litre gasoline engine (Suzuki 3 cylinder, 4 stroke) was rated at 41 kW. The rear seat was removed and a battery box constructed in the centre of the car. This battery box held 14 deep discharge, 12V lead-acid batteries providing a nominal 180V battery with about 5 kW-hr capacity.

## GENERAL RESULTS

While this car could run on gasoline as well as on electric mode, the drivers preferred to use it in electric mode because it was more powerful. There was also more noise and vibration with the gasoline engine running. The pattern of use which developed was mostly short trips where it would be possible to make the entire trip in EV mode.

HEV accumulated 2187 km, 70% of it in EV mode. Average use was 19 km per day This makes the EV inherently a low-mileage vehicle. Over the year of testing, the on those days it was used. Energy consumption on a standard driving cycle was 39 kW.hr/100 km (electric) or 8.6 L/100 km (gasoline).

## TRACTIVE ENERGY ANALYSIS

While the HEV was being used, its speed, battery voltage, battery current, and many other parameters were continuously recorded. The speed trace was later processed using a vehicle dynamic model to measure vehicle tractive energy. Comparing the tractive energy with the electric energy consumption gives a measure of powertrain efficiency during actual operation. Figure 2 shows a typical short segment of speed, tractive power, and battery power traces, chosen to illustrate different features of the tractive power analysis. During the time when positive tractive power was required, the electrical energy was greater than the tractive power giving a tractive efficiency of 57%. When negative tractive power was required, (during deceleration), electrical energy was less than the tractive power giving a regenerative braking efficiency of 48%. Over short distances, hills and random measurement errors could significantly affect measurements. However, the results are quite consistent as is shown by two additional short segments in Figure 3.

## VEHICLE HEATING

While EV's are commonly associated with California, this HEV test was conducted in the highly seasonal climate of northern Canada. Figure 4 shows the temperature and heater current data recorded on a cold (-28°C) day. The HEV's battery capacity was not directly affected by the low temperatures since it was parked and charged indoors and the batteries did not have time to cool off while the car was outside. (In fact, the battery temperature rises slightly while the vehicle is running outdoors). However, running the electric heater for passenger compartment heat and defrosting drew an almost continuous 1.5 kW from the battery. Over the trip, 22% of the electric power consumption was used for heating. This is a significant extra load which would reduce usable range in winter conditions.

## BATTERY CAPACITY

An interesting problem with EV's is to know what the battery state of charge and battery capacity are. Simple voltage measurements are not adequate. Figure 7 shows the battery voltage and current traces from a particular trip. During the initial period before the vehicle starts moving, the battery voltage gradually drops from its nominal 180V charging level towards 175 V. Once the vehicle starts driving, battery voltage drops by about 15 V each time the vehicle accelerates. However, the "rest voltage" when no current is being demanded is still close to the original level. After about ten minutes of driving, the voltage drop during accelerations increases to more than 40 V and the rest voltage starts to drop sharply as well. A detailed model of rest voltage and voltage drop for specific currents is necessary to determine the battery state of charge and actual battery capacity.

## EFFICIENCY RESULTS

Figure 5 gives a table of cumulative results from three different days of use, two with moderate weather, (days 237 and 305) and one with cold weather, (day 341). The results for the moderate weather days typically give vehicle tractive efficiency around 60% and regenerative braking efficiency around 42%. In cold weather, the apparent tractive efficiency would drop to 47% and the apparent regenerative braking efficiency dropped to 15%. The difference is mostly attributable to the greatly increased accessory load (22% of total electrical energy).

The tractive efficiency values discussed above cover the conversion of battery output energy to vehicle tractive energy. There are two other efficiencies which are critical to EV energy flows: the battery charge storage efficiency and the battery charger efficiency. Charge storage efficiency relates to the fact that the battery gives back less electricity than was used in charging it. (There are some losses due to ohmic heating during charge and discharge as well as some internal self-discharge.) The lead-acid batteries used in this HEV had a charge storage efficiency of up to 63% for a typical full charge. If the battery was only partially charged, the charge storage efficiency could be slightly higher. (Clearly there is a compromise between maximizing the battery capacity and achieving a high charge storage efficiency.) On the other hand, the HEV was often left sitting for long periods with the charger connected and trickle charging the battery. Under these conditions, the charge storage efficiency dropped sharply. A "smart" charger and a regular use schedule would be necessary to maintain a high charge efficiency.

The battery charger efficiency is the simple ratio of DC power coming out of the charger to AC grid power into the charger. Unfortunately, this is not always simple to measure. Many chargers use a large input transformer, causing significant distortion of the input voltage and current waveforms. Under these conditions, AC power meters under-represent the actual power consumption. For this study, a very stable DC power supply with input power factor correction was used for battery charging. Although these charger attributes are very desirable, they come at the expense of efficiency. Measured charger efficiency was only 60%.

Figure 6 shows a schematic of the electric energy flow into the HEV with efficiencies included. Note that the tractive (or powertrain) efficiency, the battery charge storage efficiency, and the battery charger efficiency all operate in series. Hence, a vehicle which requires 0.11 kW.hr of tractive energy to drive 1 km requires 0.11 kW.hr / (0.6*0.63*0.6) = 0.49 kW.hr of grid electricity to charge its batteries. The combined efficiencies work out to only 23% which is not too different from a gasoline engine. (It is worth mentioning that if the electricity is generated in a typical thermal power plant, an additional efficiency on the order of 37% would have to be added in series.) Clearly, work on higher efficiency chargers and batteries is imperative.

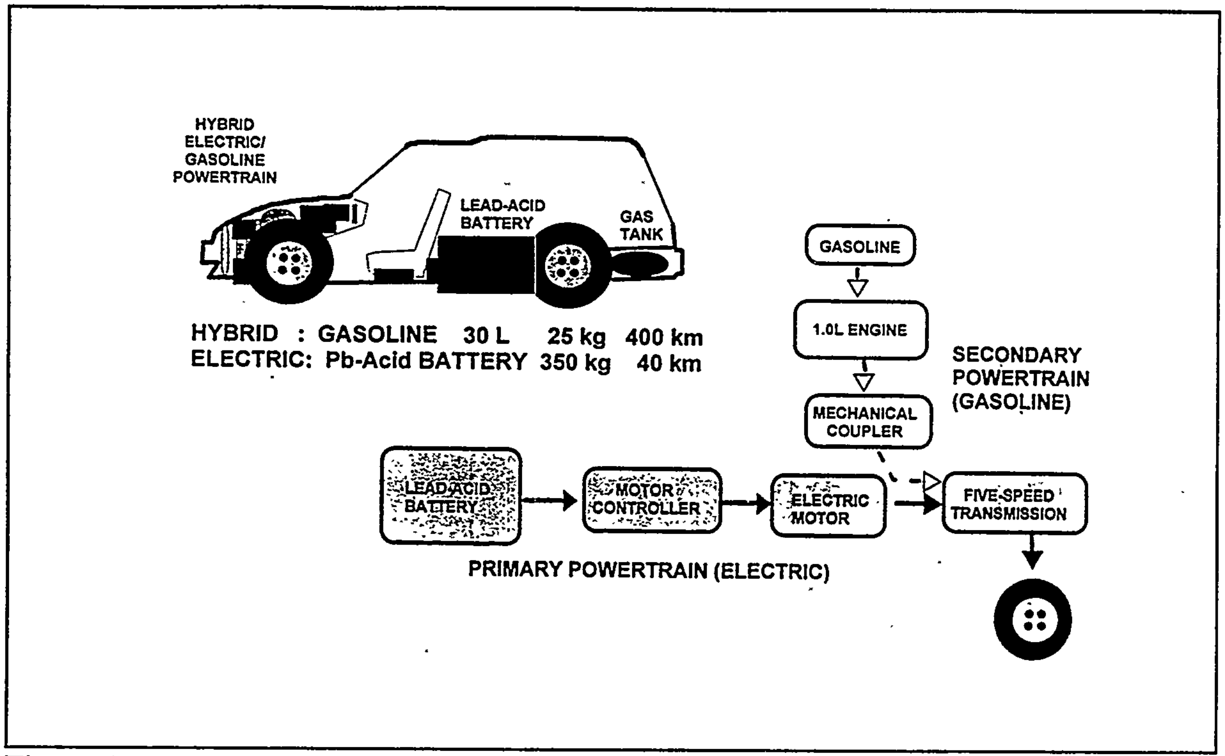


Figure 1. General Schematic of Hybrid Electric Vehicle and Electric / Gasoline Powertrain

