1996 Windsor Workshop on

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Alternative Fuels

PROCEEDINGS

June 3–5, 1996, Toronto Colony Hotel, Downtown – City Hall, Toronto, Canada

PRESENTED BY:
ORTECH Corporation

SPONSORED BY:
CANMET, Natural Resources Canada
US Department of Energy

DISCLAIMER

Proceedings of the

1996 WINDSOR WORKSHOP

on

ALTERNATIVE FUELS

June 3-5, 1996

Toronto, Ontario

Sponsored by:

CANMET, Natural Resources Canada

United States Department of Energy

DOE/GO-10096-315
DE96013100

DISCLAIMER

PREFACE

Following the successful formula of past years, 1996 again saw CANMET, Natural Resources Canada, and the US Department of Energy (US DOE) team up to sponsor the Windsor Workshop on Alternative Fuels.

The 1996 Workshop attracted 172 participants from 8 countries including, Belgium, Canada, Germany, Italy, The Netherlands, Sweden, the United Kingdom and the United States; continuing to highlight the technical progress and importance of alternative transportation fuels in the World marketplace.

The '96 Workshop maintained its established approach to encourage an informal exchange of information. The message for 1996 was "**Is it time to become an industry**?" Should alternative fuel interests build coalitions and display a united front? Can they cooperate, are the OEM's committed? Is infrastructure developing, or should it focus in specific geographical areas? Are regulations helping or hurting the alternative fuels business? How are alternative fuels being developed in Europe, with oil industry cooperation.

Since inception the Windsor Workshops have proved to be an invaluable forum for this exchange, and we will endeavour to organize such timely and productive workshops in the years to come. We hope to see you all again in 1997 when the Workshop returns to Windsor, Ontario June 9-11, 1997.

We would like to express our sincere appreciation to the presenters and participants of the 1996 Windsor Workshop, and to ORTECH Corporation for coordinating this event.

Bernie James
CANMET, Natural Resources Canada

John Russell
US Department of Energy

1996 WINDSOR WORKSHOP ON ALTERNATIVE FUELS

TABLE OF CONTENTS (Cont'd)

1996 WINDSOR WORKSHOP ON ALTERNATIVE FUELS

TABLE OF CONTENTS

1996 WINDSOR WORKSHOP ON ALTERNATIVE FUELS

TABLE OF CONTENTS (Cont'd)

1996 WINDSOR WORKSHOP ON ALTERNATIVE FUELS

TABLE OF CONTENTS (Cont'd)

OPENING SESSION

Chair: Steve Goguen, U.S. Department of Energy

NATIONAL? CONTINENTAL? GLOBAL?

John Russell

U.S. Department of Energy

(Presentation unavailable at time of publication)

COALITION BUILDING AMONG THE ENERGY INDUSTRIES

Fred Potter, Information Resources Inc.

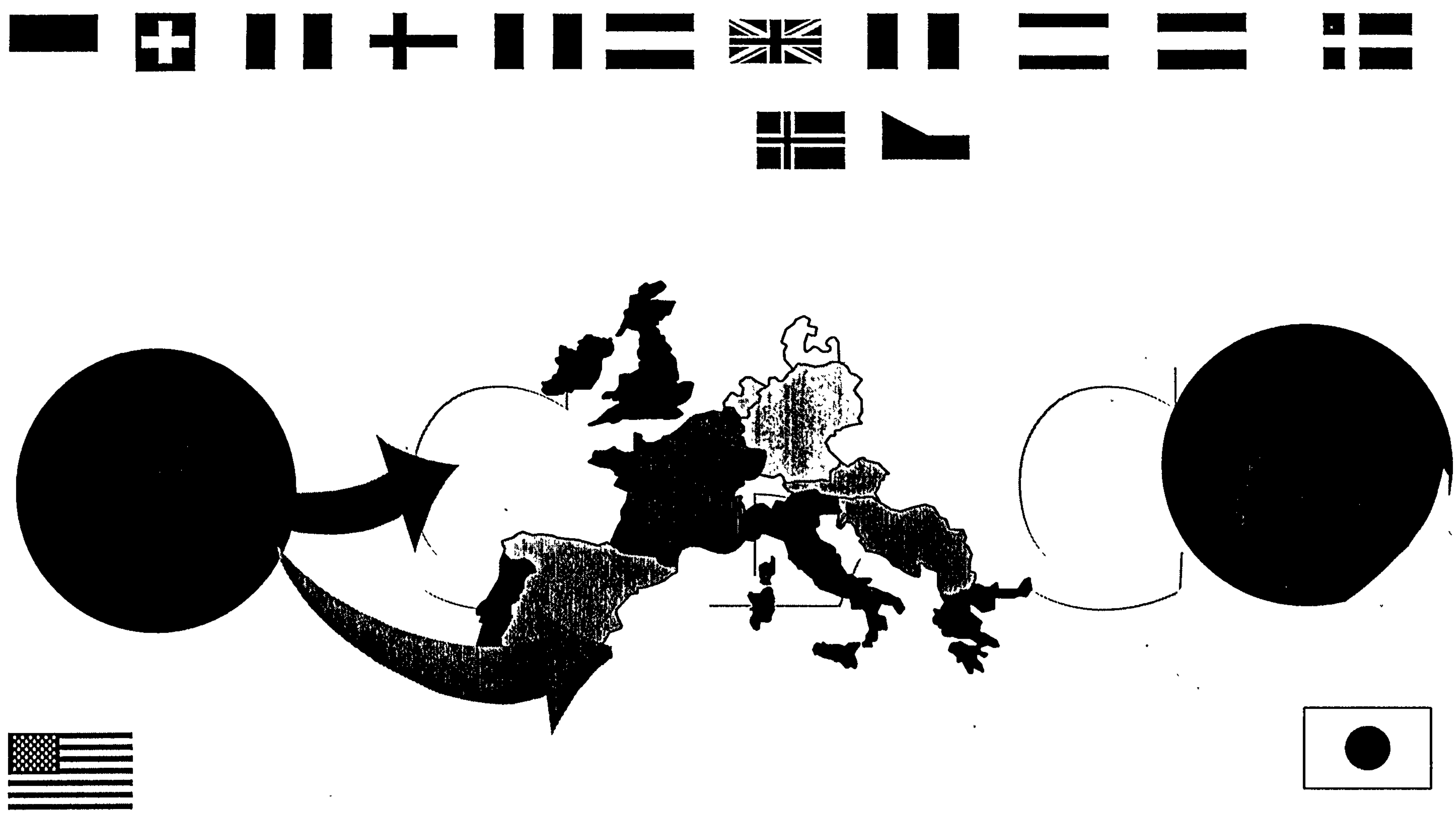
(Presentation unavailable at time of publication)

FUELLING THE ENVIRONMENTAL COLLABORATION OF THE EUROPEAN MOTOR AND OIL INDUSTRIES

FRANCIS H. PALMER

A blueprint for the way industry and government to work together on environmental issues for the benefit of the European Community and society

Performance Evaluation of Automotive Fuels & Lubricants



STRENGTHENING WORLD CONTACTS

BENEFITS OF PARTICIPATION IN CEC

- ★ Development of top quality performance tests for automotive fuels, lubricants and other fluids
- ★ Market relevance assured
- ★ Top quality assurance / accreditation provides costs-effectiveness
- ★ Underpins product specifications
- ★ Internationally recognised
- ★ Involvement means influence

BENEFITS OF PARTICIPATION IN CEC
(contd)

★ Climate of trust, truth and transparency

★ The only umbrella organisation in Europe representing the technical interests of motor, oil additive and allied industries in terms of product performance evaluation

★ Involved with EU Commissions and standards bodies such as ISO, CEN, etc...

★ Involved with world-wide industry associations

★ Low cost participation-CEC operates on non-profit making principle

MAIN INDUSTRIES REPRESENTED IN CEC

MAIN AIMS AND OBJECTIVES

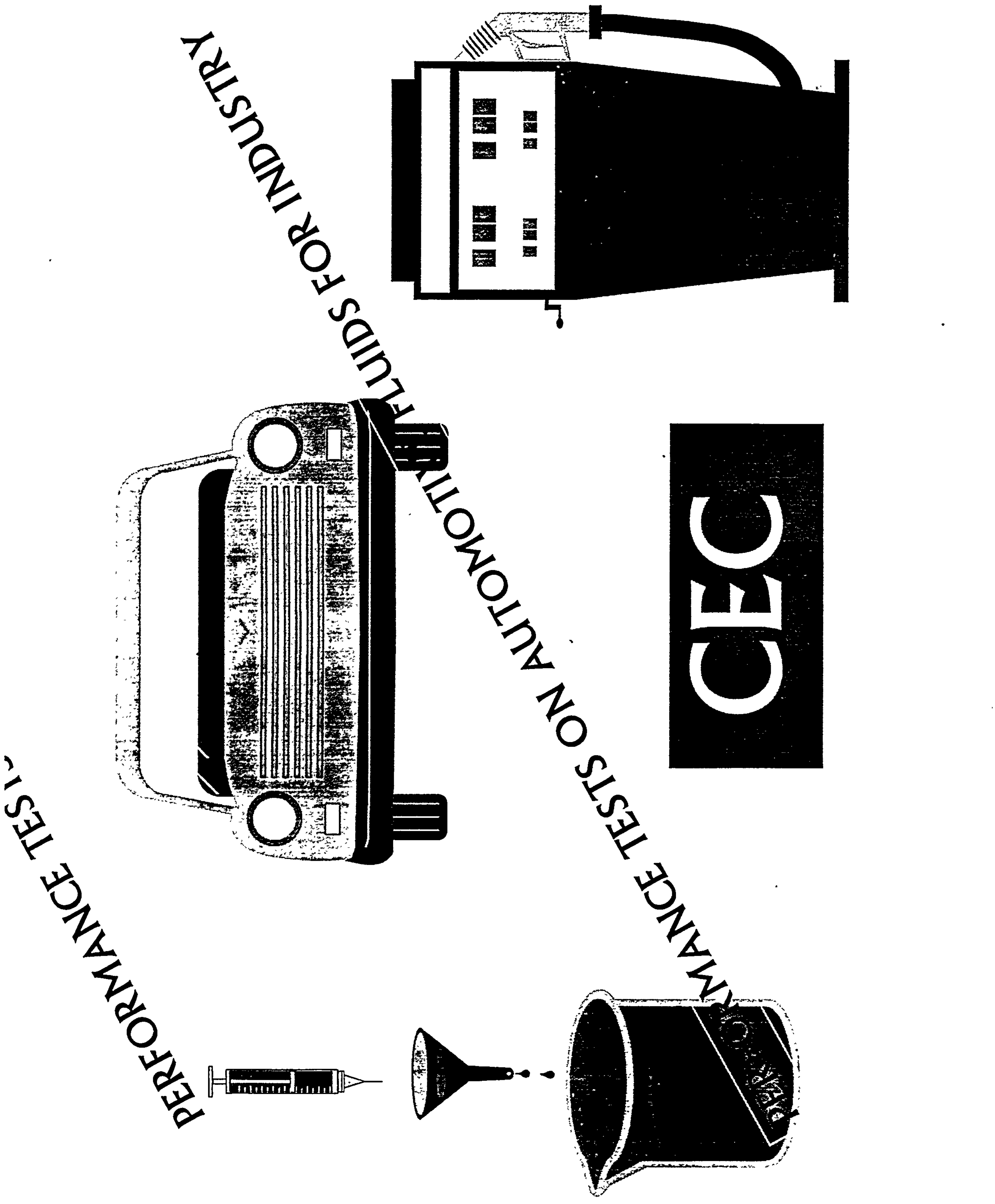
- To promote joint scientific rational approach to product performance problems of the motor, oil and additive industries
- To establish performance tests that relate to the market
- To ensure test methods and thus the result derived from them meeting the highest quality standards according to ISO 9000 series, EN 29000 series and EN 45001
- To service the needs of its members and hence the industries it represents with the highest efficiency

WHAT CEC REPRESENTS

13 COUNTRIES

300 COMPANIES

1500 PEOPLE


PERFORMANCE TEST
MANCE TESTS ON AUTOMOT FLUIDS FOR INDUSTRY
CEC

SOME QUESTIONS WHEN THINKING OF DIFFERENT FUEL OPTIONS:-

	oil	gasoline	diesel	alternatives
How much?	✹	✹	✹	✹
supply ensured?	✹			✹
from where?	✹			✹
safety?		✹		✹
pollution?	✹	✹	✹	

BIO FUELS NOT SEEN AS PART OF THE SOLUTION AT PRESENT

Questions about:-

- economics
- viability
- availability
- desirability / acceptability
- overall environmental benefits

ALTERNATIVE FUELS

ARE CONSIDERED
BY THE MOTOR AND OIL INDUSTRIES

&

THE EU

ON THE SAME SCIENTIFIC RATIONAL
COST EFFECTIVE APPROACH
AS FOR GASOLINE AND DIESEL
BASED ON AIR QUALITY NEEDS!!

ALTERNATIVE FUELS

may play a small role
in the road transportation
fuel sector but.......

Gasoline and diesel will remain
dominant in forseeable future

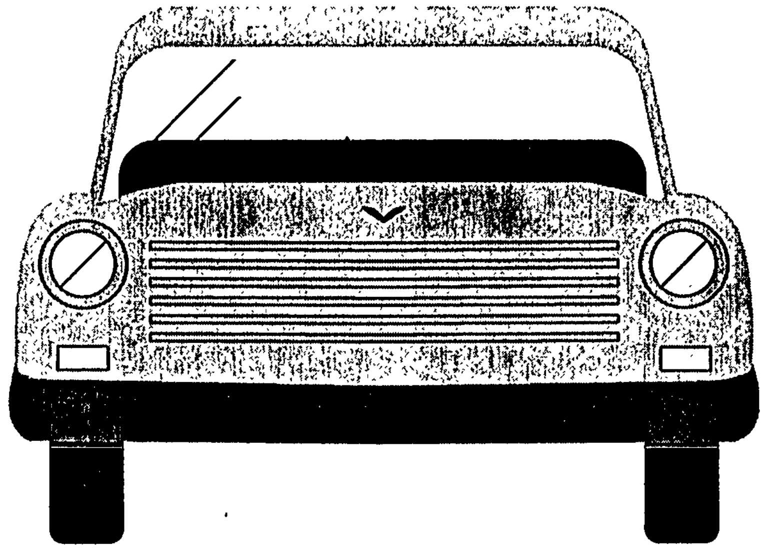
EU
ENHANCED ENVIRONMENTALLY FRIENDLY VEHICLES & ENGINES WORKING GROUP

will consider use of:-

- Natural gas for city buses and trucks
- LPG for city taxis and other captive car fleets
- Other options on cost effective basis

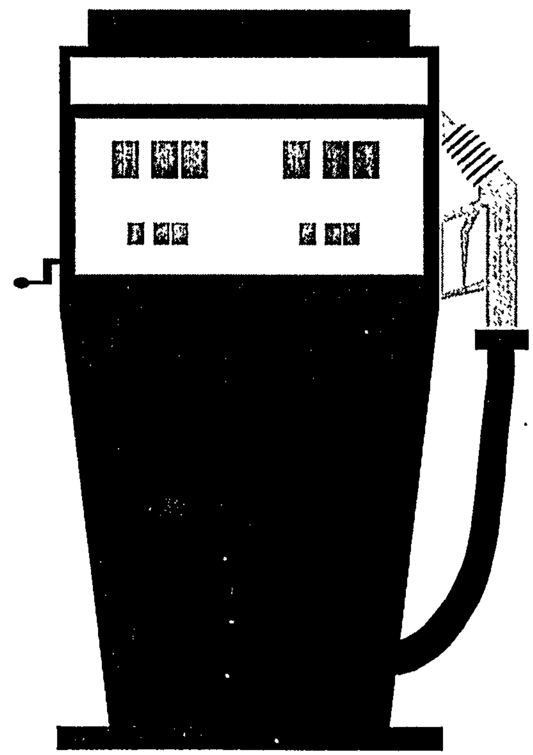
Locations where CEC Test Methods used Inside Europe

- Austria
- Belgium
- Czech Republic
- Germany
- Finland
- France
- Italy
- Netherlands
- Norway
- Spain
- Sweden
- Switzerland
- UK
- Bulgaria
- Lithuania
- Poland
- Portugal
- Hungary
- Russia
- Yugoslavia (Serbia)
- Macedonia



CEC

C + 2T + H-P =
Harmony
= Business Sucess!!