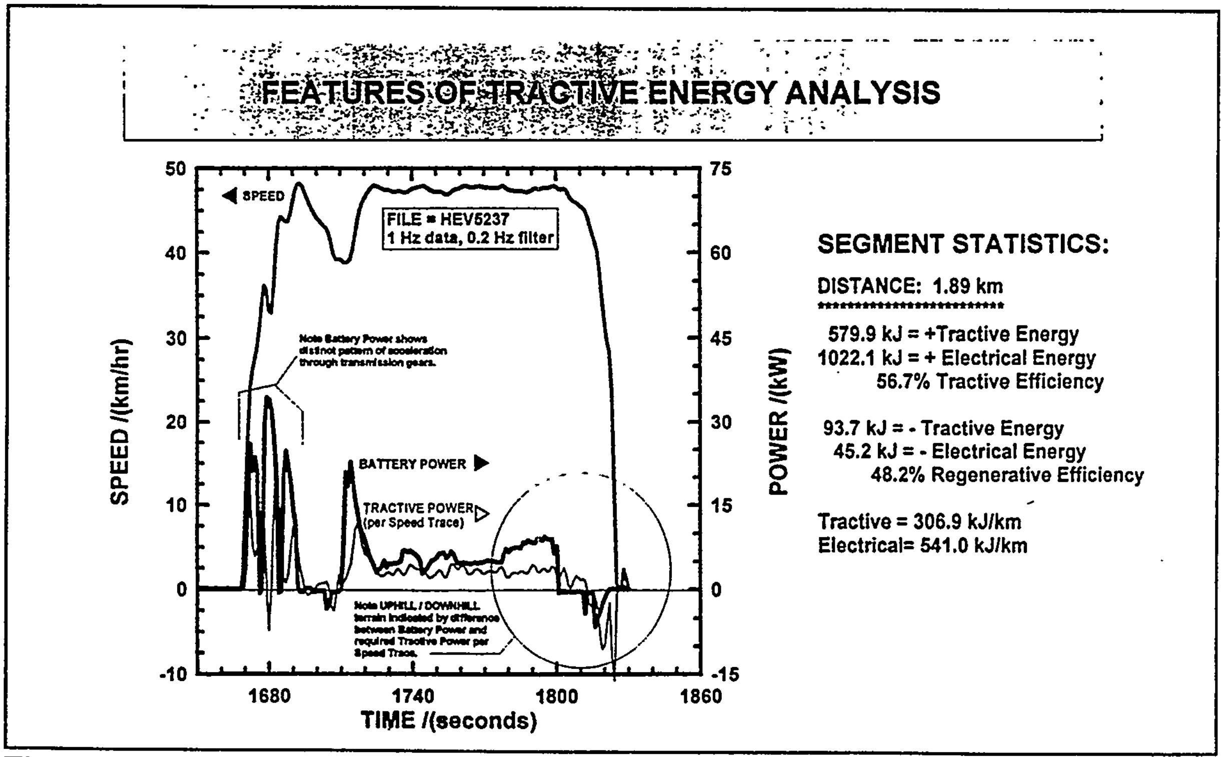
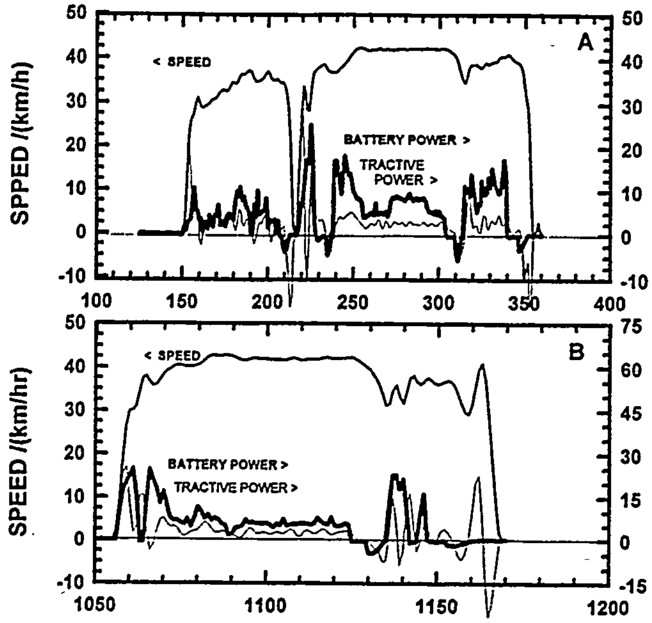


Figure 2. Recorded Speed, Battery Power, and Tractive Power Required Traces for the HEV

**EXAMPLES OF SHORT TRAVEL SEGMENTS**



SEGMENT A 2.03 km

654.3 kJ = +Tractive Energy
1191.9 kJ = + Electrical Energy
54.9% Tractive Efficiency

139.6 kJ = - Tractive Energy
50.9 kJ = - Electrical Energy
36.5% Regenerative Efficiency

Tractive = 323.0 kJ/km
Electrical= 588.5 kJ/km

SEGMENT B 1.17 km

442.6 kJ = +Tractive Energy
699.8 kJ = + Electrical Energy
63.2% Tractive Efficiency

139.6 kJ = - Tractive Energy
32.6 kJ = - Electrical Energy
23.4% Regenerative Efficiency

Tractive = 378.9 kJ/km
Electrical= 599.1 kJ/km

Figure 3. Further Examples of Tractive Power Analysis Traces for HEV Operation

HEV TRIP RECORD

(DAY 341, 11:12)

TEMPERATURES,
HEATER CURRENT,
VEHICLE SPEED

December 8, 1995

-28°C Outdoor Temperature
Car started and Ended trip
parked in garage at +10°C

TRIP ELECTRICAL: 1.89 kW.hr
HEATER/ACCESS.: 0.42 kW.hr

ACCESSORY ENERGY= 22%

Note that:

1. The heater is able to maintain cabin temperature and starts to cycle off and on after 13 minutes of running.
2. Heater Power is ~1.35 kW (9A x 150 V)
3. The cabin temperature drops when the driver switches to the gas engine since it has not yet warmed up.

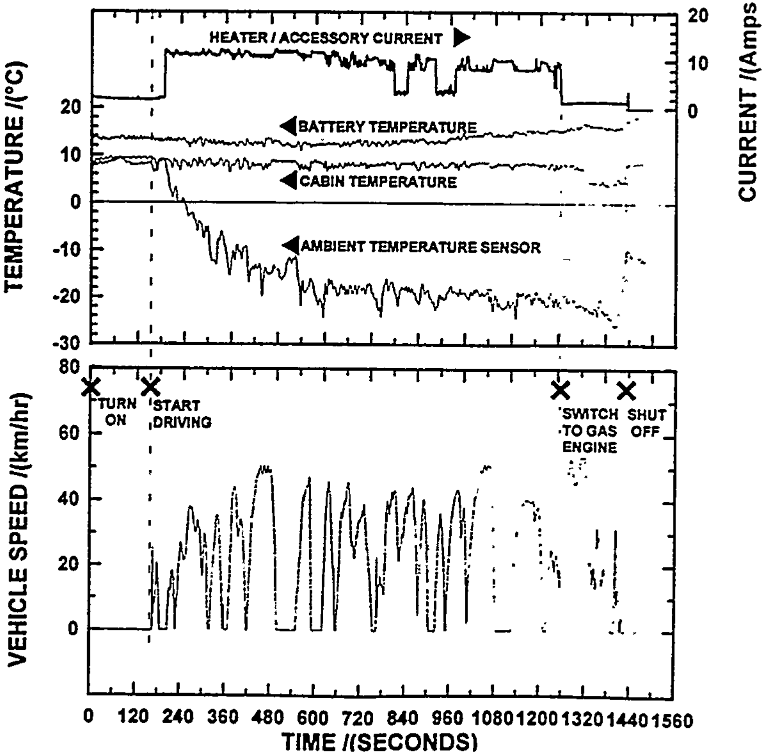
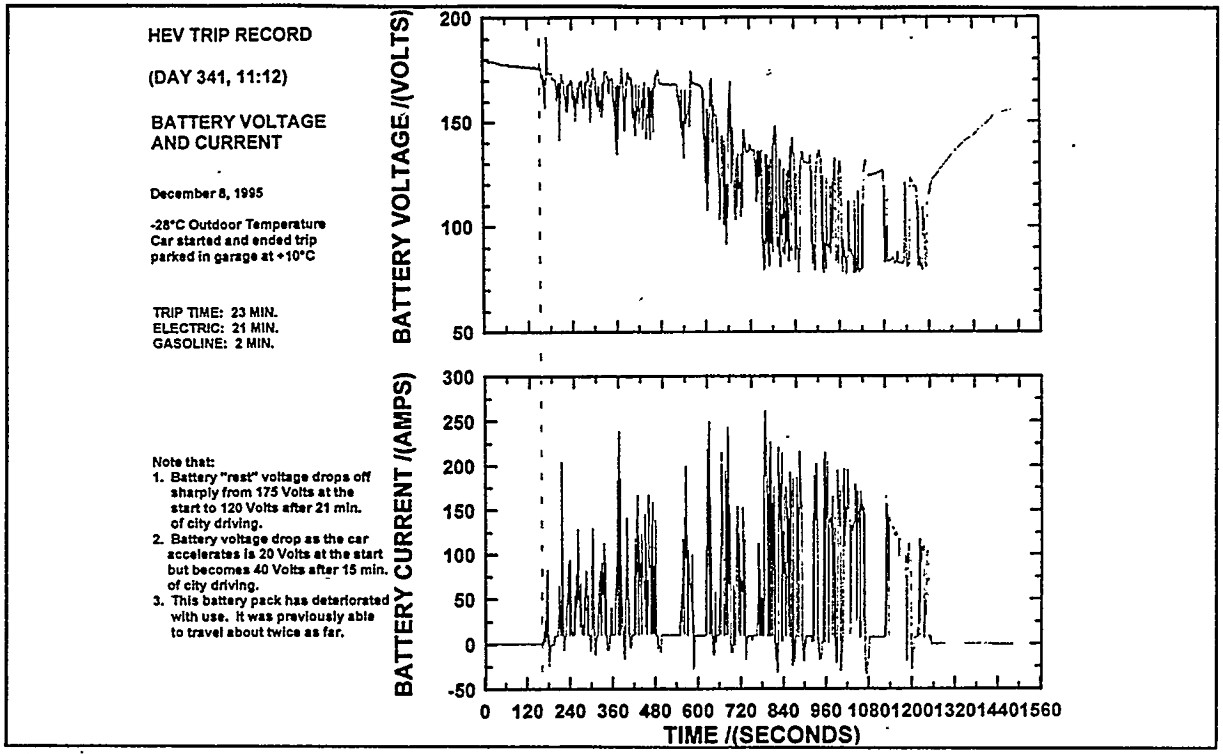


Figure 4. Heater Performance and Energy Use in Cold Weather Operation



December 8, 1995

-28°C Outdoor Temperature
Car started and ended trip
parked in garage at +10°C

TRIP TIME: 23 MIN.
ELECTRIC: 21 MIN.
GASOLINE: 2 MIN.

Note that:

1. Battery "rest" voltage drops off sharply from 175 Volts at the start to 120 Volts after 21 min. of city driving.
2. Battery voltage drop as the car accelerates is 20 Volts at the start but becomes 40 Volts after 15 min. of city driving.
3. This battery pack has deteriorated with use. It was previously able to travel about twice as far.

Figure 5. Illustration of Battery Voltage and Current Behaviour During a Typical Discharge

(a) Energy and Efficiency Values

| DAY /TRIP NUMBER | E.V. DISTANCE (km) | Positive Tractive kJ | Positive Electrical kJ | Tractive Efficiency % | Negative Tractive kJ | Negative Electrical kJ | Regen. Efficiency % |
|---|---|---|---|---|---|---|---|
| 237 | 23.09 | 9,203 | 15,160 | 60.7 | 2,303 | 936 | 39.0 |
| 305 | 8.33 | 3,390 | 5,691 | 59.6 | 1,085 | 486 | 44.7 |
| 341 | 6.25 | 2,810 | 6,033 | 46.6 | 1,137 | 170 | 14.9 |

(b) Energy per Kilometer Values

| DAY / TRIP NUMBER | POSITIVE TRACTIVE ENERGY REQUIRED (Urban Driving) | | POSITIVE ELECTRICAL BATTERY ENERGY ($\eta_{TRACTIVE}$ =63%) | | DC in to BATTERY ($\eta_{BATT.}$ =63%) | AC in to CHARGER ($\eta_{CHARG.}$ =60%) |
|---|---|---|---|---|---|---|
| | kJ/km | kW-h/100km | kJ/km | kW-h/100km | kW-h/100km | kW-h/100km |
| 237 | 399 | 11.1 | 657 | 18.2 | 28.9 | 48.2 |
| 305 | 407 | 11.3 | 683 | 19.0 | 30.2 | 50.3 |
| 341 | 449 | 12.5 | 965 | 26.7 | 42.4 | 70.7 |

Days 237 and 305 were typical summer/autumn weather. Day 341 was severe winter weather (-28°C).

Figure 6. Typical Energy Consumption / Efficiency Results from Tractive Energy Analysis

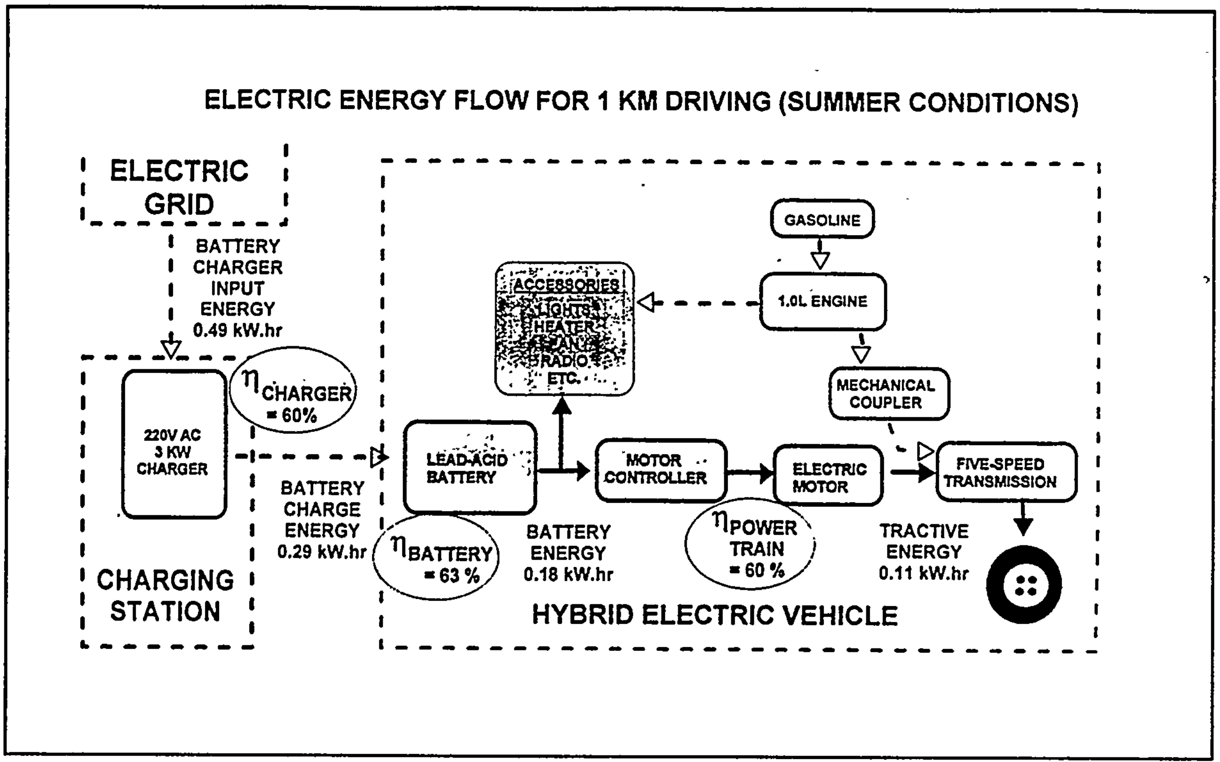


**Figure 7.** Schematic of Electrical Energy Flow in the HEV Including Measured Efficiencies

# Alternative Fuel Vehicles: The Emerging Emissions Picture

Ken Kelly, National Renewable Energy Laboratory

(Poster unavailable at time of publication)

# Electric Vehicle Infrastructure Issues

**Lawrence O'Connell, O'Connell & Associates**

(Poster unavailable at time of publication)

# Advanced Natural Gas Engine Control Technology

## Prime Contacts

Daniel Podnar
Southwest Research Institute
(210) 522-2564

John Kubesh
Southwest Research Institute
(210) 522-5941

## Sponsors

National Renewable Energy Laboratory
Gas Research Institute

## Objective

Investigate advancements in natural gas engine control technology with the goal of improving engine performance, response, and power density, while minimizing emissions. Demonstrate these technologies on a John Deere 8.1L natural gas engine.

## Technical Approach

The controls investigation focused on areas such as model-based equivalence ratio control, boost control techniques to minimize throttling losses, knock detection and control, misfire detection and control, humidity compensation and fuel metering valve evaluation. The control techniques were applied to an 8.1L John Deere Natural Gas Engine with overall engine objectives to increase engine efficiency, response, and power density while decreasing engine emissions. A highly flexible personal computer (PC) based controller platform called the Rapid Prototyping Engine Control System (RPECS) was used for the investigation, the platform is shown in Figure 1.

Results of the investigation have successfully demonstrated the ability to achieve higher levels of engine control accuracy and performance. Thus, engine calibrations could be developed nearer to engine operational limits such as knock and misfire. Performance of the engine knock and misfire control functions developed during the project are shown in Figure 2 and Figure 3, respectively. Also, the observer based techniques, applied to the equivalence ratio control algorithm, demonstrated superior control tracking during transient conditions (as shown in Figure 4). This can result in improved vehicle driveability as well as transient emissions.

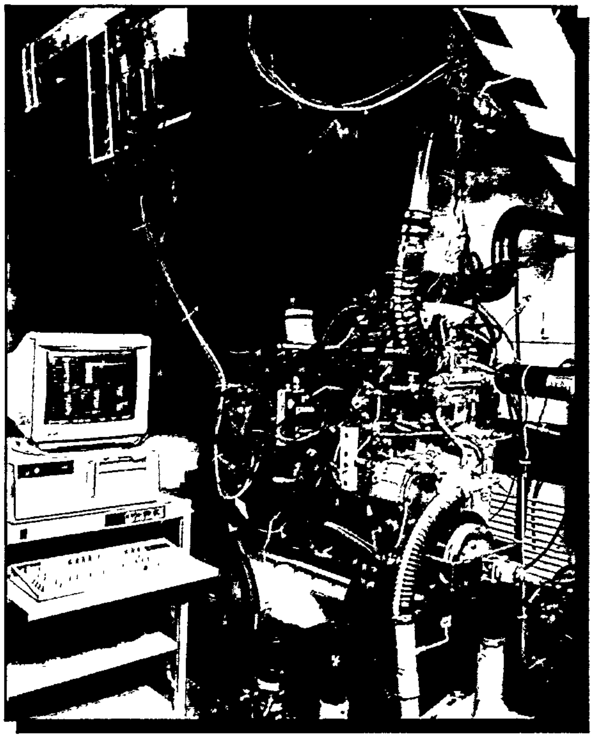


Figure 1

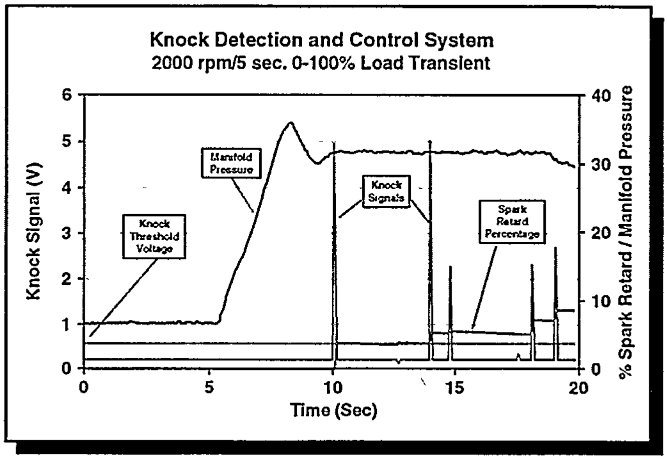


Figure 2

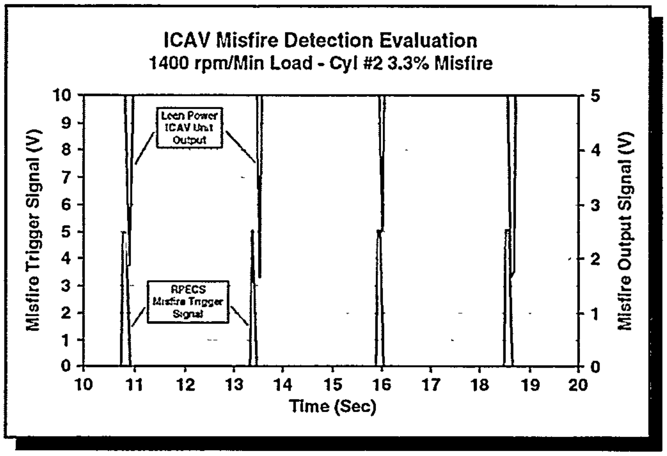


Figure 3

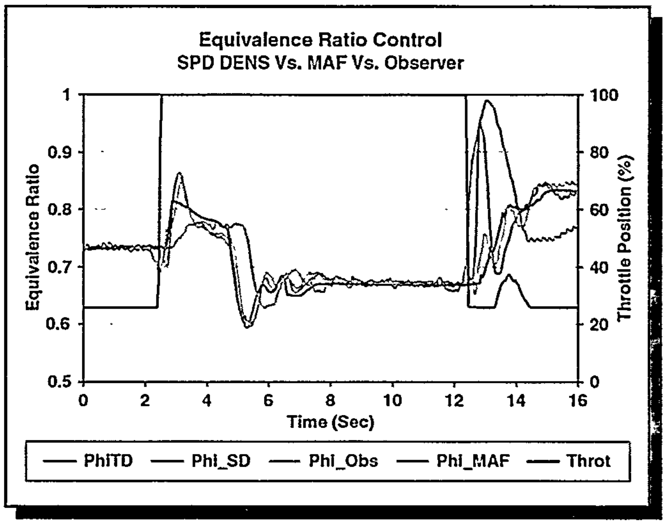


Figure 4

## Project Status

The controls investigation was completed in March 1996, and represents a portion of the overall program aimed at developing an ultra low emissions/ultra safe school bus, sponsored by NREL. Promising technologies identified during the controls investigation are being "ported" from the prototyping controller platform to the production platform for vehicle demonstration. Vehicle demonstration is planned for later in 1996. The demonstration phase of the project will include on-road vehicle testing, as well as engine dynamometer emissions testing.