- Rational scientific approach best for all partners and society

- Joint co-operation the only sensible way forward and an essential pre-requisite for the rational approach

The Current Situation

Leading to Win / Win / Win / Win situations:-

-Car industry Wins with fuels fit-for-purpose

-Oil industry Wins by providing fuels with specifications that are matched to future vehicle needs and with a sound rationale for investment needs

-consumer Wins by improved air quality derived on cost effectiveness basis

-Commission Wins by providing a framework for future sustainable environmental policy

The Current Situation

- Integrated approach involving all key partners

- Rational scientific approach based on:-
  - -air quality standards
  - -air quality modelling
  - -knowledge of interactions between advanced fuels with advanced vehicles / engines
  - -acceptance of cost effective rationale
  - -inclusion of other measures such as I & M-integrated approach

- Joint pioneering industry / government approach approach meeting today's complex needs

The Role of EPEFE in the Process

- Showed commitment to rational scientific approach

- Gave ACEA / Europia a seat at the table

- Provided forum for bi-lateral discussions where disagreements can be resolved and compromises reached:-

  "this lead to a better understanding of the problems faced by each partner"

- Kept pressure on the Commission to meet their commitments to the programme:-

  -without EPEFE result air quality modelling would not have advanced or been so robust

  -without EPEFE cost effectiveness would not have advanced

How Did We Make Progress?

- By developing **trust**:-

  -between Commission and Industry
  -between Oil and Vehicle Industries
  -within Oil and Vehicle Industries

- By working **together**:-

  -several hundreds of meetings of auto-Oil partners since 1992

- By delivering results within agreed time schedules
- By accepting the **rational** approach
- By agreeing to compromise rationally
- By sticking to jointly held positions between the ACEA and Europia
- By avoiding public disagreements that could be exploited

Situation Prior to 1992

Led to potential Lose / Lose / Lose / Lose situations:-

-Car Industry Lost	to technology forcing initiatives not based on air quality needs
-Oil Industry Lost	uncoordinated nature of regulations not specifically related to air quality needs
-Consumers Lost	because cost effectiveness of environment not used and transport / stationary sources regulated separately
-Commission Lost	through loss in time / energy in the piecemeal process as well as lack of sound scientific rational approach underpinning emerging legislation

Situation Prior to 1992

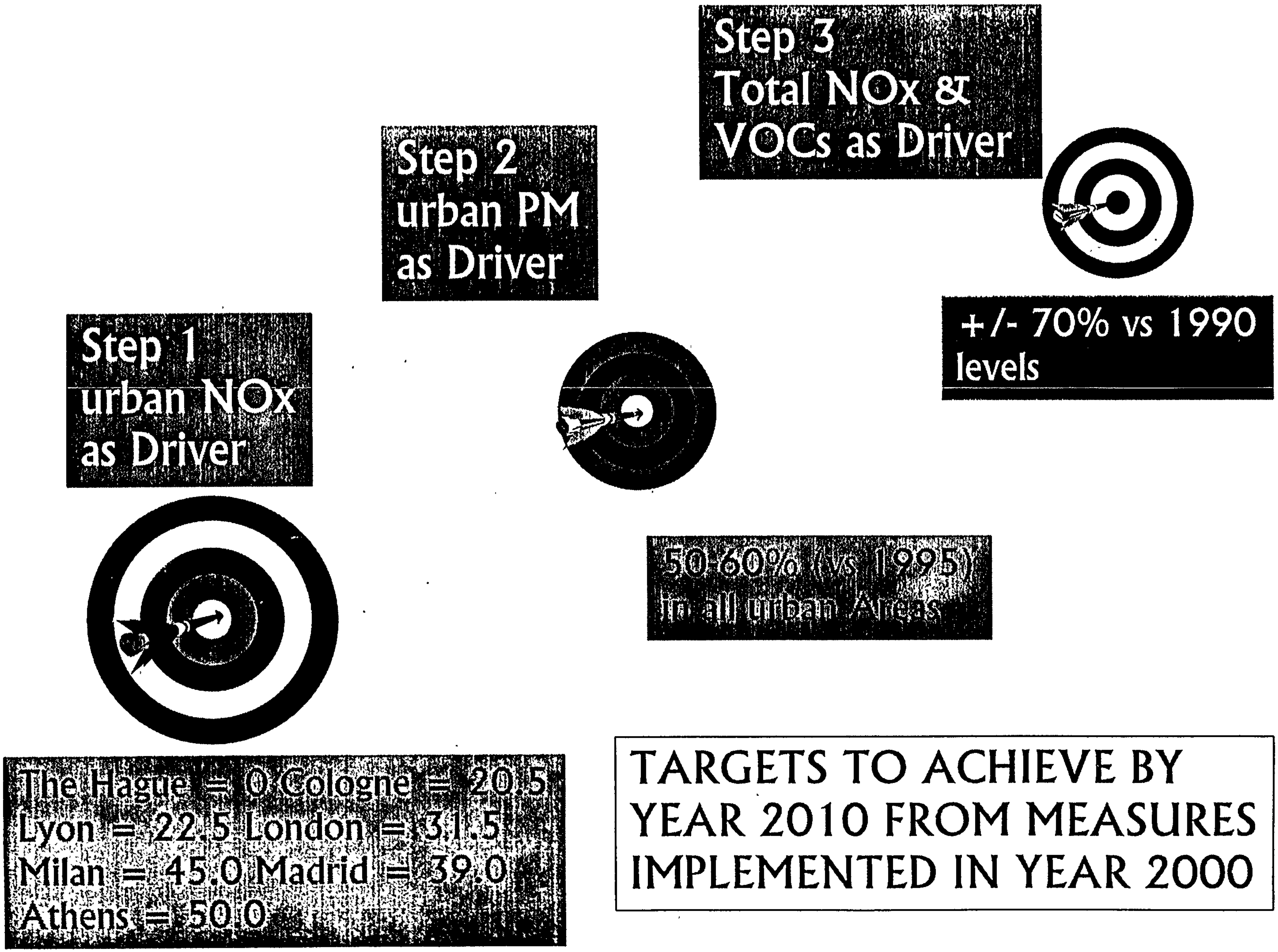
- Technology forcing best available technology at any cost
- Lack of systematic knowledge of air quality issues throughout Europe
- No air quality standards for EU
- No general acceptance of that cost effectiveness was important characteristic in environmental sustainability
- General pressure to adopt US / Californian solutions in Europe
- Uncoordinated approach to transport and environmental fuels, vehicle emissions, stationary sources, I & M, and traffic management

The Process

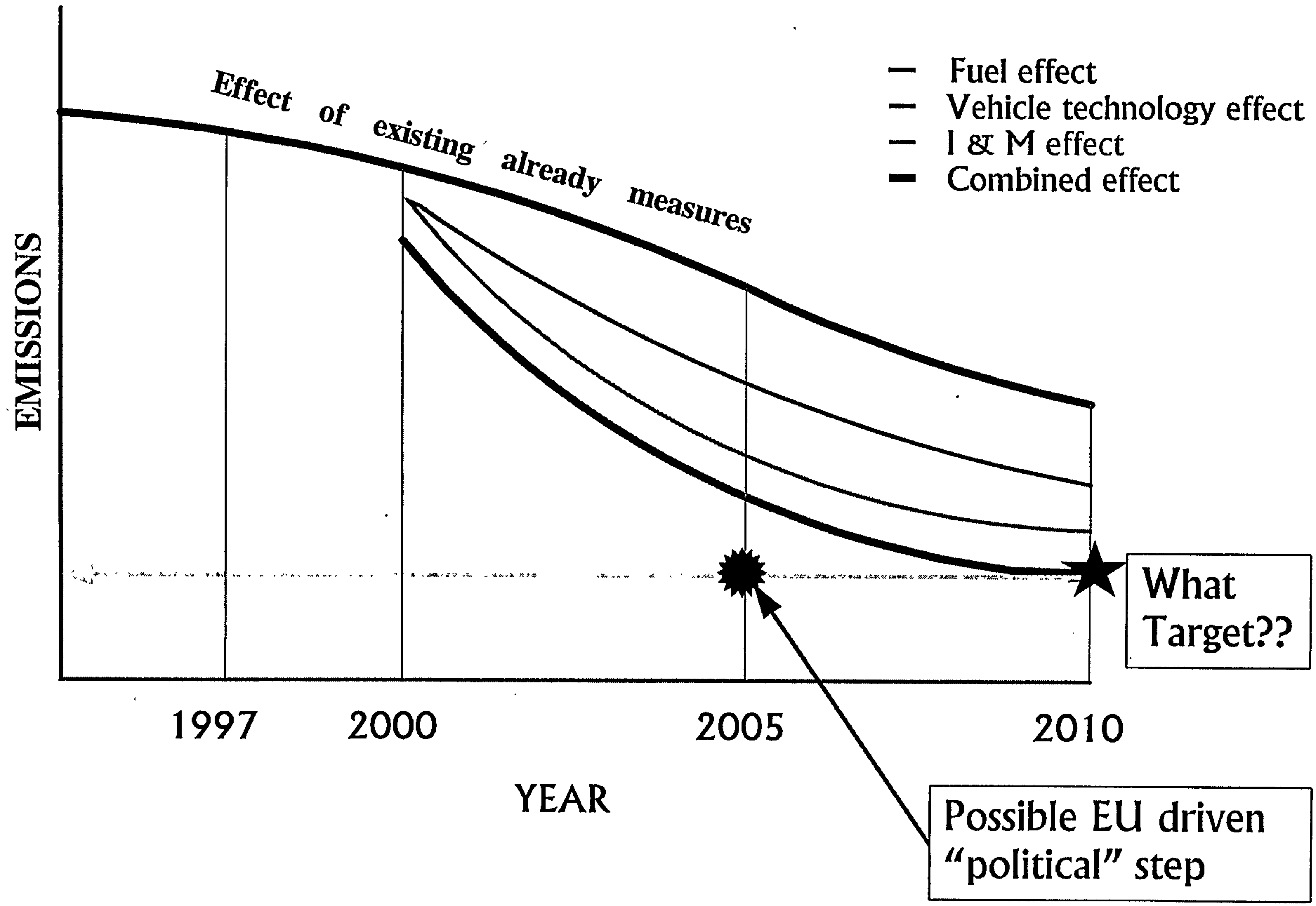
- Air quality of today
- Air quality in the future (2000 / 2010) versus air quality need
- EU Commission commitment to address future air quality issues / needs
- Common co-operation with industrial partners to prepare sound technical basis for legislative proposals

The European Auto-Oil Programme
"a win-win-win-win process"

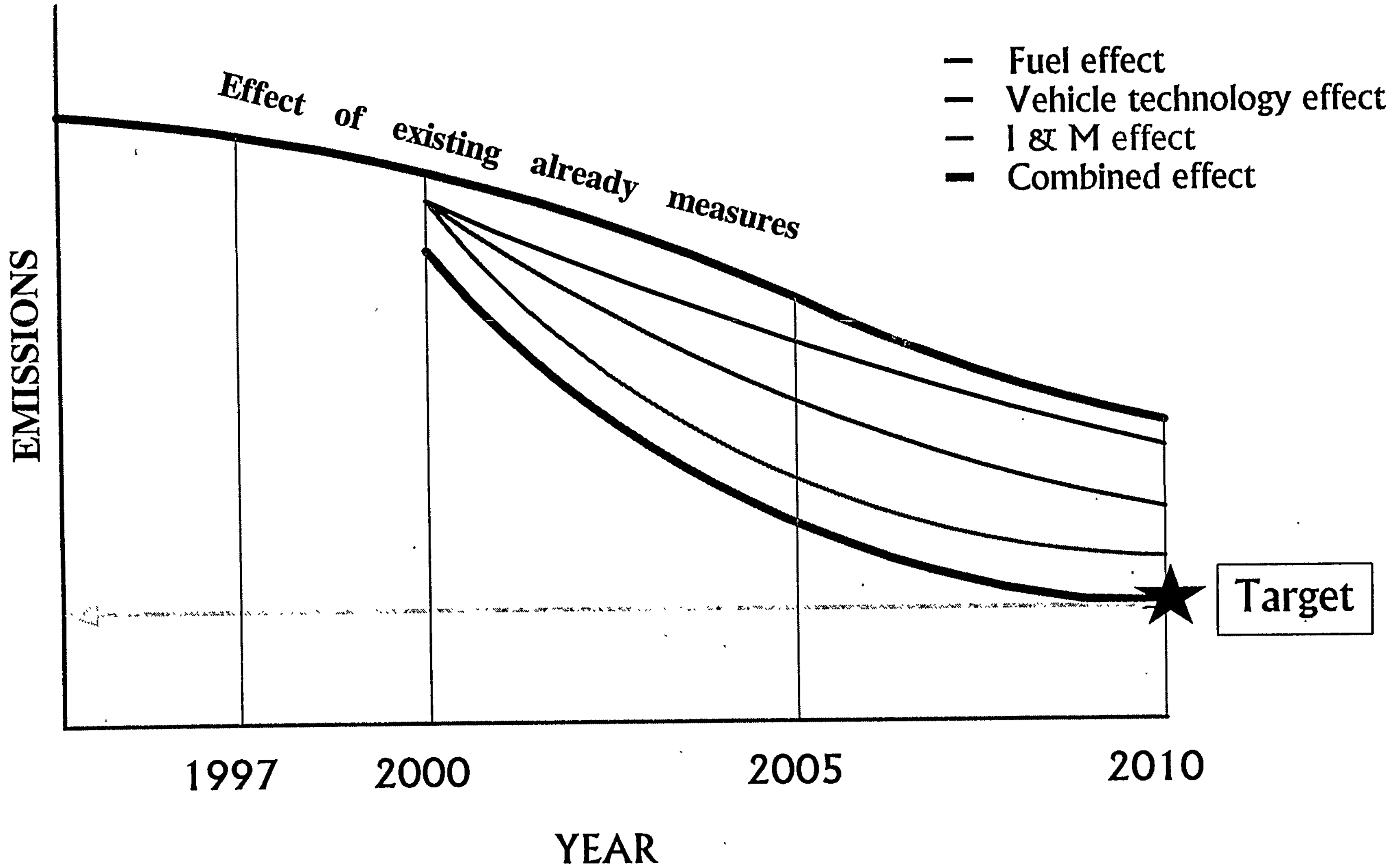
- Situation prior to 1992
- The current position
- How did we make progress
- The role of EPEFE in the process