# GasRail USA Gas-Fueled Railway Research Program

## *Prime Contacts*

**David Meyers**
**Southwest Research Institute**
**(210) 522-5581**

**John Hedrick**
**Southwest Research Institute**
**(210) 522-2336**

## *Sponsors*

**Amoco**
**California Air Resources Board**
**Electro-Motive Division of General Motors**
**Gas Research Institute**
**South Coast Air Quality Management District**
**Southern California Gas Company**
**Southern California Regional Rail Authority**
**Union Pacific Railroad**
**U.S. Department of Energy**

## *Objectives*

**Develop and demonstrate a natural gas fueled locomotive that provides significant economic and emissions advantages over present day diesel locomotives. Specific goals are to achieve a 75 percent NOx reduction without sacrificing power output, fuel economy, and increases in other emissions.**

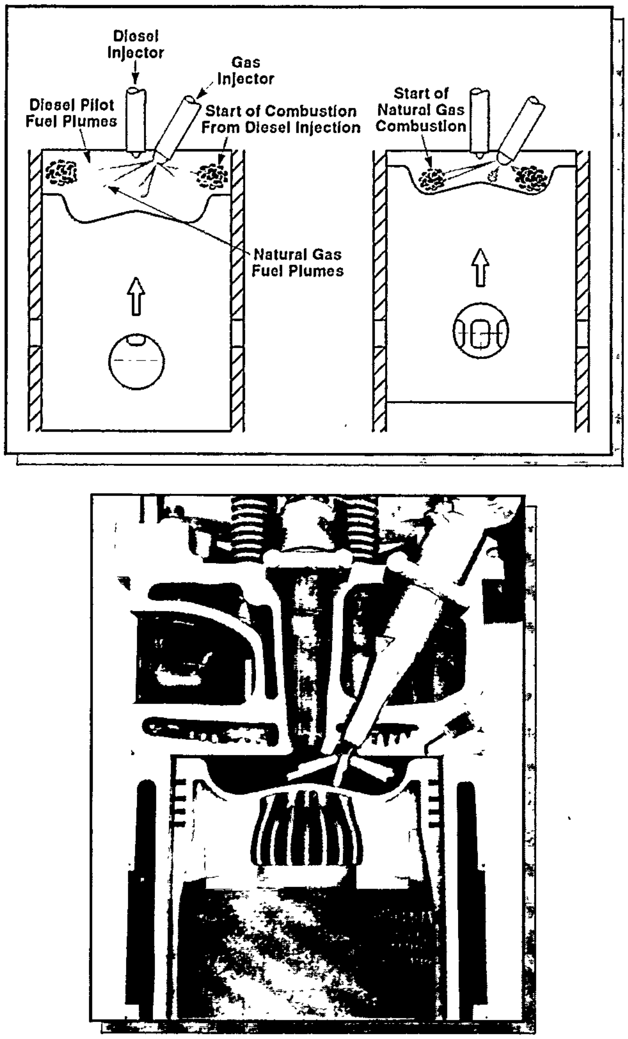


*Figure 1*

## *Technical Approach*

**Several natural gas combustion systems were tested during this research effort to determine which one provided the greatest flexibility compatible with the desired goals. Each of the candidate combustion systems listed below was tested in an EMD 1-710 single-cylinder engine to quantify the trade-offs between emissions, power output, and fuel economy.**

- **Late-Cycle High Injection Pressure (LaChip)**
- **Dual-Fuel**
- **Micro-Pilot Pre-Chamber**
- **Lean-Burn, Open-Chamber**
- **Lean-Burn, Pre-Chamber**

**The LaCHIP combustion system (Figure 1) proved to be best suited for the two-stroke, locomotive engine, combining high pressure natural gas injection with a diesel cycle. Thus, the need for spark plugs and an intake throttle were avoided. The LaChip combustion system utilizes an electro-hydraulic injector. Computational Fluid Dynamic (CFD) modeling of the natural gas/air interaction (performed at SwRI ) generated spray penetration data and air utilization contours to assist engineers in developing the injector and optimizing the tip for the gas locomotive engine application.**

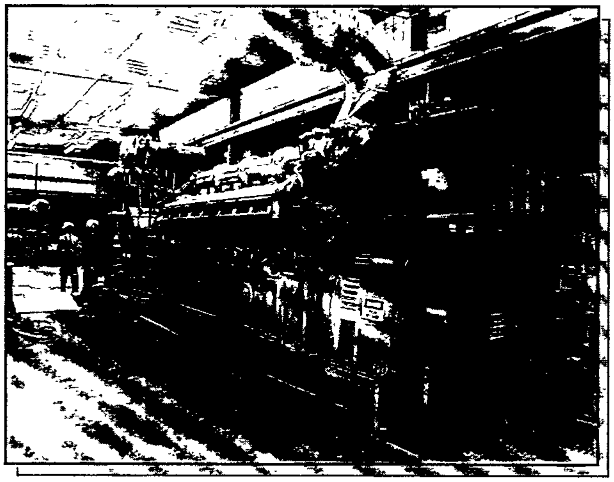


*Figure 2*

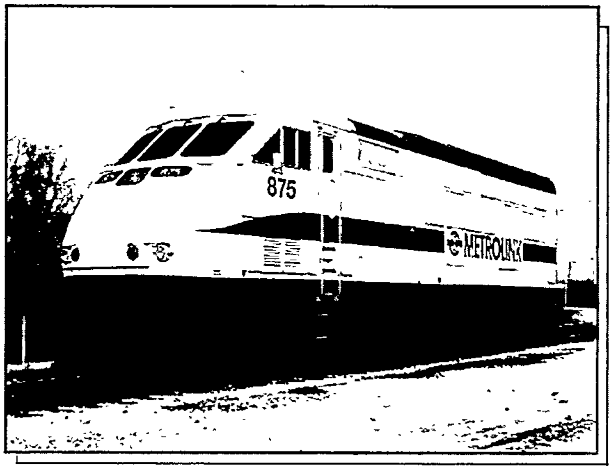


*Figure 3*

## *Project Status*

**GasRail USA began in the Fall of 1993 and is currently entering the final development phase before a field demonstration commences. The Moog Controls injector has successfully completed a rigorous 50 million cycle durability bench test. The LaChip combustion system and Moog Controls injector are being optimized for multi-cylinder testing in the EMD 16-710 locomotive engine (Figure 2). The South Coast Regional Rail Authority has selected a F59PHI passenger locomotive (Figure 3) to serve as the demonstration.**

# The Hybrid Rich-Burn/Lean-Burn Low NOx Engine

## Prime Contacts

Jack A. Smith
Southwest Research Institute
(210) 522-2971

David P. Meyers
Southwest Research Institute
(210) 522-5581

## Sponsors

South Coast Air Quality Management District
Southern California Gas Company
Waukesha/Dresser Engine Division

## Objective

Develop a natural gas fueled, stationary Hybrid Rich-Burn/Lean-Burn engine to reduce NOx emissions to near 5 parts per million at brake thermal efficiencies greater than 34 percent.

## Motivation

The South Coast Air Basin is facing stringent emissions standards mandated by the South Coast Air Quality Management District in rule number 1110.2. This rule requires that all new and existing stationary internal combustion engines that generate more than 50 brake horsepower yield no more than a nominal 36 ppm of NOx. It has been predicted that an electrically driven motor is the sole technology capable of meeting this emissions standard. However, replacing all engines with electrically powered motors in non-attainment areas would undoubtedly place a significant economic burden on municipalities and utility companies that currently employ engines to power gas compressors, electrical generators, and water pumps. The Hybrid Rich-Burn/Lean-Burn engine was developed to provide a cost-effective alternative to switching to electrically powered motors.

## Technical Approach

The Hybrid Rich-Burn/Lean-Burn engine is predicated on the simultaneous combustion of extremely rich and lean natural gas-air mixtures in separate cylinders. The physical arrangement of the engine requires that one cylinder be separated from the conventional intake and exhaust manifolding of a multi-cylinder engine. See Figure 1. The single cylinder (rich-bank) operates on an rich gas-air mixture with an equivalence ratio approaching 1.4. All of the exhaust gas from the rich burning cylinder is routed through a water-gas shift catalyst where carbon monoxide (CO) and water vapor ($H_2O$) react to form additional carbon dioxide ($CO_2$) and hydrogen ($H_2$). The catalyzed rich exhaust gas supplements lean gas-air mixtures ($\phi < 0.6$) in the remaining cylinders (lean-bank) to aid ignitability. The ignitability of the lean gas-air mixtures is enhanced by the additional $H_2$ due to its broad flammability limits, low ignition energy, and increased flame speed relative to natural gas.

Ignition timing, manifold pressure, and equivalence ratio control for the rich- and lean-banks is accurately performed by a modified, SwRI Rapid Prototyping Engine Control System (RPECS). The RPECS essentially controls two engines operating as a single unit. Communication between the rich and lean-banks is performed via the RPECS with the aid of off-the-shelf sensors. The RPECS controls rich-bank operating conditions based on the commanded operating condition in the lean-bank.

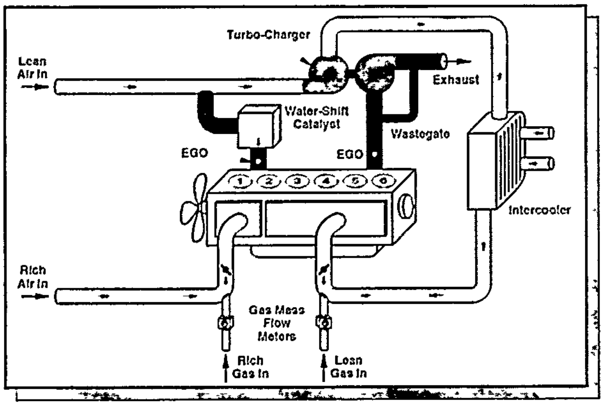


Figure 1

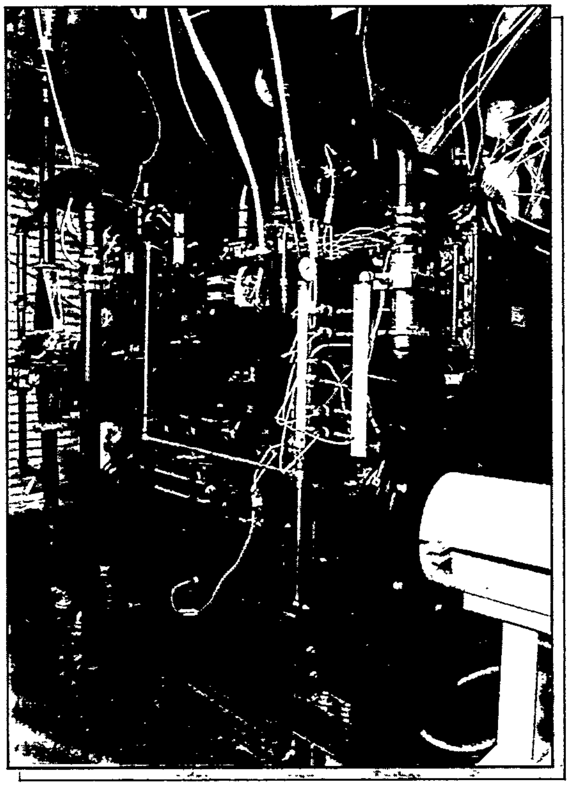


Figure 2

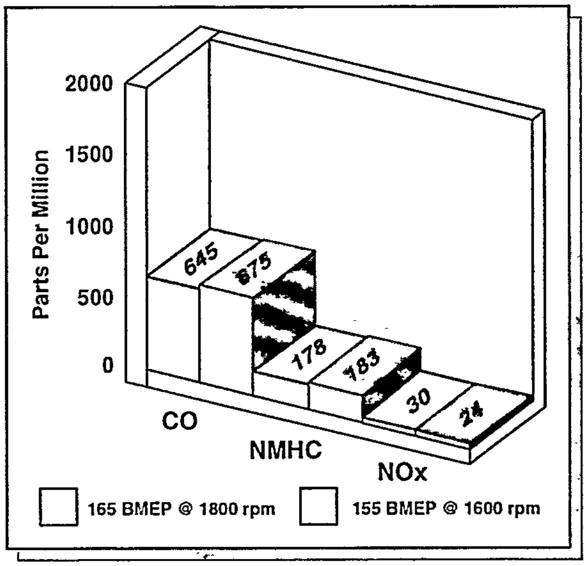


Figure 3

## Project Status

The Hybrid Rich-Burn/Lean-Burn engine concept has been applied to a turbocharged and aftercooled, Waukesha VGF F18 GLD inline 6 cylinder stationary engine. See Figure 2. All hardware modifications and software calibrations have been completed. The engine has demonstrated very low NOx at targeted efficiency levels. The best NOx emissions have been between 20 and 30 ppm at greater than 34 percent brake thermal efficiency (BTE). NOx emissions in the mid-teens have also been demonstrated at lower BTEs. Figure 3 shows emissions from two operating conditions. The 1800 rpm condition was at 34.6 percent BTE while the 1600 rpm condition was at 36.1 percent BTE. The emissions levels are currently being reviewed by the South Coast Air Quality Management District in preparation for a one year field demonstration in Southern California.

# FINAL PARTICIPANTS LIST

# 1996 WINDSOR WORKSHOP
# ON
# ALTERNATIVE FUELS

# Participants List - 1996 Windsor Workshop on Alternative Fuels

| | | |
|---|---|---|
| **John Andreas**<br>Mgr. Product Engineering | **Ford Power Products**<br>28333 Telegraph Road<br>Suite 300<br>Southfield, MI 48176 USA | 810-304-7976 |
| **Chris Atkinson** | **West Virginia University**<br>P.O Box 6106<br>Morgantown, WV 26506 U.S.A. | (304) 293-4111 x333 |
| **Lloyd Austin**<br>President | **GFI Control Systems Inc.**<br>100 Hollinger Crescent<br>Kitchener, ON N2K 2Z3 Canada | 519-576-4270 |
| **Brent Bailey**<br>Sr. Program Engineer | **National Renewable Energy Laboratory**<br>1617 Cole Boulevard<br>Bldg. 16/3<br>Golden, CO 80401-3393 USA | 303-275-4468 |
| **Colvin Barrigar**<br>Standards Engineer | **IAS Canada Inc.**<br>55 Scarsdale Road<br>Toronto, ON M3B 2R3 Canada | (416) 447-6468 x273 |
| **John Bartel** | **Mack Truck Inc.**<br>1999 Pennsylvania Avenue<br>Hagerstown, MD 21740 USA | 301-790-5762 |
| **Richard L. Bechtold**<br>Sr. Project Manager | **EA Engineering**<br>8401 Colesville Road<br>Suite 500<br>Silver Spring, MD 20910 USA | 301-565-4216 |
| **Ken Bee**<br>Director | **Ontario Soybean Grower's Marketing Board**<br>Box 1199<br>Chatham, ON N7M 5L8 Canada | 519-352-7730 |
| **Andy Beregszaszy**<br>Res. Advisor-Gaseous Fuels | **Natural Resources Canada, CANMET**<br>Energy Technology Branch<br>580 Booth Street, Room 714<br>Ottawa, ON K1A 0E4 Canada | 613-996-8557 |
| **Lee Birch**<br>Product Compliance Mgr. | **Luxfer USA Ltd.**<br>1995 Third Street<br>Riverside, CA 92507 USA | 909-341-2214 |
| **William H. Bird**<br>Tech. Service Rep. | **ICG Propane Inc.**<br>789 Bayview Drive<br>Barrie, ON L4M 6E7 Canada | 705-734-3772 |

# Participants List - 1996 Windsor Workshop on Alternative Fuels

| | | |
|---|---|---|
| **Larry Blackman**<br>Prod. Engineering Techn. | **Engine Control Systems Ltd.**<br>165 Pony Drive<br>Newmarket, ON L3Y 7V1 Canada | 905-853-5500 |
| **Michael D. Blair**<br>Program Manager | **Thiokol Corporation**<br>P.O. Box 707<br>M/S 230 C/C 2210<br>Brigham City, UT 84302-0707 USA | 801-863-6824 |
| **Matthew A. Bol**<br>Principal Consultant | **Sypher:Mueller**<br>220 Laurier Avenue W.<br>Suite 500<br>Ottawa, ON K1S 2G2 Canada | 613-236-4318 |
| **Tapan K. Bose**<br>Professor | **Hydrogen Research Institute**<br>**Universitie du Quebec a Trois Rivieres**<br>3351, boul des Forges<br>Trois Rivieres, Quebec G9A 5H7 Canada | 819-376-5139 |
| **Ron Bright**<br>Director, Environmental Affairs | **Ford Motor Company of Canada, Limited**<br>The Canadian Road<br>Oakville, ON L6J 5E4 Canada | (905) 845-2511 x 1209 |
| **Lou Bruno**<br>General Mgr. Engine & Transp. Technol. | **ORTECH Corporation**<br>2395 Speakman Drive<br>Mississauga, ON L5K 1B3 Canada | 905-822-4111 X449 |
| **Doug Cameron**<br>Fleet Segment Mgr. - NGV | **Union Gas**<br>750 Richmond Street<br>P.O. Box 2001<br>Chatham, ON N7M 5M1 Canada | 519-436-5208 |
| **Stephen A. Carter**<br>Director, Engine Technologies | **ORTECH Corporation**<br>2395 Speakman Drive<br>Mississauga, ON L5K 1B3 Canada | 905-822-4111 X443 |
| **Paul Cassidy** | **Ricardo North America**<br>7850 Grant Street<br>Burr Ridge, IL 60521 USA | 708-789-0003 |
| **Dario Catanese**<br>Mech. Engineer | **Landi Renzo SpA**<br>Via Fratelli Cervi 75/2<br>Reggio Emilia, 42100 Italy | 39-522-382678 |
| **William B. Chamberlin**<br>Project Leader | **Lubrizol Corporation**<br>29400 Lakeland Blvd.<br>Wickliffe, OH 44092-2298 USA | 216-943-1200 X2496 |

# Participants List - 1996 Windsor Workshop on Alternative Fuels

| | | |
|---|---|---|
| **Kevin Chandler**<br>Principal Research Scientist | **Battelle**<br>505 King Avenue<br>Columbus, OH 43021 U.S.A. | (614) 424-5127 |
| **Raynald Charest**<br>Snr. Informaton Officer | **Natural Resources Canada**<br>580 Booth Street<br>18th Floor<br>Ottawa, On K1A 0E4 Canada | 613-992-8778 |
| **M. David Checkel** | **University of Alberta**<br>Department of Mechanical Engineering<br>Edmonton, AB T6G 2G8 Canada | 403-492-2340 |
| **John Christie**<br>Manager, Powertrain Design | **General Motors of Canada Ltd.**<br>Engineering 098-001<br>1908 Colonel Sam Drive<br>Oshawa, ON L1H 8P7 Canada | 905-644-4171 |
| **Jack Chu**<br>Officer, Fleet Design & Acquisition | **Canada Post Corporation**<br>Fleet Management<br>2701 Riverside Dr. Suite N0881<br>Ottawa, ON K1A 0B1 Canada | 613-734-7789 |
| **Wendy L. Clark**<br>Mgr. of Program Development | **Automotive Testing Labs. Inc.**<br>P.O. Box 289<br>Route 33, Bldg. C, TRC Complex<br>East Liberty, OH 43319 USA | 513-666-4351 |
| **Nigel Clark**<br>Professor | **West Virginia University**<br>Dept. of Mech. & Aerospace Eng.<br>P.O. Box 6101<br>Morgantown, WV 26506-6101 USA | 304-293-3111 X311 |
| **James J. Cole**<br>Mgr. Gas & Industrial Engine Dev. | **Southwest Research Institute**<br>6220 Culebra Road<br>P.O. Drawer 28510<br>San Antonio, TX 78228-0510 USA | 210-522-5473 |
| **John Convey**<br>General Mgr. Market Development | **ORTECH Corporation**<br>2395 Speakman Drive<br>Mississauga, ON L5K 1B3 Canada | 905-822-4111 X696 |
| **Kim Cooper**<br>Marketing Specialist | **Ontario Soybean Grower's Marketing Board**<br>Box 1199<br>Chatham, ON N7M 5L8 Canada | 519-352-7730 |
| **Ken Czerwinski**<br>Project Engineer | **Michigan Consolidated Gas Co.**<br>3900 Greenfield Road<br>Melvindale, MI 48122 USA | 313-388-0205 |