Step 1
urban NOx
as Driver
Step 2
urban PM
as Driver
Step 3
Total NOx &
VOCs as Driver
+/- 70% vs 1990
levels
50-60% (vs 1995)
in all urban Areas
The Hague = 0 Cologne = 20.5
Lyon = 22.5 London = 31.5
Milan = 45.0 Madrid = 39.0
Athens = 50.0
TARGETS TO ACHIEVE BY
YEAR 2010 FROM MEASURES
IMPLEMENTED IN YEAR 2000

Principle of implementation of year 2000 measures



Principle of implementation of year 2000 measures



COST/EFFECTIVENESS APPROACH

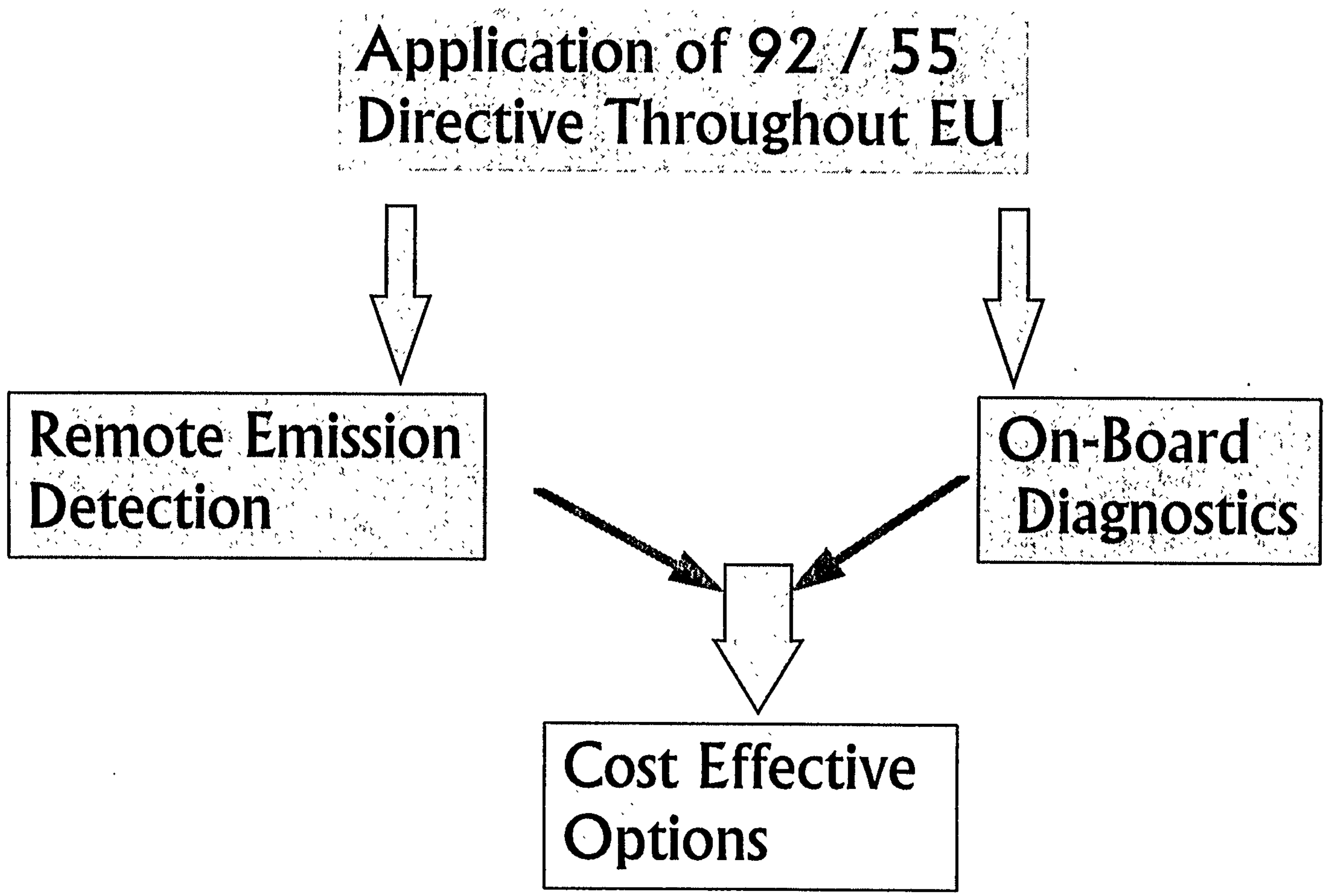
1) Automotive technology

2) Fuels technology

3) Non technical measures

4) Optimisation and measures

INSPECTION & MAINTENANCE



NON TECHNICAL MEASURES

1 - Road pricing

2 - Traffic restrictions

3 - Speed regulations

4 - Enhancements to urban public transport

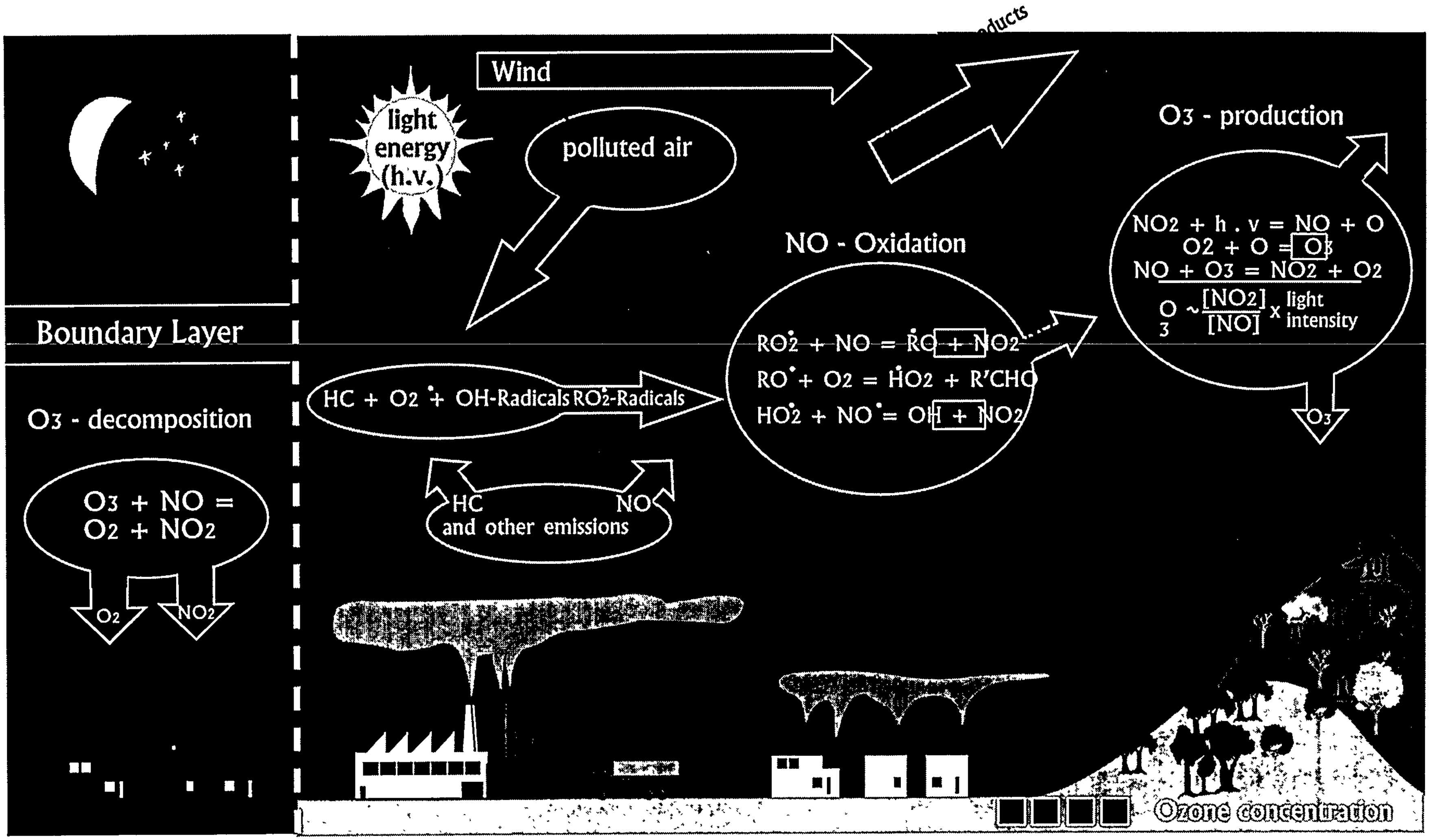
5 - Fuel tax

6a - Vehicle purchase tax
6b - Gas guzzler tax
6c - Emission vehicle tax

7 - Scrappage subsidy

8 - Freight subsidy

"SUMMER-SMOG" THROUGH OZONE ?



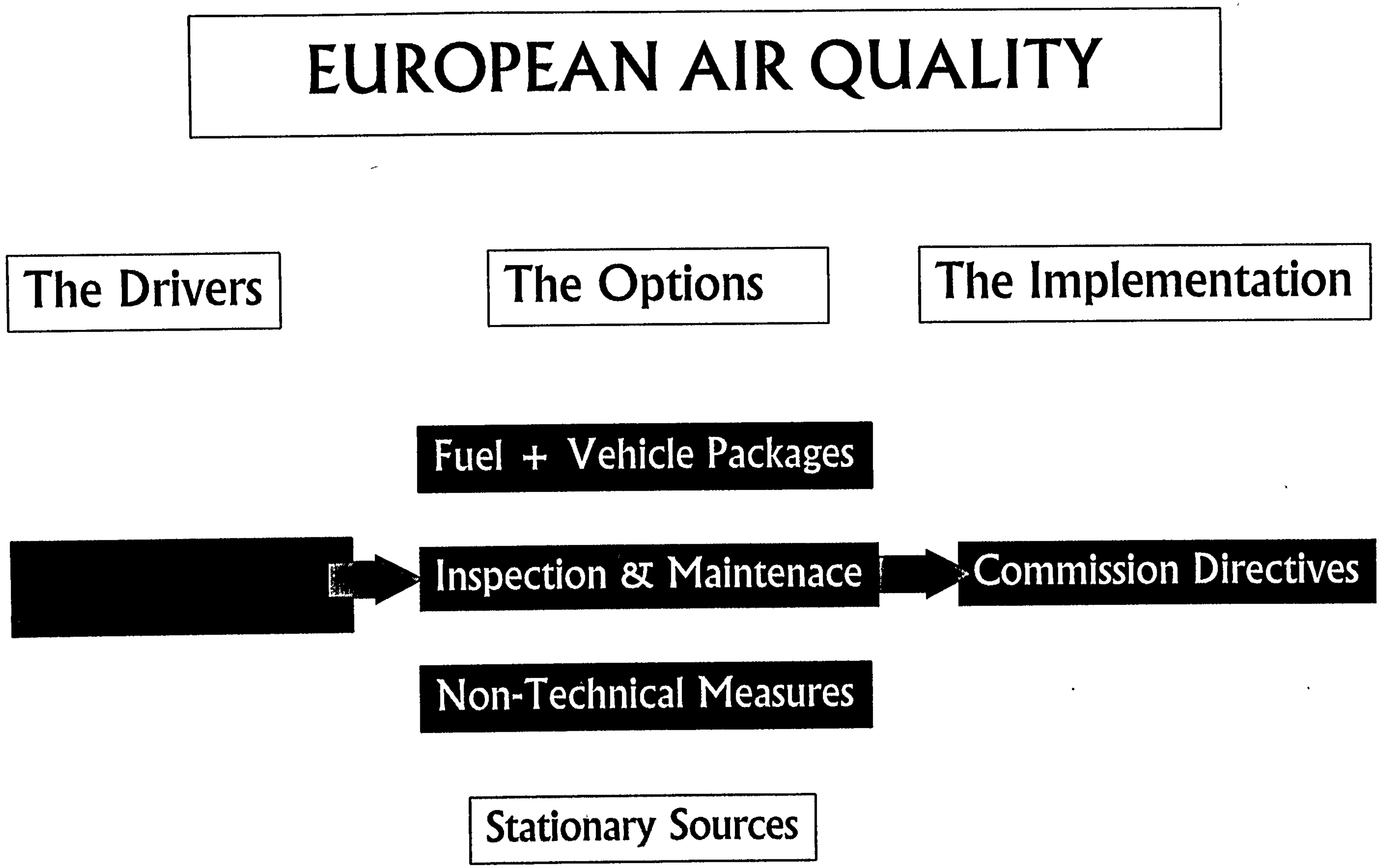
Adapted from Landesanstalt fur immissionsschutz