# Participants List - 1996 Windsor Workshop on Alternative Fuels

| | | |
|---|---|---|
| **Allan Dolenko**<br>Director - Alternative Energy Division | **Natural Resources Canada CANMET**<br>Energy Technology Branch<br>580 Booth Street<br>Ottawa, ON K1A 0E4 Canada | 613-996-6162 |
| **Daniel Doucet**<br>Sales Manager | **Megatech Electro Inc.**<br>2801, 3e rue, Grand-Mere<br>Quebec City, Quebec G9T 5Z8 Canada | 819-533-3201 |
| **Walt Dudek**<br>Project Engineer | **Automotive Testing Labs. Inc.**<br>P.O. Box 289<br>Route 33, Bldg. C, TRC Complex<br>East Liberty, OH 43319 USA | 513-666-4351 |
| **Vinod Duggal**<br>Director, Alternative Fuels | **Cummins Engine Company, Inc.**<br>P.O. Box 3005<br>Mail Code 50179<br>Columbus, IN 47202-3005 USA | 812-377-7338 |
| **Michael Duoba**<br>Research Engineer | **Argonne National Laboratory**<br>9700 South Cass Avenue<br>Bldg. 362/C264<br>Argonne, IL 60439 USA | 708-252-6398 |
| **Charles Elliott**<br>Managing Editor | **Butane-Propane News**<br>P.O. Box 660698<br>Arcadia, CA 90601 USA | 818-357-2168 |
| **Kurt Ettenger**<br>Information Specialist | **Information Resources Inc.**<br>1925 North Lynn Street<br>Arlington, VA 22209 USA | 703-528-3500 |
| **John Finch**<br>Mgr. Mktg. NGV Bus.Dev. | **Consumers Gas**<br>2235 Sheppard Avenue E.<br>P.O. Box 650<br>Toronto, ON M1K 5E3 Canada | 416-495-5795 |
| **Tom Fisher**<br>Project Coord. FleetWise Program | **Natural Resources Canada CANMET**<br>580 Booth Street<br>Ottawa, ON K1A OE4 Canada | 613-947-0128 |
| **Nigel Fitzpatrick**<br>Director, Clean Transportation | **BC Research Inc.**<br>3650 Wesbrook Mall<br>Vancouver, BC V6S 2L2 Canada | 604-224-4331 |
| **Roydon A. Fraser**<br>Associate Professor | **University of Waterloo**<br>Dept. of Mechanical Engineering<br>200 University Avenue W.<br>Waterloo, ON N2L 3G1 Canada | 519-888-4764 |

# Participants List - 1996 Windsor Workshop on Alternative Fuels

| | | |
|---|---|---|
| **Brian French**<br>Section Mgr. DSVPM | **Department of National Defence**<br>National Defence HQ, DSVPM-4<br>Maj. Gen.George R. Pearkes Bldg.<br>Ottawa, ON K1A OK2 Canada | 819-997-9655 |
| **John Garbak** | **U.S. Department of Energy**<br>Forrestal Bldg. CE-332<br>1000 Independence Avenue S.W.<br>Washington, DC 20585 USA | 202-586-1723 |
| **David Gardiner**<br>Project Manager, Automotive R&D | **Thermotech Engineering**<br>415 Norris Court<br>Kingston, ON K7P 2R9 Canada | 613-384-7894 |
| **David Gelman**<br>Senior Project Manager | **Antares Group Inc.**<br>8240 Professional Place<br>Suite 207<br>Landover, MD 20785 USA | 301-731-1900 |
| **Adrian Ghelesel**<br>Technology Dev. Engineer | **BC Gas Utility Ltd.**<br>1111 West Georgia<br>Vancouver, BC V6E 4M4 Canada | 604-443-6788 |
| **Wendel Goetz**<br>Mgr. Business Develop. Engines | **ORTECH Corporation**<br>11603 Parkedge Drive<br>N. Bethesda, MD 20852 USA | 301-468-5980 |
| **Steve Goguen** | **U.S. Department of Energy**<br>Forrestal Bldg. CE-332<br>1000 Independence Avenue S.W.<br>Washington, DC 20585 USA | 202-586-8044 |
| **Bryan Goulden**<br>Manager, Technology Marketing | **Union Gas/Centra Gas Ontario**<br>50 Keil Drive N.<br>P.O. Box 2001<br>Chatham, ON N7M 5M1 Canada | 519-436-4637 |
| **Jim Gray**<br>Manager, Series 50G/60G Product Group | **Detroit Diesel Corporation**<br>13400 Outer Drive West<br>Detroit, MI 48239-4001 USA | 313-592-7126 |
| **Dave Gregorika**<br>Service Engineer | **Ford Customer Service Div.**<br>1555 Fairlane Drive<br>Allen Park, MI 48101 USA | 313-248-7629 |

# Participants List - 1996 Windsor Workshop on Alternative Fuels

| | | |
|---|---|---|
| **Rob Groeneveld**<br>General Manager | **BK Gas BV**<br>P.O. Box 547<br>Hoofddorp, 2130 AM The Netherlands | 31-23 566 2200 |
| **John Heenan**<br>VP, Marketing & Engineering | **Sherex/OPW.Inc.**<br>4180 Morris Drive<br>Burlington, Ontario L7L 5L6 Canada | 905-639-9400 |
| **Hartmut Heinrich** | **Volkswagen AG**<br>K-EFVT<br>Letter Box 1774<br>D-38436 Wolfsburg, Germany | 49-5361-976040 |
| **Pamela Heneault** | **P.R. Heneault & Associates**<br>87 Chemin Kamanik<br>Val des Monts, Quebec J0X 2R0 Canada | 819-671-6620 |
| **Nobuyoshi Hirakochi**<br>V.P. / General Manager | **Mitsubishi Motors R&D of America Inc.**<br>100 Center Square Road<br>Bridgeport, NJ 08014 USA | 609-467-4664 |
| **Steve Hood**<br>Principal | **AERA Technology Management Services**<br>51 Harrison Avenue<br>Guelph, ON N1H 5K3 Cananda | (519) 836-8059 |
| **Susan Horton**<br>Workshop Coordinator | **ORTECH Corporation**<br>Engine Technologies<br>2395 Speakman Drive<br>Mississauga, ON L5K 1B3 Canada | 905-822-4111 X515 |
| **Steve Howell** | **National Biodiesel Board**<br>6807 W. 202nd Terrace<br>Bucyrus, KS 66013 U.S.A. | (913) 681-0400 |
| **John Hutchison**<br>Principal | **John D. Hutchinson Consulting**<br>47 Soudan Avenue<br>Toronto, ON M4S 1V5 Canada | 416-487-2428 |
| **Shinichi Iguchi**<br>Vice President, Technology | **Nippon Steel USA Inc.**<br>10 East 50th Street<br>29th Floor<br>New York, N.Y. 10022 USA | 212-207-0178 |
| **Burt Jabri**<br>Works Engineer | **City of North York**<br>5100 Yonge Street<br>North York, ON M2N 5V7 Canada | 416-395-6386 |

# Participants List - 1996 Windsor Workshop on Alternative Fuels

| | | |
|---|---|---|
| **Mike Jackson**<br>Manager, Alternative Fuels | **Acurex Environmental Corporation**<br>555 Clyde Avenue<br>P.O. Box 7044<br>Mountain View, CA 94039 USA | 415-254-2450 |
| **Walter Jacques** | **AFV Associates**<br>30 Elm Court<br>Grosse Pointe, Mi 48236 USA | 313-417-0643 |
| **Bernard James**<br>Chief, Transportation Group | **Natural Resources Cànada CANMET**<br>Alt. Energy Div. Energy Technology Branch 580 Booth Street, Room 720<br>Ottawa, Ontario K1A OE4 Canada | 613-943-2258 |
| **Roberto Javèllana**<br>Product Maket Manager | **Deere Power Systems Group**<br>P.O. Box 5100<br>Waterloo, IA 50704 USA | 319-292-5348 |
| **Iain Johnstone**<br>Key Account Representative - NGV | **BC Gas Utility Ltd.**<br>207 - 4190 Lougheed Highway<br>Burnaby, BC V5C 6A8 Canada | 604-293-8813 |
| **Kenneth R. Katz** | **U.S. Department of Energy**<br>Forrestal Bldg. EE-33<br>1000 Independence Avenue S.W.<br>Washington, DC 20585 USA | 202-586-6116 |
| **Franz Keiling**<br>President | **Kraft Fuels**<br>50 Ritin Lane<br>Unit 20<br>Concord, ON L4K 4C9 Canada | 905-738-0287 |
| **Ken Kelly** | **National Renewable Energy Laboratory**<br>1617 Cole Blvd.<br>Golden, CO 80401-3393 USA | 303-275-4465 |
| **Matt Keyser** | **National Renewable Energy Laboratory**<br>1617 Cole Blvd.<br>Bldg. 15/1<br>Golden, CO 80401-3393 USA | 303-275-3876 |
| **Gordon Kinsler**<br>Production Control | **Sherex/OPW.Inc.**<br>4180 Morris Drive<br>Burlington, Ontario L7L 5L6 Canada | 905-639-9400 |