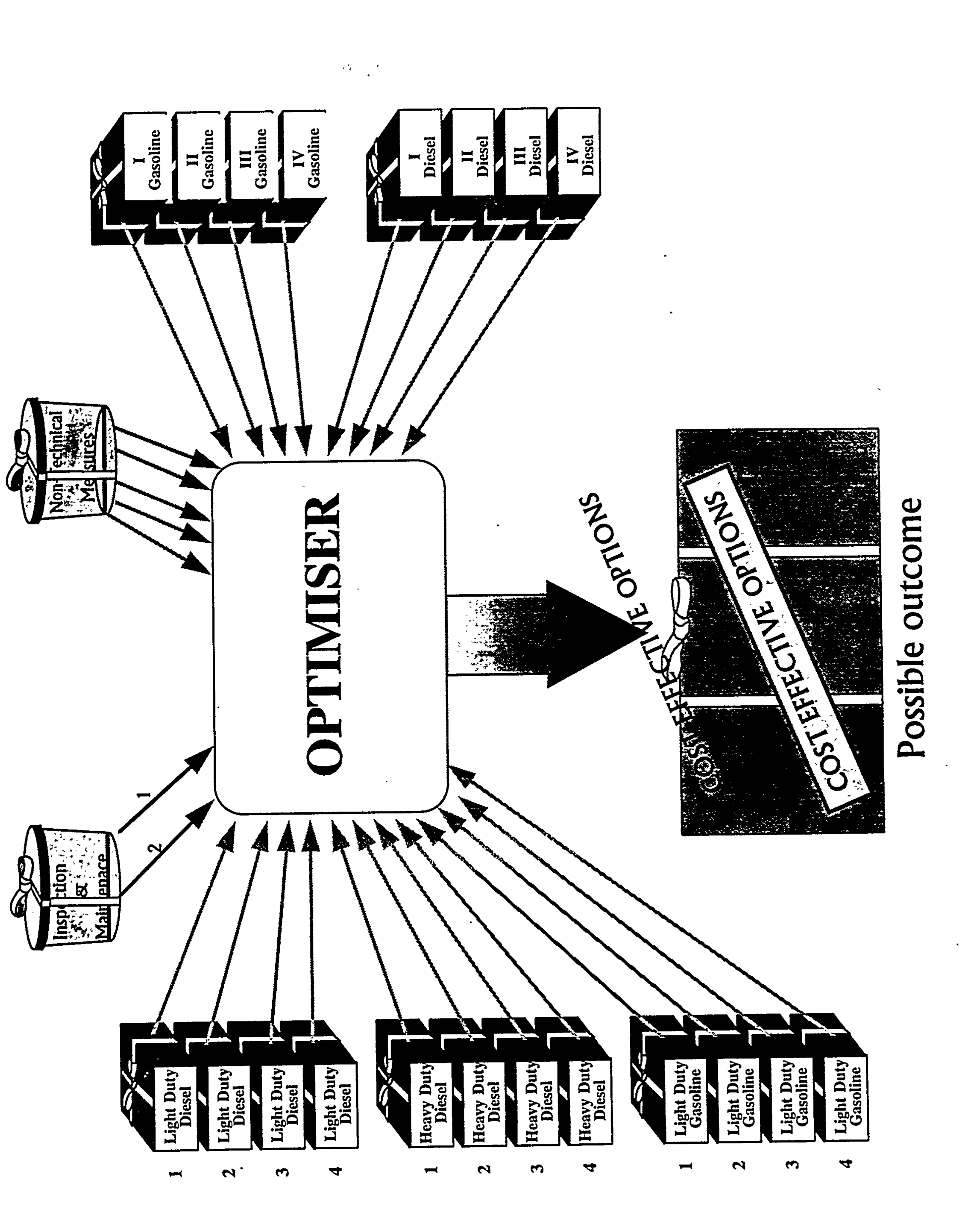
Non-reactive
pollutants:

- Nitrogen oxides (nitrogen dioxide)
- Carbon monoxide
- Benzene
- (Particulates)

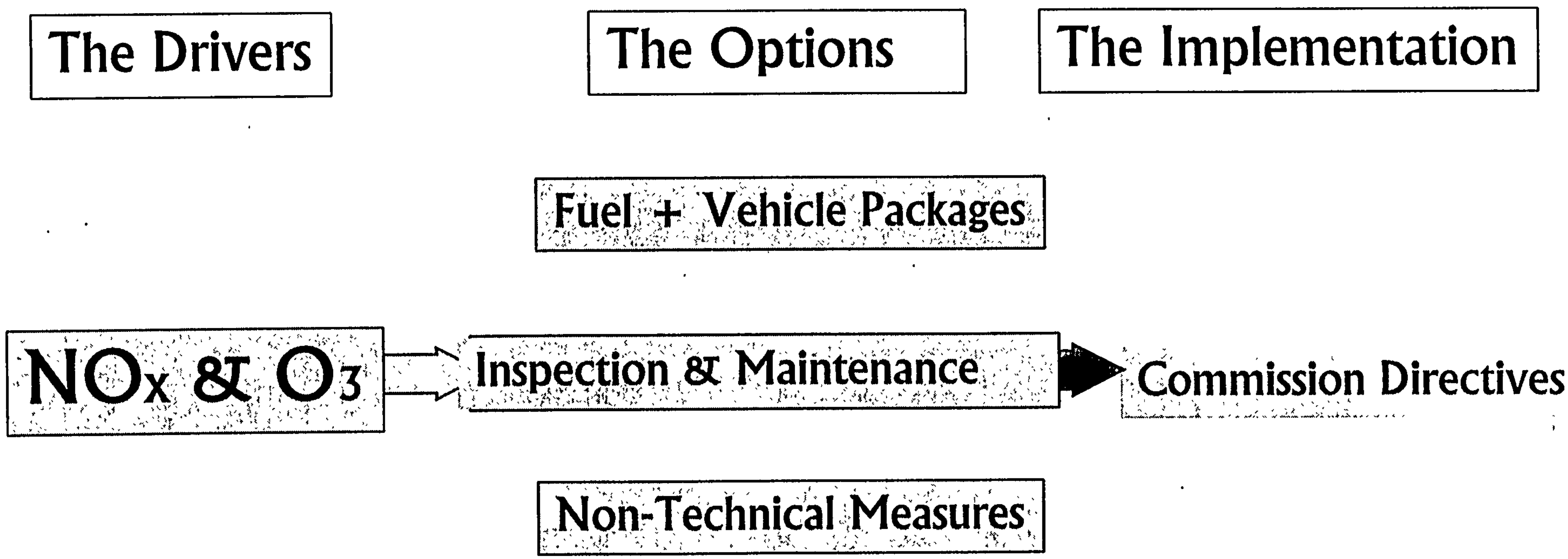
Reactive
pollutants:

- Ozone
- (precursors: nitrogen oxides, volatile, organic compounds, carbon monoxide)


EUROPEAN AIR QUALITY
The Drivers
The Options
The Implementation
Fuel + Vehicle Packages
[redacted]
Inspection & Maintenace
Commission Directives
Non-Technical Measures
Stationary Sources


I Gasoline
II Gasoline
III Gasoline
IV Gasoline
I Diesel
II Diesel
III Diesel
IV Diesel
Non-Technical Measures
Inspection & Maintenace
1
2
OPTIMISER
Light Duty Diesel
Heavy Duty Diesel
Light Duty Gasoline
1
2
3
4
COST EFFECTIVE OPTIONS
COST EFFECTIVE OPTIONS
Possible outcome

EUROPEAN AIR QUALITY



EPEFE AND THE EUROPEAN AUTO-OIL PROGRAMME

by
Francis H Palmer

Background

The European Union (EU) Auto-Oil Programme is a joint activity between the EU Commission, the European oil industry (Europia) and the European motor industry (ACEA) that was established in the wake of rising public concerns about motor vehicle exhaust emissions and their effects on health and air quality.

Since 1970, when the first exhaust emission legislation for motor vehicles emerged, progressively more severe legislation has been introduced (see Figure 1), culminating with legislation in 1996 that will make emission limits directionally more severe than many USA regulations that will be in force at the time. Further directives on emissions aimed at the year 2000 and beyond are likely to emerge from the European Union Commission Directorates later in 1995. Auto / Oil is designed to provide European legislators with a rational scientific basis for the setting of future European vehicle exhaust emission limits for road transport **on a cost effective basis, linked to air quality needs, taking into account motor technology and fuels, as well as other non-technical measures such as inspection and maintenance, and traffic management systems.**

Guidelines and principles to this unique approach to cost effectiveness measures were agreed by the European Parliament and Council as laid down in Article 4 of Directive 94/12/EC. Although this Directive applies to the emissions of light duty vehicles for 1996/7, guidelines were included for the construction of future legislation that would apply in the year 2000 and beyond. (Figures 2 & 3).

Auto / Oil is an extremely large undertaking, bringing together the Commission and the automobile and oil industries for the first time at a European level in a co-operative programme. The EPEFE Research Programme into the inter-industry relationships between vehicle and fuel technologies and their impact on exhaust emissions, and which is just one part of the Auto / Oil Process, has cost more than ten million ECU (US$ eleven million), not including the cost of developing prototype technology and advanced fuels. (More detailed information may be obtained from the ACEA and Europia Secretariats based in Brussels. A draft report was formally released on 17 July at a meeting organised by the Commission to brief Member States on the status of the Auto-Oil Programme. The EPEFE Programme was designed to enhance data already available within Europe and from the USA, where relevant, to help establish the relationships between fuel composition and vehicle technology and to identify and quantify what reductions in road traffic emissions could be achieved by combining advanced fuels with advanced vehicle / engine technologies under development for the year 2000. Results from the EPEFE Programme were embodied into Tables and used to quantify complex equations that were associated with fuels and vehicle / engine technologies for inclusion into the Commission's Air Quality Modelling studies. This process facilitated the search for the optimum combination of measures to achieve the European Union's Air Quality objectives. (Figures 4, 5 & 6). **Impact of already agreed Measures**

The mandatory use of catalytic converters from the beginning of 1993 and other agreed measures that have been or will be implemented in the near future, such as the introduction of a 0.05 %m sulphur in diesel fuel and the halving of exhaust emission limits in 1996, will have a profound effect in reducing road transport derived air pollution in the coming years despite the expected growth in road traffic. Figure 7 shows the expected change in the passenger car fleet whilst Figures 8, 9 & 10 show the influence on emissions with time. Figure 11 shows the time trend for all road transportation vehicles. The effect on such emissions as NOx, CO and HC shows a significant downward trend despite vehicle population growth but, the impact of the already agreed and existing measures vary from country to country depending upon existing vehicle population and consumer buying habits. A comparison of Greece and the UK illustrates the point in Figures 12, 13 & 14). A slow turn-over of purchasing new technology in the market place in some countries will delay the beneficial impact of the already agreed and existing measures. Even on an average European basis, the passenger car life span is around 10-15 years and for commercial vehicles, the life span is somewhat longer. (Figure 15). In addition, more recent Commission ozone results has shown that existing plus already agreed measures will result in a 20% to 30% reduction in ground ozone by the year 2010. What is more, even with a total ban on city traffic, ground ozone will only be reduced by a further 10%. One of the main conclusions from this outcome was that it is important to tackle stationary sources. A flow chart identifying the already agreed measure is outlined in Figure 16.

Air Quality Needs and Results

Urban air quality will improve significantly as a consequence of the already agreed measures indicated above. Even so, the Commission still has a mandate, from the EU Directive 94/12/EC, to establish compliance of reactive and non-reactive pollutants in the urban environment. The question of whether "Summer-Smog" was responsible for respiratory and other health related problems as a result of traffic pollution causing too high ozone levels needed to be addressed. Figure 17.

Air quality target bands were identified, based largely on the World Health Organisation (W.H.O) guidelines, with upper and lower (tighter) target bands (see Figure 18). A 7 city air quality study was undertaken to assess current and future air problems associated with reactive and non-reactive pollutants. (see Figure 19). These 7 cities namely, London, The Hague, Cologne, Lyon, Milan, Madrid and Athens, were chosen to be representative across urban Europe. (Figure 20).

The main conclusions from the emissions / air quality modelling studies confirms that:-

Urban air quality in all 7 cities:-

- Improves significantly as a consequence of already agreed measures
- CO and benzene meet the lower criteria by the year 2000 / 2005
- NO2 lower criteria band determines that further emission reduction measures are needed.

- Severe NOx emission reductions are required to achieve NO2 targets in almost all of the 7 representative cities

The outcome shows clearly that NOx is the real problem for 100% compliance with the lower air quality band. Figure 21 shows an example for London for 1990-2010). As an example, NOx reductions for the year 2010 are:-

55% for Athens
40% for London

However, CO and benzene were not found to be a problem after the year 2000 / 2005 because of the benefits of the existing and agreed measures.

A full list of the required reductions for each pollutant and each of the 7 cities, for the years 2005 and 2010, is shown in Figures 22 and 23. The Commission recognises that reductions in NOx brings other benefits. For example, every 10% reduction in NOx would generate reductions of:-

-12 to 15% in CO
-9 to 13% in HC
-12 to 15% in Benzene
-10 to 11% in PM

While the existing and agreed measures, together with those measures required to meet the NOx air quality targets will significantly reduce ozone episodes, they will still not be sufficient to meet the ozone air quality target. Even the extreme measures directed at traffic will have limited effect. This clearly demonstrates that a total integrated approach aimed at reducing emissions from all sources, including those from stationary sources, is required.

Cost Effectiveness

Fuel parameter ranges studied are given in Figure 24, whilst the vehicle / engine technology assessed is shown in Figures 25 and 26.

The base average fuel qualities for gasoline and diesel fuel, used in the cost effective study are shown in Figures 27 and 28, together with increasingly severe compositional changes and the estimated potential reductions in emissions such changes bring. Also included in Figure 29, are the emission reduction targets for different levels of severity of diesel and gasoline technology changes.

Preliminary results recently released indicate that about 90% of European cities can meet the NOx targets with a set of non-extreme measures. The remaining 10% of European cities, which generally lie in southern Europe, can not meet the NOx targets even with a much more severe set of measures. Only the use of local, non-technical measures such as fleet replacement, traffic management, enhanced public transport and better vehicle maintenance, offers any hope of attaining the NOx emission reduction targets in these cities.

City diesel, once postulated as a possible solution, is not considered cost effective, although it is recognised that there may be scope for urban buses, municipal trucks and taxi fleets using CNG or LPG as a dedicated fuel.

Non-technical measures are also to be included in the analysis as indicated in Figure 30 , as are inspection and maintenance programmes, including on-board diagnostics and remote emission detection. Figure 31. However, non-technical measures do not affect emission levels directly but rather indirectly through changing driver / vehicle owner behaviour via economic instruments.(Figure 32).

A full set of the cost effectiveness results, including the contribution from non-technical and inspection and maintenance measures, should be available by the end of October.

Perhaps an easy way to explain the European Air Quality objectives and their relationships with cost effectiveness, is shown in Figures 33 & 34.

Conclusion

In summary, the EU Auto-Oil Process can be considered as a 5 step Process. This is described graphically in Figure 35. As this process approaches its "final" stages, and having identified urban NOx is a key driver, additional steps are now being considered which include the particulate mass and ozone precursors (VOC's and total NOx), in addition addition to urban NOx. Whilst the inclusion of these will increase the emission reduction severity, they will also increase the costs of the severity of the cost effective measures.

The ultimate aim is to produce cost effective options after considering all possible packages, both technical and non-technical. With most of the practical studies having been completed or very nearly completed, in line with a sound scientific rational approach, Europe stands at a cross road, with the political debate just starting.