# Participants List - 1996 Windsor Workshop on Alternative Fuels

| | | |
|---|---|---|
| **Phil Kling**<br>Technology Planner | **General Motors of Canada Ltd.**<br>1908 Colonel Sam Drive<br>098-001<br>Oshawa, ON L1H 8P7 Canada | 905-644-1200 |
| **Spencer Knipping**<br>Advisor | **Ontario Ministry of Energy and Environment**<br>135 St. Clair Avenue West<br>6th Floor<br>Toronto, ON M4V 1P5 Canada | 416-323-5664 |
| **Alina Kulikowski-Tan**<br>Vice President | **The ADEPT Group, Inc.**<br>10920 Wilshire Blvd.<br>Suite 1203<br>Los Angeles, CA 90024 USA | 310-208-8074 |
| **Macie L. LaMotte**<br>Air Pollution Control Specialist | **Colorado Department of Public Health & Environment**<br>APCD-MS-B1<br>4300 Cherry Creek Drive South<br>Denver, CO 80222-1530 USA | 303-692-3133 |
| **John Lapetz** | **Ford Motor Company**<br>Danou Technical Center<br>Suite 155, 16630 Southfield Road<br>Allen Park, MI 48101 USA | 313-337-5636 |
| **Robert P. Larsen**<br>Leader, Technol. Eng. Section | **Argonne National Laboratory**<br>Center for Transportation Research<br>9700 S. Cass Av. Bldg. ES/362-B209<br>Argonne, IL 60439-4815 USA | 708-252-3735 |
| **Louis A. Lautman**<br>Sr. Product Manager, NGV Products | **Gas Research Institute**<br>8600 West Bryn Mawr Avenue<br>Chicago, IL 60631-3562 USA | 312-399-5461 |
| **Alex Lawson**<br>Director of Engineering | **GFI Control Systems Inc.**<br>100 Hollinger Crescent<br>Kitchener, ON N2K 2Z3 Canada | 519-576-4270 |
| **Sophie Levesque** | **Department of National Defence**<br>National Defence HQ, DSVPM-4<br>Maj. Gen.George R. Pearkes Bldg.<br>Ottawa, ON K1A OK2 Canada | 819-997-9655 |
| **Stephanie Lines**<br>Research Advisor | **Natural Resources Canada CANMET**<br>Energy Technology Branch<br>580 Booth Street, 7th Floor<br>Ottawa, ON K1A OE4 Canada | 613-992-8744 |

# Participants List - 1996 Windsor Workshop on Alternative Fuels

| | | |
|---|---|---|
| **Bill Lupkoski**<br>Bus Engine Business Mgr. | **Cummins Engine Company, Inc**<br>301 Wyecroft Road<br>Oakville, ON L6K 2H2 Canada | 905-844-5851 |
| **Ian MacIntyre**<br>Research Officer-Gaseous Fuels | **Natural Resources Canada CANMET**<br>Alt. Energy Div. Energy Technology Branch<br>580 Booth Street, 7th Floor<br>Ottawa, ON K1A OE4 Canada | 613-943-2257 |
| **Norman Marek** | **Illinois Dept. of Commerce & Community Affairs**<br>325 West Adams, Room 300<br>Springfield, IL 62704 USA | 217-785-0184 |
| **Harry McAdie**<br>Consultant | **H.G. McAdie Associates**<br>245 Eglinton Avenue East<br>Suite 340<br>Toronto, ON M4P 3B7 Canada | 416-489-7067 |
| **Peter McCallum**<br>Senior Project Engineer | **Antares Group Inc.**<br>8240 Professional Place<br>Suite 207<br>Landover, MD 20785 USA | 301-731-1900 |
| **Jim McCandless** | **AVL Powertrain Engineering, Inc.**<br>41249 Vincenti Court<br>Novi, MI 48375 USA | 810-477-1203 |
| **Grant McVicar** | **Manitoba Energy and Mines**<br>360-1395 Ellice Avenue<br>Winnipeg, Manitoba R3G 3P2 Canada | (204) 945-3674 |
| **Zoher Meratla**<br>President | **CDS Research**<br>20 Brooksbank Avenue<br>North Vancouver, BC V7J 2B8 Canada | 604-985-2865 |
| **Ken Mitchell**<br>Staff Research Engineer | **Shell Canada Ltd.**<br>400 - 4th Avenue S.W.<br>P.O. Box 100, Station M<br>Calgary, AB T2P 2H5 Canada | 403-691-2877 |
| **Daniel Most** | **Hitachi Automotive Products**<br>34500 Grand River Avenue<br>Farmington Hills, MI 48335 USA | 810-477-5400 |
| **Gregory E. Mott**<br>Research Engineer | **West Virgina University**<br>Mech & Aerosp. Eng. MAE Dept. Rm 357<br>P.O. Box 6106<br>Morgantown, WV 26505-6106 USA | 304-293-2419 |

# Participants List - 1996 Windsor Workshop on Alternative Fuels

| | | |
|---|---|---|
| **Rob Motta**<br>Snr. Transportation Engineer | **National Renewable Energy Laboratory**<br>1617 Cole Blvd.<br>Bldg. 15/1<br>Golden, CO 80401-3393 USA | 303-275-4482 |
| **Gary Murray**<br>Market Development Officer | **Natural Resources Canada**<br>Transportation Energy Division<br>580 Booth Street, 15th Floor<br>Ottawa, ON K1A OE4 Canada | 613-996-8736 |
| **Brett Nelson** | **GFI Control Systems Inc.**<br>100 Hollinger Crescent<br>Kitchener, ON N2K 2Z3 Canada | 519-576-4270 |
| **Khiem Nguyen**<br>Fleet Engineer | **Regional Municipality of Ottawa-Carleton**<br>Corporate Fleet Services<br>Ottawa, ON K1Z 5A6 Canada | 613-724-4244 |
| **Roberta J. Nichols**<br>Alternative Fuel Consultant | **Alternative Fuels Consultant**<br>8645 N. Territorial Road<br>Plymouth, MI 48170-5043 USA | 313-459-7313 |
| **Mike Nielsen**<br>Service Engineer | **Ford Customer Service Div.**<br>1555 Fairlane Drive<br>Allen Park, MI 48101 USA | 313-248-9719 |
| **Ralph Nine** | **West Virginia University**<br>Dept. of Mech. & Aerospace Eng.<br>P.O. Box 6106, room 357 ESB<br>Morgantown, WV 26506-6106 USA | 304-293-3111 X463 |
| **Roy Nishizaki**<br>Senior Development Officer | **Transport Canada/TDC**<br>800 Rene Levesque Blvd. W.<br>6th Floor<br>Montreal, Quebec H3B 1X9 Canada | 514-283-0026 |
| **Paul Norton**<br>Staff Project Engineer | **National Renewable Energy Laboratory**<br>1617 Cole Boulevard<br>Bldg. 16/3<br>Golden, CO 80401-3393 USA | 303-275-4424 |
| **Lawrence O'Connell** | **O'Connell & Associates**<br>501 Fourteenth Street<br>Suite 250<br>Oakland, CA 94612 USA | 510-444-3771 |
| **Don O'Connor** | **Mohawk Canada Ltd.**<br>6400 Robert Street<br>Burnaby, BC V5G 4G2 Canada | 604-293-4127 |

# Participants List - 1996 Windsor Workshop on Alternative Fuels

| | | |
|---|---|---|
| **Kevin O'Connor** | **National Renewable Energy Laboratory**<br>1617 Cole Blvd.<br>Golden, CO 80401-3393 USA | 303-275-4387 |
| **Juan Osborn** | **California Air Resources Board**<br>Mobile Source Division<br>9528 Telstar Avenue<br>El Monte, CA 91731 USA | 818-575-6998 |
| **Madis Paas**<br>Alternative Fuels Consultant | **M. Paas Consulting Ltd.**<br>70 McCallum Cr.<br>Winnipeg, Manitoba R3R 2S6 Canada | 204-895-9078 |
| **Francis Palmer**<br>Technical Director | **Coordinating European Council**<br>Madou Plaza - 25th Floor<br>Place Madou 1<br>Brussels, B - 1210 Belgium | 32-2 226 1930 |
| **Stuart Perkins**<br>Director of Engineering | **Chrysler Canada Ltd.**<br>2450 Chrysler Centre<br>CIMS 232-02-48<br>Windsor, ON N9A 4H6 Canada | 519-973-2250 |
| **Campbell Perry** | **BC Research Inc.**<br>3650 Wesbrook Mall<br>Vancouver, BC V6S 2L2 Canada | 604-224-4331 |
| **Ross Petrini**<br>Fleet Manager | **City of North York**<br>5100 Yonge Street<br>North York, ON M2N 5V7 Canada | 416-395-6354 |
| **Robert Petsinger**<br>President | **CNG Services of Pittsburgh, Inc**<br>Wellington Square, Suite 453<br>3940 Old William Penn Highway<br>Pittsburgh, PA 15235-4849 USA | 412-372-5568 |
| **Leslie J. Phillips**<br>Consultant | **Logtech**<br>2695 Hickson Cr.<br>Ottawa, ON K2H 6Y5 Canada | 613-828-4764 |
| **Rene Pigeon**<br>Research Advisor, Liquid Motor Fuels | **Natural Resources Canada CANMET**<br>Alt. Energy Div. Energy Technology Branch<br>580 Booth Street<br>Ottawa, ON K1A 0E4 Canada | 613-943-4480 |
| **Felix Pilorusso**<br>Principal | **Pilorusso Research & Consulting Inc.**<br>14A Hazelton Avenue<br>Suite 302<br>Toronto, ON M5R 2E2 Canada | 416-975-8497 |

# Participants List - 1996 Windsor Workshop on Alternative Fuels

| | | |
|---|---|---|
| **Frederick L. Potter**<br>President | **Information Resources Inc.**<br>1925 North Lynn Street<br>Arlington, VA 22209 USA | 703-528-2500 |
| **Chandra Prakash**<br>Head, Transportation Fuels | **Environment Canada**<br>Industrial Sectors Branch<br>Place Vincent Massey Bldg. 13th Floor<br>Hull, Quebec K1A OH3 Canada | 819-997-1614 |
| **David Quinn** | **Royal Military College**<br>Dept. of Chem. & Chem. Eng.<br>Kingston, ON K7K 5LO Canada | 613-541-6318 |
| **Ralph Rackham**<br>VP Engineering & Research | **FuelMaker Corporation**<br>60 Worcester Road<br>Rexdale, Ontario M9W 5X2 Canada | 416 674-3034 |
| **Peter Reilly-Roe** | **Natural Resources Canada CANMET**<br>EAEB<br>580 Booth Street, 15th Floor<br>Ottawa, ON K1A OE4 Canada | 613-996-6001 |
| **Edward P. Richards**<br>Commercial Manager | **Engine Control Systems Ltd.**<br>165 Pony Drive<br>Newmarket, ON L4P 3A6 Canada | 905-853-5500 |
| **Greg Rideout**<br>Head, Emissions Research Group | **Environment Canada**<br>MSED - Environmental Tech. Centre<br>3439 River Road<br>Ottawa, Ontario K1A OH3 Canada | 613-990-1364 |
| **Mark R. Riechers**<br>Vice President | **Automotive Testing Labs. Inc.**<br>P.O. Box 289<br>Route 33, Bldg. C, TRC Complex<br>East Liberty, OH 43319 USA | 513-666-4351 |
| **Greg Rodrigues** | **Honda R & D**<br>1900 Harpers Way<br>Torrance, CA 90501 USA | 310-781-5746 |
| **Gerald Roger**<br>Eng. & Sales Manager | **Sherex/OPW.Inc.**<br>4180 Morris Drive<br>Burlington, Ontario L7L 5L6 Canada | 905-639-9400 |
| **Pat Ross-Smith** | **ORTECH Corporation**<br>2395 Speakman Drive<br>Mississauga, ON L5K 1B3 Canada | 905-822-4111 X257 |

# Participants List - 1996 Windsor Workshop on Alternative Fuels

| | | |
|---|---|---|
| **Jerry Roussel**<br>Principal Staff Engineer | **Ford Motor Company**<br>The American Road<br>Dearborn, MI U.S.A. | (313) 323-8126 |
| **Floyd R. Running**<br>Dist. Sales Manager | **Gas Equipment Supplies**<br>6597 Kitimat Road<br>Mississauga, ON L5N 4J4 Canada | 905-858-8440 |
| **John A. Russell**<br>Director, Office of Technol. Utiliz. | **U.S. Department of Energy**<br>Forrestal Bldg. EE-33<br>1000 Independence Avenue S.W.<br>Washington, DC 20585 USA | 202-586-8038 |
| **Warren Salt** | **National Renewable Energy Laboratory**<br>1617 Cole Blvd.<br>Golden, CO 80401-3393 USA | 303-275-4422 |
| **Bengt Savbark**<br>Managing Director | **Ecotraffic R & D AB**<br>Box 5671<br>Stockholm, S-11486 Sweden | 46-8-614-5056 |
| **Ellesworth Schanerberger**<br>Consultant | **Consultant**<br>15964 N. Swathmore Ct.<br>Livonia, MI 48154-1005 USA | 313-591-7851 |
| **Leon G. Schumacher**<br>Assistant Professor | **University of Missouri**<br>Room 235 Agricultural Eng. Bldg.<br>Columbia, MO 65211 USA | 314-882-2126 |
| **Rodney Semotiuk**<br>Analyst, Alternative Energy | **Natural Resources Canada CANMET**<br>580 Booth Street<br>Ottawa, ON K1A OE4 Canada | 613-947-0273 |
| **JanJeen Seppen**<br>Head, Internal Combustion Engines | **TNO Road Vehicles Research Institute**<br>P.O. Box 6003<br>Schoemakerstr 97<br>Delft, 2625 KB The Netherlands | 31-15-269 69 00 |
| **Don Singleton**<br>Research Officer | **National Research Council**<br>Montreal Road<br>Ottawa, ON K1A 0R6 Canada | 613-993-2500 |
| **Monique Sivret**<br>ATF Consultant | **Monique Sivret Consulting Services**<br>580 Booth Street<br>Ottawa, ON K1A 0E4 Canada | 613-947-0383 |

# Participants List - 1996 Windsor Workshop on Alternative Fuels

| | | |
|---|---|---|
| **Lee A. Slezak**<br>Manager, Federal Fleet AFV Program | **U.S. Department of Energy**<br>1000 Independence Ave., S.W.<br>Washington, D.C. 20585-0121 U.S.A. | (202) 586-2335 |
| **Ry Smith**<br>Mgr. NGV Eng. & Vendor Relations | **Union/Centra Gas**<br>750 Richmond Street<br>P.O. Box 2001<br>Chatham, ON N7M 5M1 Canada | 519-436-4618 |
| **Tom Smyth**<br>Manager, Vehicle Technologies | **Natural Resources Canada CANMET**<br>Energy Technology Branch<br>580 Booth Street, 7th Floor<br>Ottawa, ON K1A OE4 Canada | 613-992-7598 |
| **Alex Spataru**<br>President | **The ADEPT Group, Inc.**<br>10920 Wilshire Blvd.<br>Suite 1203<br>Los Angeles, CA 90024 USA | 310-208-8074 |
| **Peter Spyche**<br>Sales Engineer | **Sherex Industries**<br>1400 Commerce parkway<br>Lancaster, NY 14086 USA | 716-681-6250 |
| **Vernel Stanciulescu** | **National Resources Canada**<br>580 Booth Street<br>16th Floor<br>Ottawa, ON K1A 0E4 Canada | 613-995-2100 |
| **Bob Stemmler** | **Impco Technologies, Inc.**<br>16804 Gridley Place<br>Cerritos, CA 90701 USA | 310-860-6666 |
| **Mike Sulatisky**<br>Team Leader | **Saskatchewan Research Council**<br>15 Innovation Blvd.<br>Saskatoon, SK S7N 2X8 Canada | 306-933-5468 |
| **Mehboob Sumar** | **ORTECH Corporation**<br>2395 Speakman Drive<br>Mississauga, ON L5K 1B3 Canada | 905-822-4111 X654 |
| **Victor Suski**<br>Automotive Engineer | **American Trucking Association**<br>2200 Mill Road<br>Alexandria, VA 22314 U.S.A. | (705) 838-1846 |
| **John A. Taylor** | **Petro Canada**<br>111 - 5th Avenue S.W.<br>P.O. Box 2844<br>Calgary, AB T2P 3E3 Canada | 403-296-4931 |

# Participants List - 1996 Windsor Workshop on Alternative Fuels

| | | |
|---|---|---|
| **Chuck Taylor**<br>Service Engineer | **Ford Customer Service Div.**<br>1555 Fairlane Drive<br>Allen Park, MI 48101 USA | 313-621-6580 |
| **Tom Timbario**<br>Vice President | **EA Engineering**<br>8401 Colesville Road<br>Suite 500<br>Silver Spring, MD 20910 USA | 301-565-4216 |
| **Michael Tremayne**<br>Manager, Operations/Engineering NGV | **Consumers Gas Company**<br>500 Consumers Road<br>P.O. Box 650<br>Scarborough, ON M1K 5E3 Canada | 416-495-5989 |
| **Vasso Tsatsami** | **BP Oil International Ltd.**<br>Oil Technology Centre<br>Chertsey Road<br>Sunbury-on-Thames, Middlesex TW16 7LN UK | 1932-764393 |
| **Sean H. Turner**<br>Director of Technology | **Natural Gas Vehicle Coalition**<br>1515 Wilson Blvd.<br>Suite 1030<br>Arlington, VA 22209 USA | 703-527-3022 |
| **Jeffery Turner**<br>Project Research Engineer | **Ministry of Transportation of Ontario**<br>Room 328, Central Building<br>1201 Wilson Avenue<br>Downsview, Ontario M3M 1J8 Canada | 416 235-5012 |
| **Vlad Ulmet**<br>R & D Engineer | **Engine Control Systems Ltd.**<br>165 Pony Drive<br>Newmarket, ON L3Y 7V1 Canada | 905-853-5500 |
| **James S. Wallace**<br>Professor | **University of Toronto**<br>Dept. of Mechanical Engineering<br>5 King's College Road<br>Toronto, ON M5S 1A4 Canada | 416-978-5736 |
| **Michael Wang**<br>Policy Analyst | **Argonne National Laboratory**<br>9700 S. Cass Avenue<br>Argonne, IL 60439 U.S.A. | (708) 252-2819 |
| **Peter Ward** | **California Energy Commission**<br>1516 9th Street<br>Mail Stop 41<br>Sacramento, CA 95814-5512 USA | 916-654-4689 |

# Participants List - 1996 Windsor Workshop on Alternative Fuels

| | | |
|---|---|---|
| **Tim Warlick**<br>Project Leader | **Cummins Engine Co. Inc.**<br>P.O. Box 3005<br>Mail Code 50196<br>Columbus, IN 47202-3005 USA | 812-377-7548 |
| **William J. Way** | **GM Advanced Technology Vehicles**<br>Mail Code 483-619-426<br>1996 Technology Drive<br>Troy, MI 48007-7083 USA | 810-680-5513 |
| **Gary Webster**<br>President | **Advanced Engine Technology Ltd.**<br>17 Fitzgerald Road<br>Suite 102<br>Nepean, ON K2H 9G1 Canada | 613-721-1234 |
| **Don R. Welliver**<br>Director | **Cummins Engine Company, Inc.**<br>Box 3005<br>Columbus, IN 47202-3005 USA | 812-377-7303 |
| **Nick White**<br>Director, NGV Technology | **Gas Technology Canada**<br>55 Scarsdale Road<br>Don Mills, ON M3B 2R3 Canada | 416-449-0040 |
| **Donald F. Wilford**<br>Manager, Engine Technologies | **ORTECH Corporation**<br>2395 Speakman Drive<br>Mississauga, ON L5K 1B3 Canada | 905-822-4111 X596 |
| **Bryan Williamson**<br>Senior Engineer | **GFI Control Systems Inc.**<br>100 Hollinger Cres.<br>Kitchener, ON N2K 2Z3 Canada | (519) 576-4270 |
| **Robert Wimmer** | **Georgetown University**<br>Office of Energy Programs<br>The Car Barn, Suite 223<br>Washington, DC 20057 USA | 202-687-5055 |
| **Kurt Wipp**<br>Market Development Mgr. | **Methanex Corporation**<br>1800 - 200 Burrard Street<br>Vancouver, BC V6C 3M1 Canada | 604-661-2625 |
| **Lois Wright** | **Sacramento Municipal Utility District**<br>P.O. Box 15830<br>MS A351<br>Sacramento, CA 95852-1830 USA | 916-732-6143 |
| **Shawn Yates**<br>LPG Program Coordinator | **Chrysler Canada Ltd.**<br>2450 Chrysler Centre<br>CIMS 232-02-48<br>Windsor, Ontario N9A 4H6 Canada | 519-973-2045 |