As particulates (PM) remain the big unknown in terms of their derivation, size, life span and their impact on air quality and health, and in terms of their contribution to air pollution, (there are currently no W.H.O. standards), debates and studies on this topic will grow concomitant with the growing interest in using gaseous fuels, with potentially very low particulates, to replace the use of diesel in dedicated buses, trucks and taxis.

A draft directive is expected to emerge from the Commission soon for consideration by the EU member states and ultimately the European Parliament. Whilst politics are inevitable in legislation and law making, it is comforting to know that one of the basis on which future European legislation will be made with respect to air quality improvement, has itself been based on a unique rational scientific approach of which Europe can be justly proud.

Frank Palmer
26th February 1996

PS:- Additional slides used in the presentation are attached.
Please note that the EPEFE Report is now available and can be obtained for the ACEA and Europia Secretariats. Purchase price is 500 ECU +P & P & bank charges, etc.
ACEA:-Ph:32 2 732 5550. fax:32 2 732 6001/4267, Europia:Ph:32 2226 1911. fax:322219 9551

EVOLUTION OF THE REGULATORY EXHAUST EMISSION STANDARDS FOR PASSENGER CARS IN THE EU

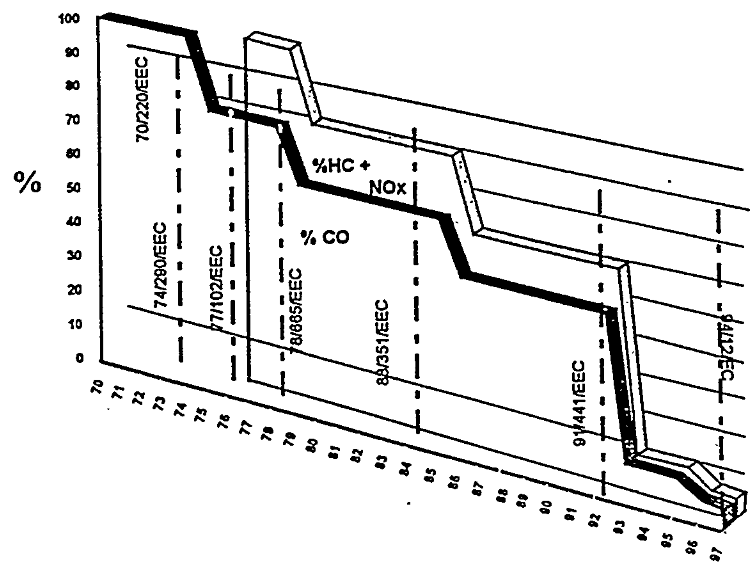


Figure 1

ARTICLE 4 OF DIRECTIVE 94/12/EC OF EUROPEAN PARLIAMENT AND THE COUNCIL

In these stage 2000 proposals the Commission shall take the following approach:

- the measures will produce effects to meet the requirements of the Community's air quality criteria
- a cost effectiveness assessment shall be taken of the potential contributions from:
  - traffic management, for example by spreading the environmental costs appropriately,
  - enhanced urban public transport,
  - new propulsion technologies (e.g. electric transmission)
  - the use of alternative fuels (e.g. biofuels)

  towards improving air quality,
- the measures shall be proportional and reasonable in the light of the intended objectives.

Figure 2

REQUIREMENTS OF DIRECTIVE 94/12

The proposals, aimed at a substantial reduction of pollutant emissions, shall comprise in particular the following elements : -

1. Further improvements in the requirements of 94/12 based on the assessment of :

- the potential of the traditional engine and post combustion technology
- possible improvements in the test procedures e.g.
  - cold start, starting in low or wintry temperatures
  - durability (e.g. in the conformity tests)
  - evaporative emissions.
- measures at the level of type-approval supporting strengthened inspection and maintenance requirements, including for example, on-board diagnostic systems
- the possibility of checking the conformity of vehicles in circulation
- the proportional need for : -
  - specific limits for HC and NOx in addition to a cumulative limit value, and
  - measures to cover pollutants not yet regulated

2. Complementary technical measures in the framework of specific Directives, including :

- improvements in fuel quality as far as vehicle emissions of dangerous substances (in particular benzene) are concerned,
- strengthening of the requirements of the inspection and maintenance programme.

Figure 3

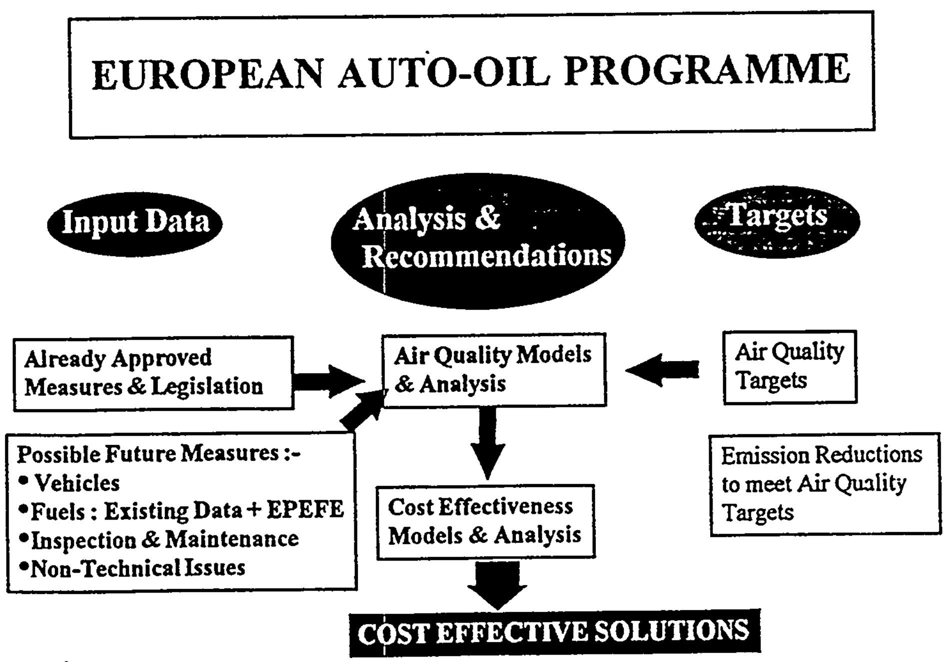


Figure 4

PERSPECTIVE ON THE EU AUTO-OIL PROGRAMME

Easy Technology Solutions already implemented

➡ New Approach needed

AUTO-OIL PROGRAMME

- **Pioneering**
- **Complex-Not perfect, designed for Today's Needs**
- **Despite Auto-Oil complexity, commitment to help find solutions for year 2000 plus**
- **Proposals for year 2000 to European Parliament & Council late 1995**

Figure 5

EVOLUTION OF ROAD TRANSPORT EMISSIONS ASSESSMENT

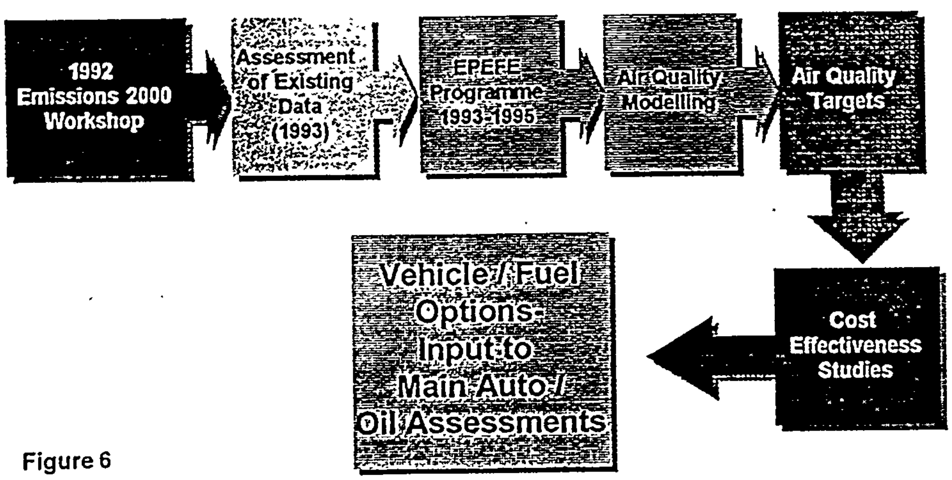


Figure 6

EU 12 PASSENGER CARS

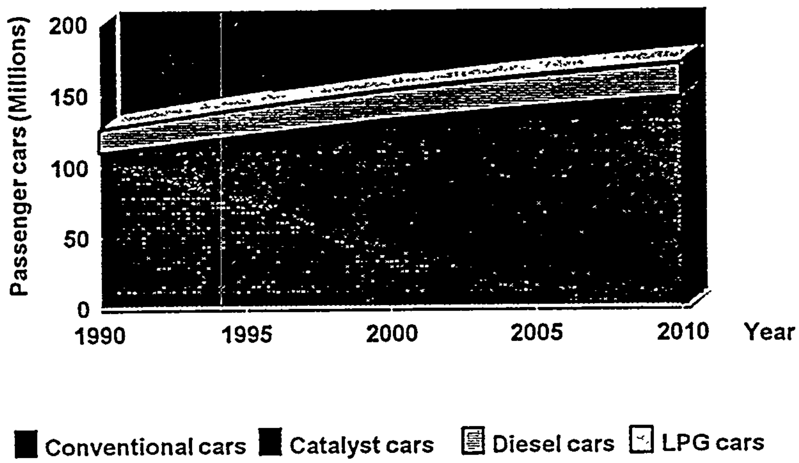


Figure 7

PREDICTED TREND IN NOx EMISSIONS FROM PASSENGER CARS AS A CONSEQUENCE OF ALREADY AGREED MEASURES (FOREMOVE)

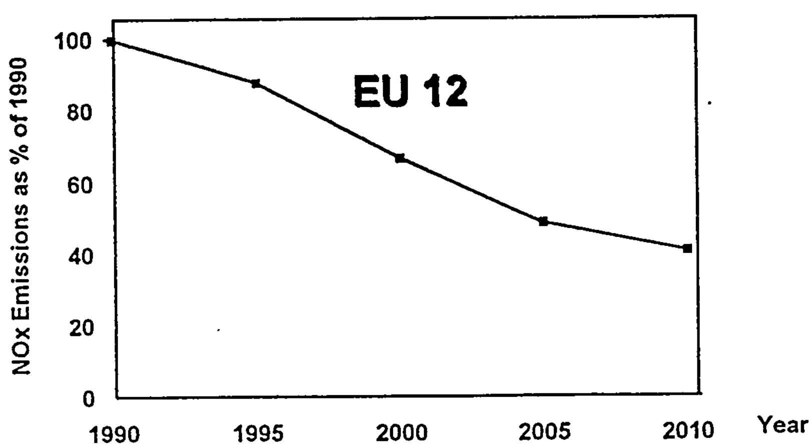


Figure 8

PREDICTED TREND IN HC EMISSIONS FROM PASSENGER CARS AS A CONSEQUENCE OF ALREADY AGREED MEASURES (FOREMOVE)

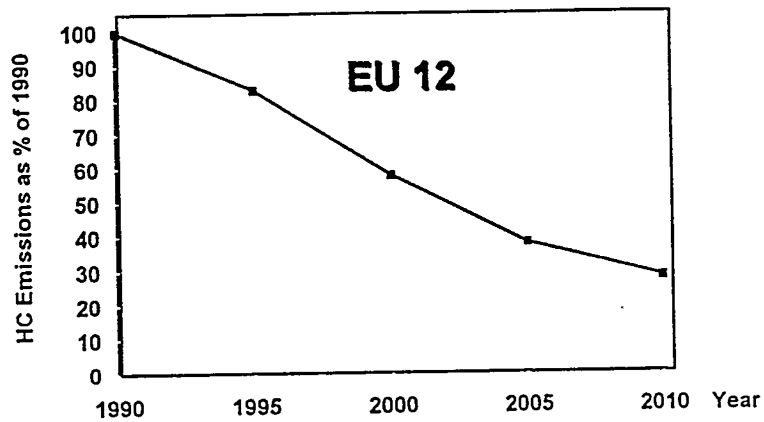


Figure 9

PREDICTED TREND IN CO EMISSIONS FROM PASSENGER CARS AS A CONSEQUENCE OF ALREADY AGREED MEASURES (FOREMOVE)

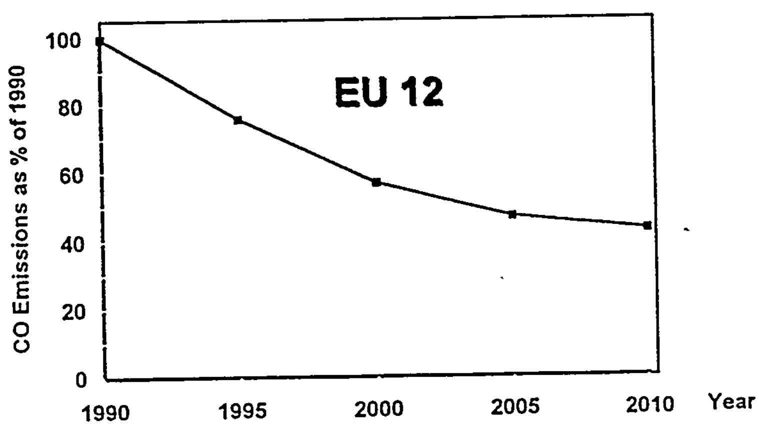


Figure 10

VEHICLE FLEET EU-12

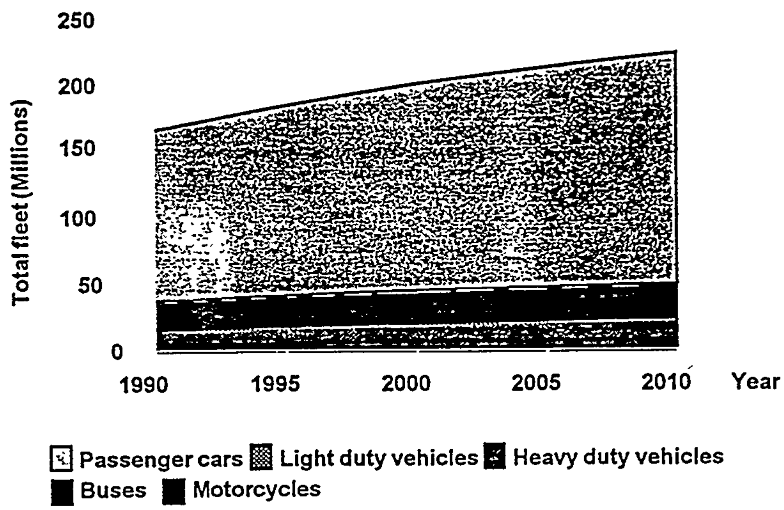


Figure 11

PREDICTED TREND IN NOx EMISSIONS FROM PASSENGER CARS AS A CONSEQUENCE OF ALREADY AGREED MEASURES (FOREMOVE)

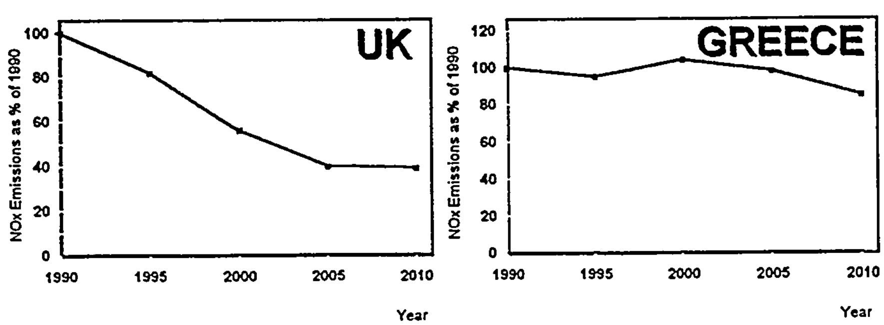


Figure 12

PREDICTED TREND IN HC EMISSIONS FROM PASSENGER CARS AS A CONSEQUENCE OF ALREADY AGREED MEASURES (FOREMOVE)

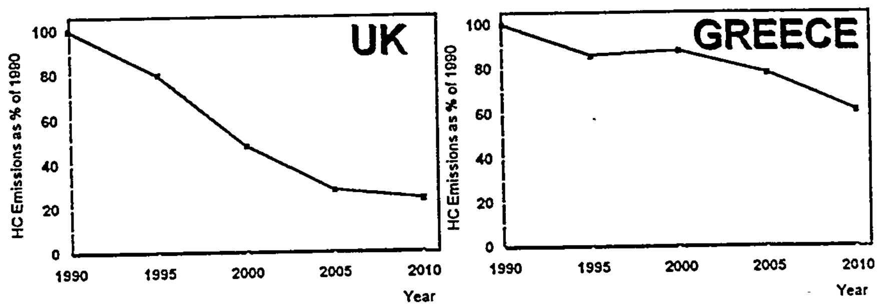


Figure 13

PREDICTED TREND IN CO EMISSIONS FROM PASSENGER CARS AS A CONSEQUENCE OF ALREADY AGREED MEASURES (FOREMOVE)

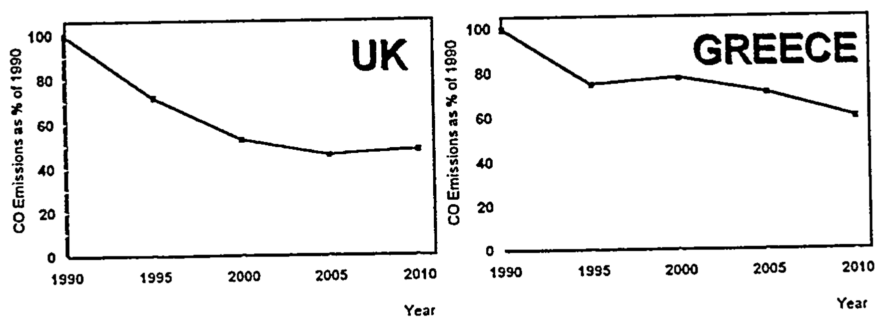


Figure 14

LIFETIME FUNCTION OF PASSENGER CARS IN THE EUROPEAN UNION

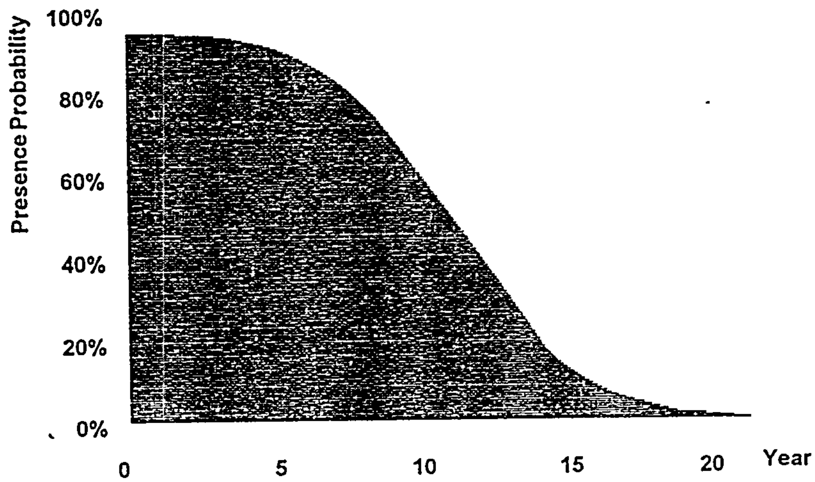


Figure 15

EVOLUTION OF AGREED TECHNICAL MEASURES

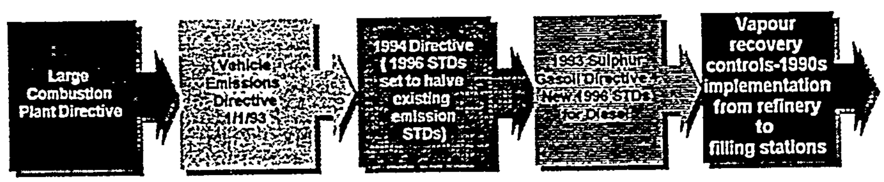


Figure 16

"SUMMER-SMOG" THROUGH OZONE ?

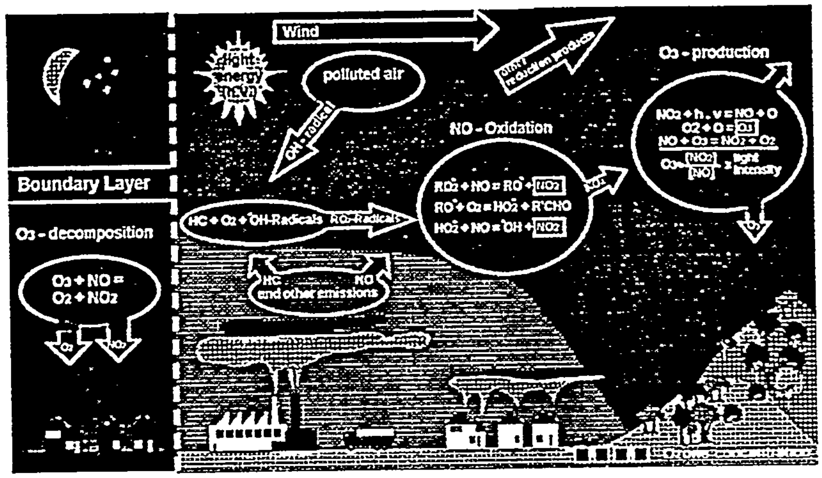


Figure 17

Adapted from Landesanstalt fur immissionsschutz

AIR QUALITY TARGET BANDS (µg/m3)

POLLUTANT	TARGET BAND VALUES UPPER	LOWER	RATIONALE	CORRESPONDING US STANDARD
NO2 (1 HOUR AVG)	200	93	EC NO2 DIRECTIVE	100 (1) (ANNUAL MEAN)
CO (8 HOUR AVG)	10	5	W.H.O	10
BENZENE (ANNUAL MEAN)	16	10 (2.5) (2)	COMPROMISE BASED ON M.S. ACTIONS	NO STANDARD
OZONE (8 HOUR AVG)	120	120	W.H.O	156
(1 HOUR AVG)	180	180	E.C. OZONE DIRECTIVE	235

(1) E.C. ANNUAL MEAN 50 µg/m3
(2) LONGER TERM TARGET VALUE

Figure 18

Non-reactive pollutants:

- Nitrogen oxides (nitrogen dioxide)
- Carbon monoxide
- Benzene
- (Particulates)

Reactive pollutants:

- Ozone
- (precursors: nitrogen oxides, volatile, organic compounds, carbon monoxide)

Figure 19

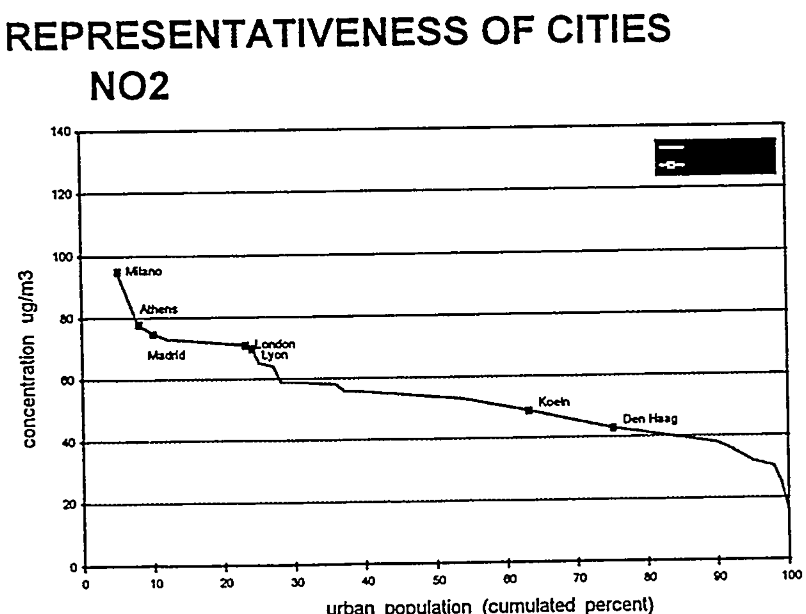


Figure 20

LONDON AQ MODEL RESULTS 1990 - 2010

NOx

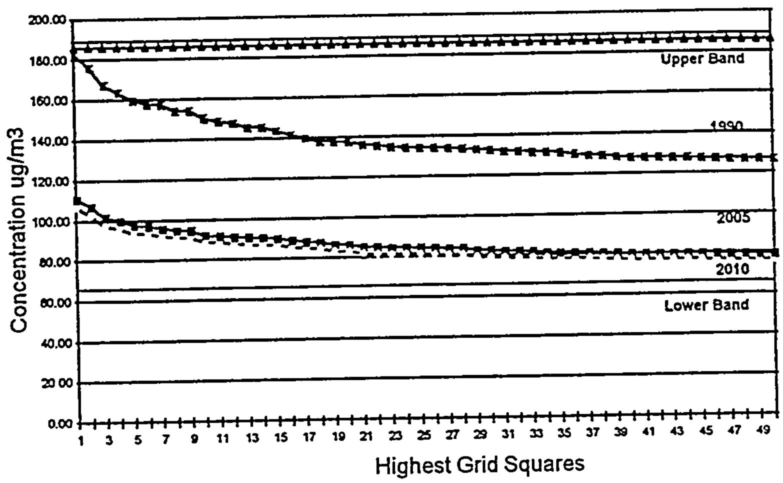


Figure 21

URBAN AIR QUALITY MODELLING - SUMMARY OF THE REQUIRED EMISSION REDUCTIONS 2005

CITY	2005								
	NOX			CO			benzene		
	conc µg/m3	emission reduction % upper 186 µg/m3	emission reduction % lower 66 µg/m3	conc µg/m3	emission reduction % upper 3000 µg/m3	emission reduction % lower 1500 µg/m3	conc µg/m3	emission reduction % upper 16 µg/m3	emission reduction % lower 10 µg/m3
ATHENS	147	0	55	992	0	0	7.0	0	0
COLOGNE	103	0	35	454	0	0	3.0	0	0
DEN HAAG	69	0	5	361	0	0	2.0	0	0
LONDON	111	0	40	589	0	0	2.7	0	0
LYON	115	0	45	653	0	0	4.6	0	0
MADRID	147	0	55	0	0	0	5.6	0	0
MILAN	152	0	55	0	0	0	5.2	0	0

Figure 22

URBAN AIR QUALITY MODELLING - SUMMARY OF THE REQUIRED EMISSION REDUCTIONS 2010

CITY	2010									
	NOX			CO			benzene			
		emission reduction %			emission reduction %			emission reduction %		
	conc µg/m3	upper 186 µg/m3	lower 66 µg/m3	conc µg/m3	upper 3000 µg/m3	lower 1500 µg/m3	conc µg/m3	upper 16 µg/m3	lower 10 µg/m3	2.5 µg/m3
ATHENS	140	0	55	762	0	0	5.2	0	0	50
COLOGNE	89	0	25	386	0	0	2.1	0	0	0
DEN HAAG	68	0	5	328	0	0	1.6	0	0	0
LONDON	107	0	40	575	0	0	2.1	0	0	0
LYON	107	0	40	533	0	0	3.1	0	0	20
MADRID	135	0	50	N/A	0	0	3.9	0	0	35
MILAN	131	0	50	N/A	0	0	3.0	0	0	15

Figure 23

PARAMETER RANGES

Fuel / Parameter	Study Range
Gasoline	
Lead	0.013 - 0.005 g/l
Oxygenates	0 - 2.7% O_2
Aromatics	50 - 20%
Benzene	3 - 0.7%
Olefins	15 - 5%
Sulphur	500 - 30 ppm
RVP	80 - 60 kpa
E 100	35 - 65%
E 150	85 - 90%
Diesel	
Sulphur	500 - 50 ppm
Density	820 - 855 kg/m^3
Poly Aromatics	8 - 1%
Cetane No	50 -58
T95	370 - 330 °C

Figure 24

VEHICLE TECHNOLOGIES FOR HEAVY DUTY VEHICLE ENGINES

1. Very high pressure fuel injection
2. Electronic unit injectors
3. Electronic engine control
4. Variable pressure turbocharging
5. Controlled intercooling
6. Multi valve engines
7. Improved engine clearance volumes *
8. Exhaust gas recirculation (EGR)
9. Particulate traps
10. De-NOx catalysts
11. Alternative fuel technology **
12. *** Manufacturer other
13. *** Manufacturer other

Figure 25

VEHICLE TECHNOLOGIES BEING ASSESSED

	GASOLINE		DIESEL
1	Improved electronic engine control	1	Very high pressure injection
2	Exhaust gas recirculation (EGR)	2	Increased cylinder pressure
3	Improved & low "light off" washcoats	3	Improved clearance volumes
4	Greater catalyst loading	4	Multi valve engines
5	Dual oxygen sensors	5	Exhaust gas recirculation
6	Sequential fuel injection	6	Controlled intercooling
7	Reduced engine clearance volumes	7	Variable pressure turbo
8	Leak free exhausts	8	Electronic unit injectors
9	Cylinder disablement	9	Particulate traps
10	Electrically heated catalysts	10	De - NOx catalysts
11	Low temp stable lambda sensors	11	Manufacturer other
12	Auxiliary air injection		
13	Air assisted injectors		
14	Double wall exhaust pipes		
15	Close coupled & Under body Cats		
16	Carbon canisters - Improved charcoal		
17	Low loss systems / minimum joints		
18	Manufacturer other		

Figure 26

European Auto-Oil Programme

Average Fuel Parameter Levels for Costing

Gasoline Fuel	Base Average	I	II	III	IV
Sulphur.	300	30	30	100	100
RVP (Summer)	68	58	58	58	58
Aromatics	40	37	36	30	25
Benzene	2.3	2.1	1.8	1.0	0.7
Oxygen	0.6	≥ 1.0	≥ 1.7	~ 1.6*	~ 2.0*
Olefins	11	9	10	9	8
E100	53	55	56	62	65
E150	84	85	88	89	92
Emission Changes	HC	-5%	-8%	-8%	-12%
	NOx	-3%	-1%	+1%	+2%
	Benzene	-17%	-27%	-34%	-45%

Figure 27 * Denotes maximum of 2.7

European Auto-Oil Programme

Average Fuel Parameter Levels for Costing

Diesel Fuel	Base Average	I	II	III	IV
Cetane No.	51	53	54	55	58
Density	843	835	831	828	825
Poly-Aromatics	9	6	4.5	2.2	1
T95	355	~348	~345	~340	~340
Sulphur	450	300	200	50	30
Emission Changes	NOx	-2%	-2%	-3%	-3%
	PM	-6%	-10%	-14%	-15%

Figure 28

AVERAGE FUEL QUALITIES FOR COSTING

Mogas	Base Average	I	II	III	IV
Sulphur	300	30	30	100	100
RVP (Summer)	68	58	58	58	58
Aromatics	40	37	36	30	25
Benzene	2.3	2.1	1.8	1	0.7
O2	0.6	Š1.0	Š1.7	~1.6 *	~2 *
Olefins	11	9	10	9	8
Evaporated 100°C	53	55	56	62	65
Evaporated 150°C	84	85	88	89	92
Emission Changes	HC	-5%	-8%	-8%	-12%
	NOx	-3%	-1%	+1%	+2%

* = (Max 2.7)

Diesel Fuel	Base Average	I	II	III	IV
Cetane Numbers	51	53	54	55	58
Density	843	835	831	828	825
Poly Aromatics	9	6	4.5	2.2	1
95% Dist. Temp.	355	~348	~345	~340	~340
Sulphur	450	300	200	50	30
Emission Changes	NOx	-2%	-2%	-3%	-3%
	PM	-6%	-10%	-14%	-15%

Figure 29

NON-TECHNICAL MEASURES

Instruments Evaluated

MECHANISM	INSTRUMENT	INCLUDED IN EVALUATION Passenger cars	HGVs
Vehicle ownership	- Taxes - Scrappage subsidy	✓✓	
Vehicle use	- Fuel tax - Road pricing	✓✓	✓✓
Improved traffic management	- Traffic bans - Parking fees	✓✓	✓✓
Enhanced public/ freight transport	- Cheaper prices - Improved accessibility - Advanced telematics	✓✓✓	✓✓✓

Figure 30

INSPECTION & MAINTENANCE

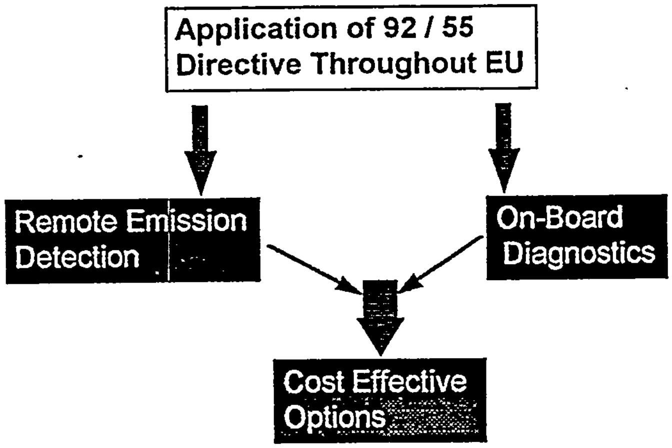


Figure 31

NON - TECHNICAL MECHANISMS CANNOT BE CHANGED DIRECTLY BUT ONLY VIA ECONOMIC INSTRUMENTS

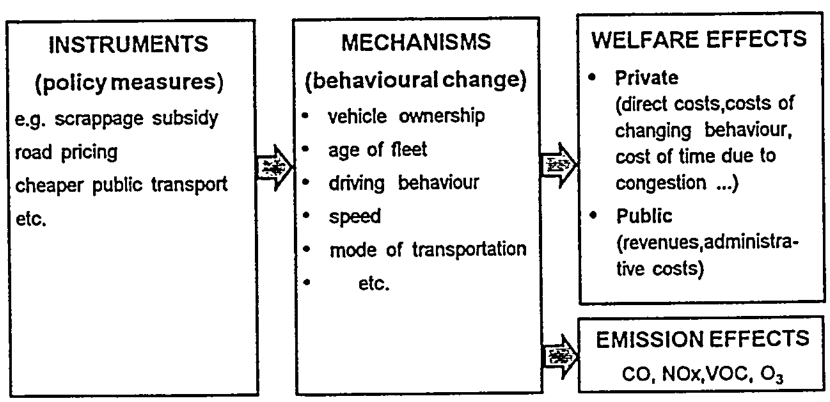


Figure 32

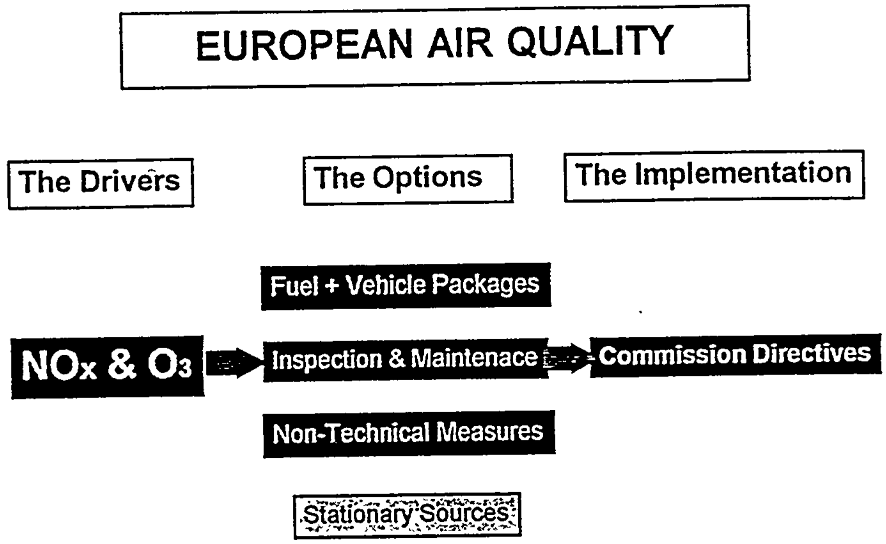
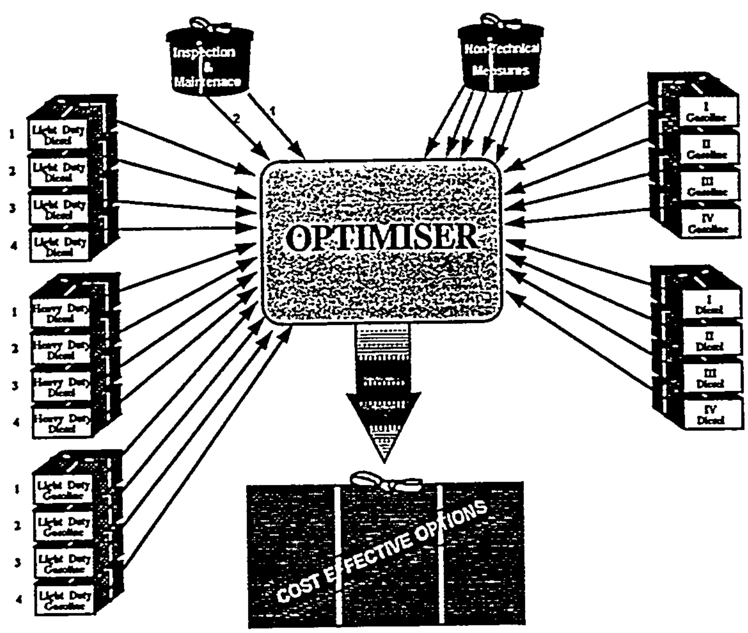


Figure 33



Possible outcome

Figure 34

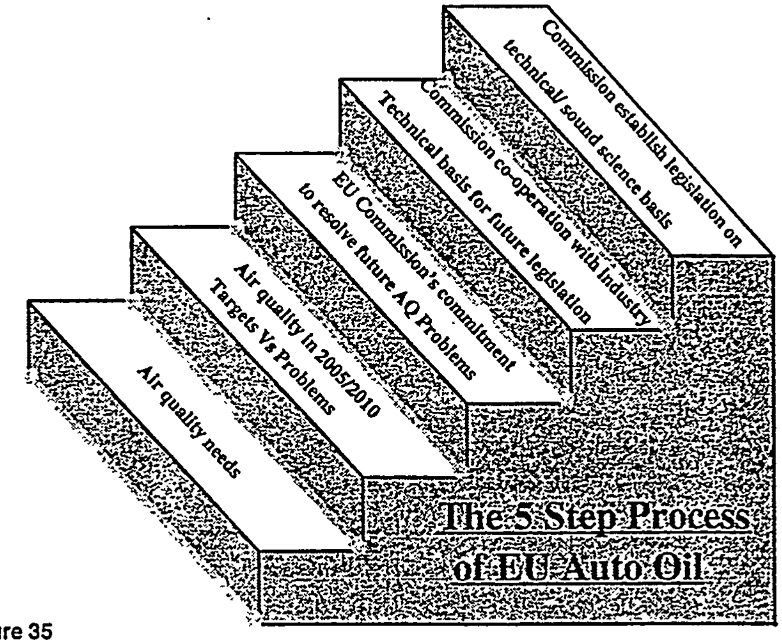
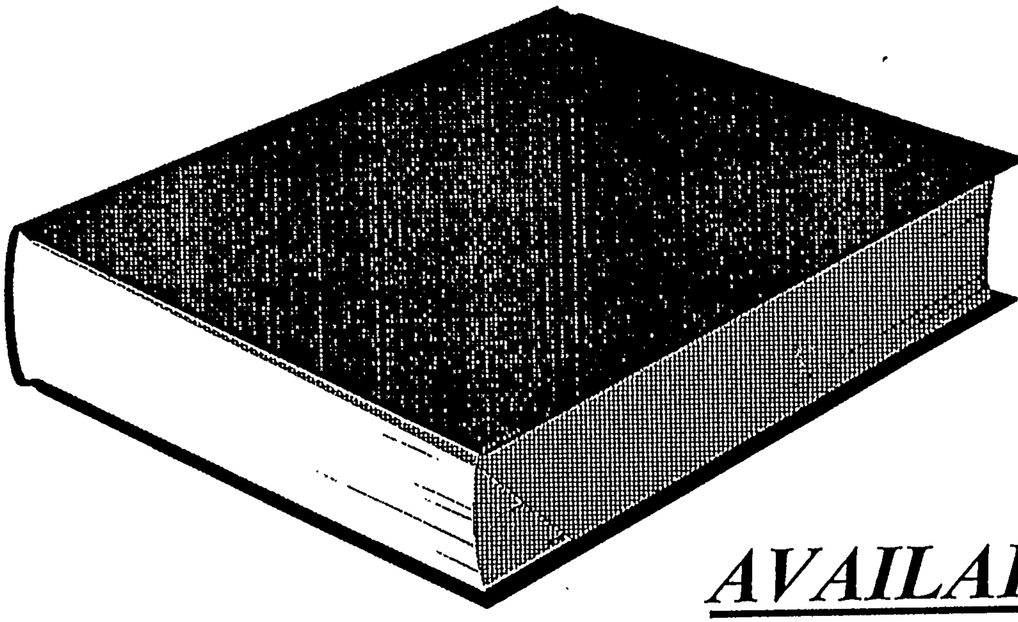
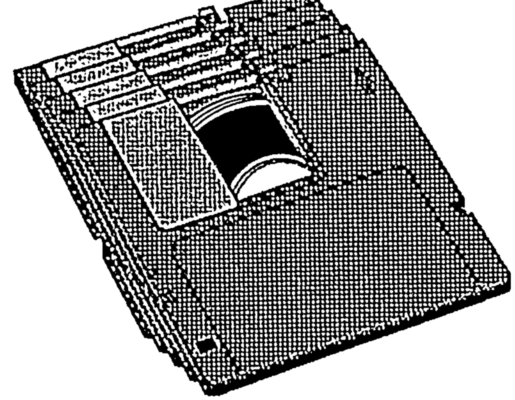

Air quality needs
Air quality in 2005/2010
Targets Vs Problems
EU Commission's commitment
to resolve future AQ Problems
Commission co-operation with industry
Technical basis for future legislation
Commission establish legislation on
technical/ sound science basis
The 5 Step Process
of EU Auto Oil

Figure 35

EPEFE REPORT





RAW DATA

AVAILABLE NOW

(via ACEA & Europia secretariats)

EPEFE EFFORT & SCOPE (filling the knowledge gaps)

Companies
- 14 motor (ACEA)
- 32 oil (Europia)

vehicles
LD:- 16 gasoline
19 diesel
HD:- 5 engines
(all 1996+ spec)

EPEFE
11mECU ha! ha!

Fuels
- 12 gasolines (arom/E100/S)
- 11 diesel (density/T95/arom/CN)

- 500,000+ data points
- 2000+ emission tests
- 17 vehicle / engine labs
- 4 fuel blending labs
- 16000 mhs

Companies Directly Involved in EPEFE

OIL	MOTOR
SHELL	BMW
ESSO	FORD
BP	RENAULT
TOTAL	VW
STATOIL	GM / OPEL
ELF	ROVER
OeMV	PSA
MOBIL	IVECO
EURON	VOLVO
FINA	MAN
REPSOL	MB
CEPSA	FIAT
	RVI
	DAF

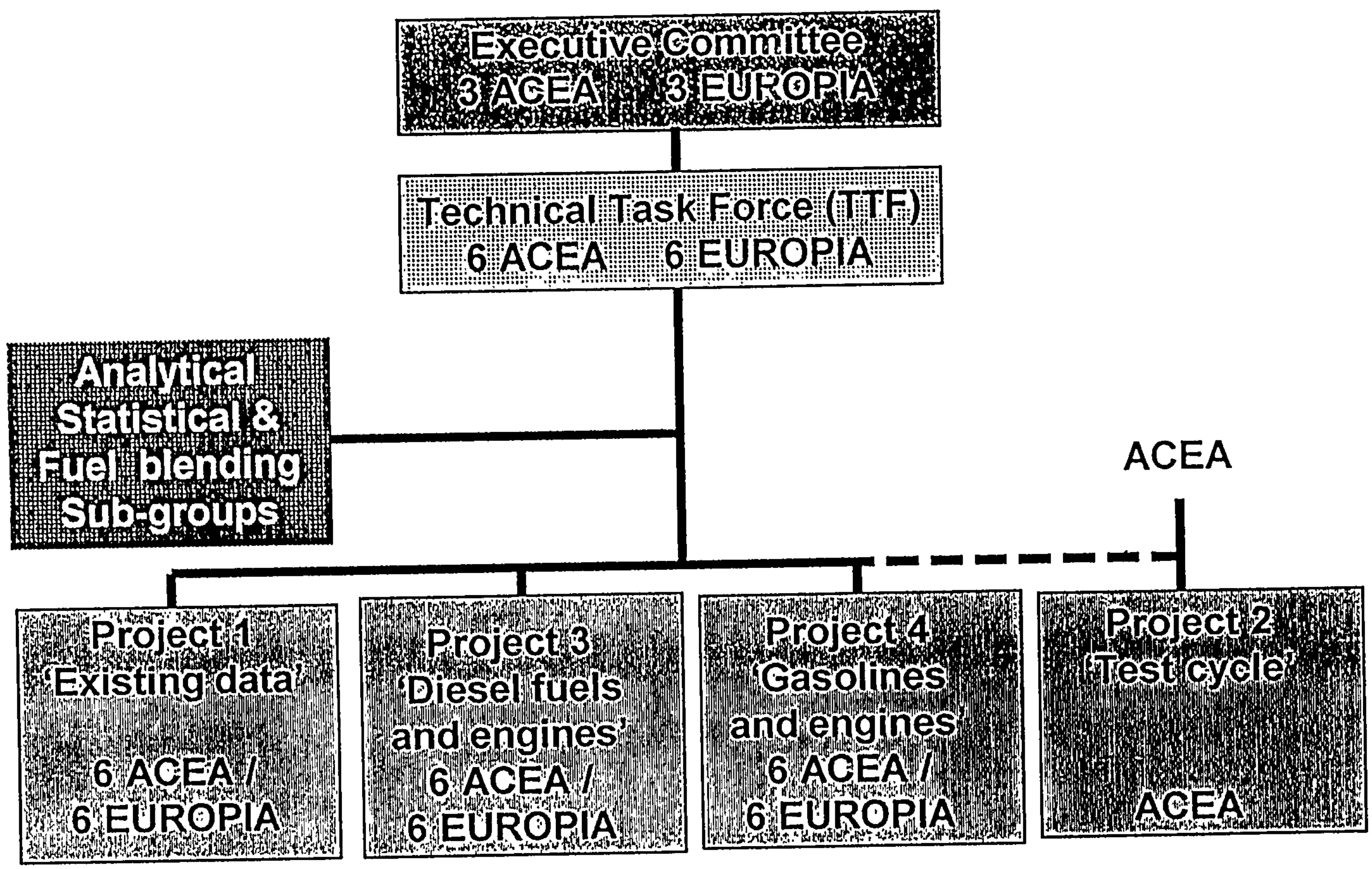
NB:- INDICATIVE LISTINGS ONLY-ALL MEMBERS OF ACEA & EUROPIA CONTRIBUTED TO THE COSTS

EPEFE HISTORY / TIMING

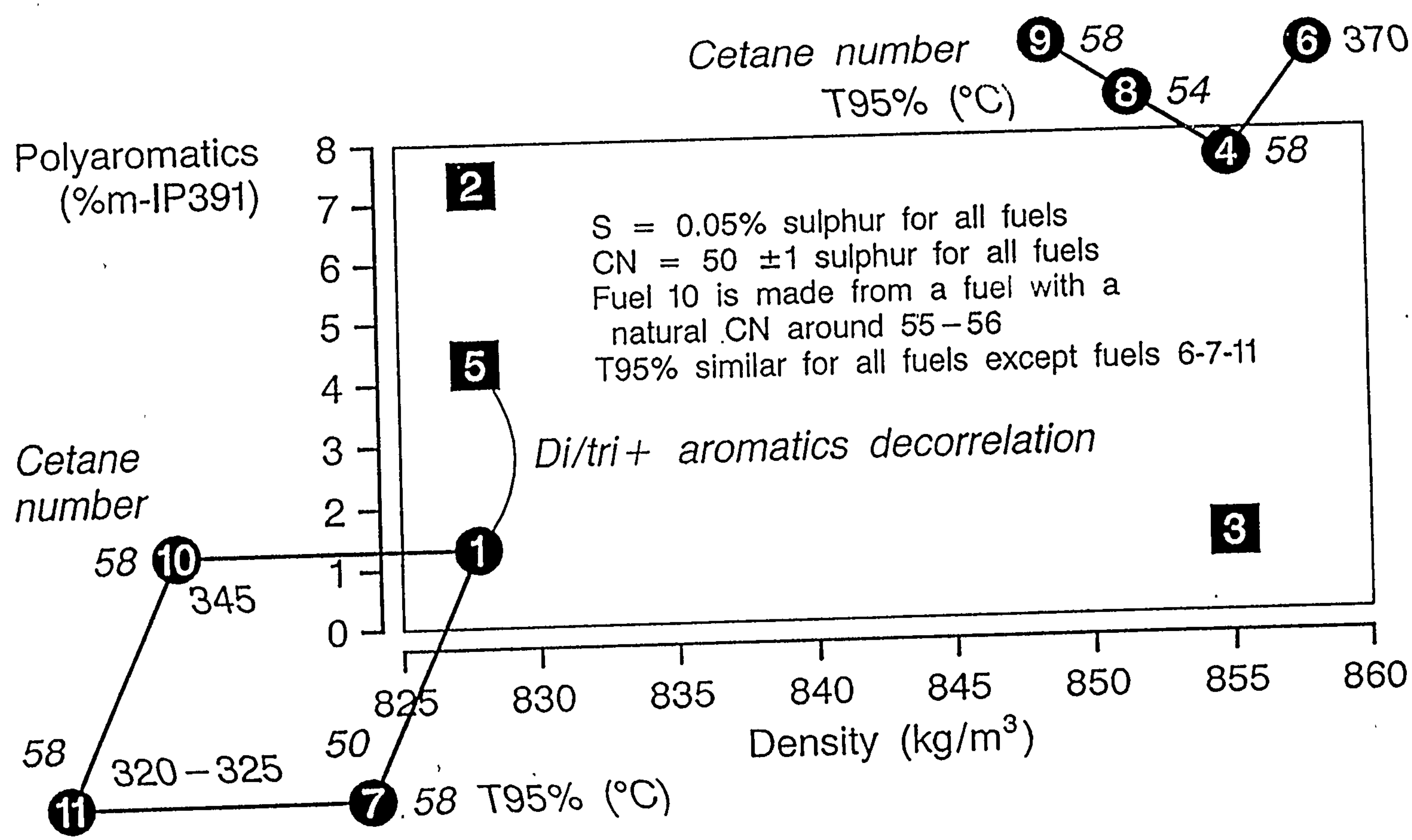
LATE '92	FRENCH/ITALIAN OIL COMPANIES INITIATIVE
Q1 '93	MAJOR OIL COMPANIES INVOLVEMENT
MID '93	ORGANISATION ESTABLISHED
LATE '93	FUELS / CARS/ ENGINE BASIS AGREED
Q2 '94	TEST PROTOCOLS/FUEL BLENDING
Q3 '94	TESTING STARTS
END Q4 '94	TESTING COMPLETE
FEB '95	AQ MODELLING INPUT
END OF 95	EPEFE REPORT

LOBBYING

The EPEFE Team Structure



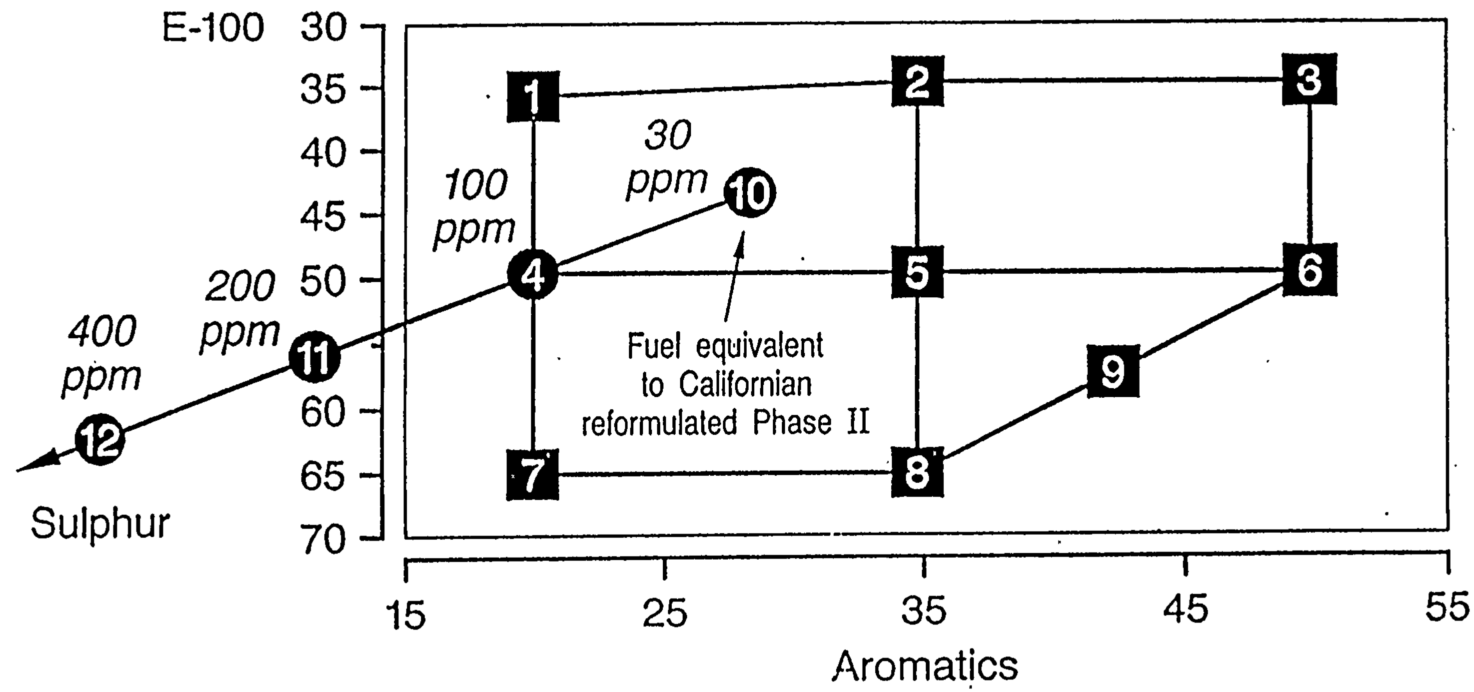
EPEFE diesel matrix



CG 39489

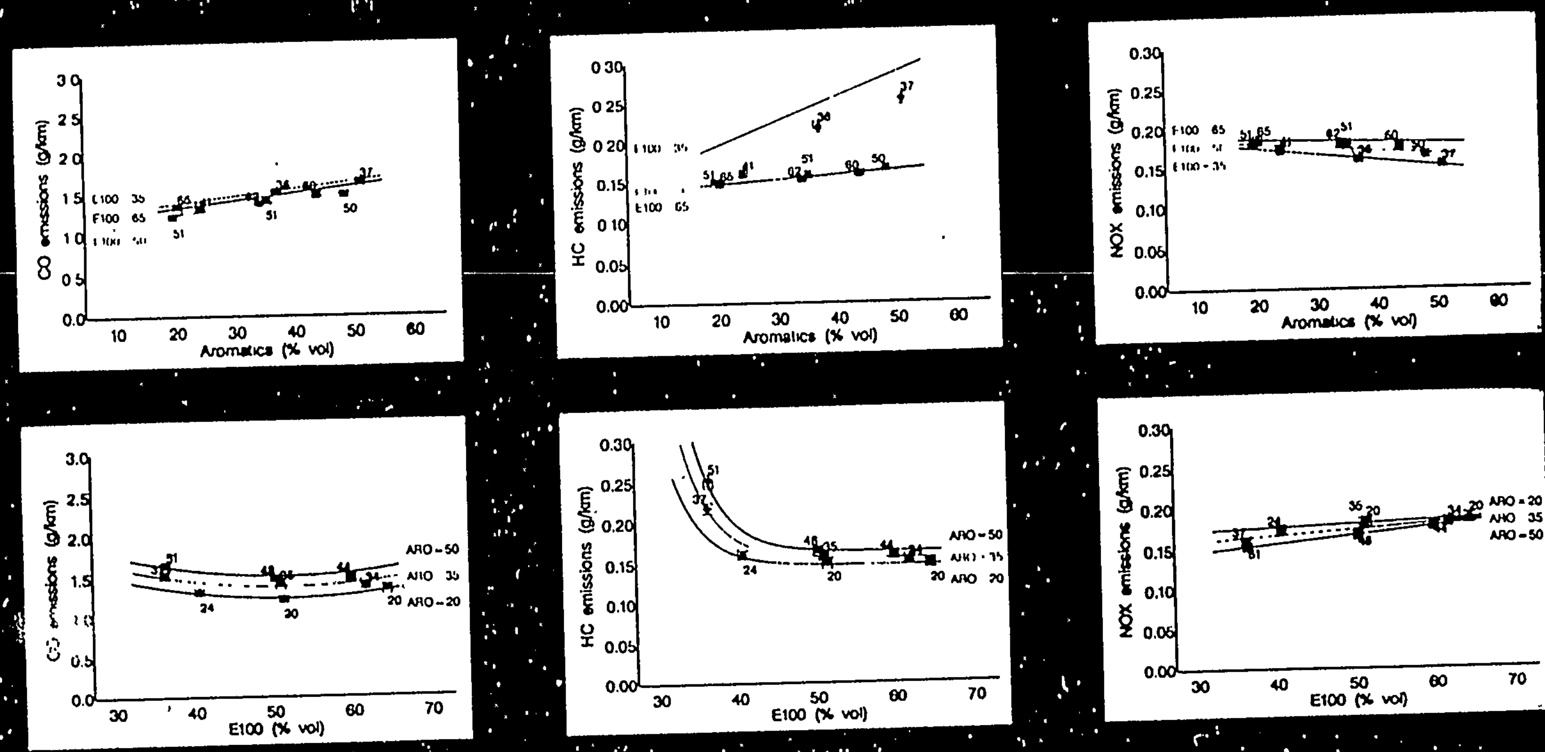
EPEFE gasoline matrix

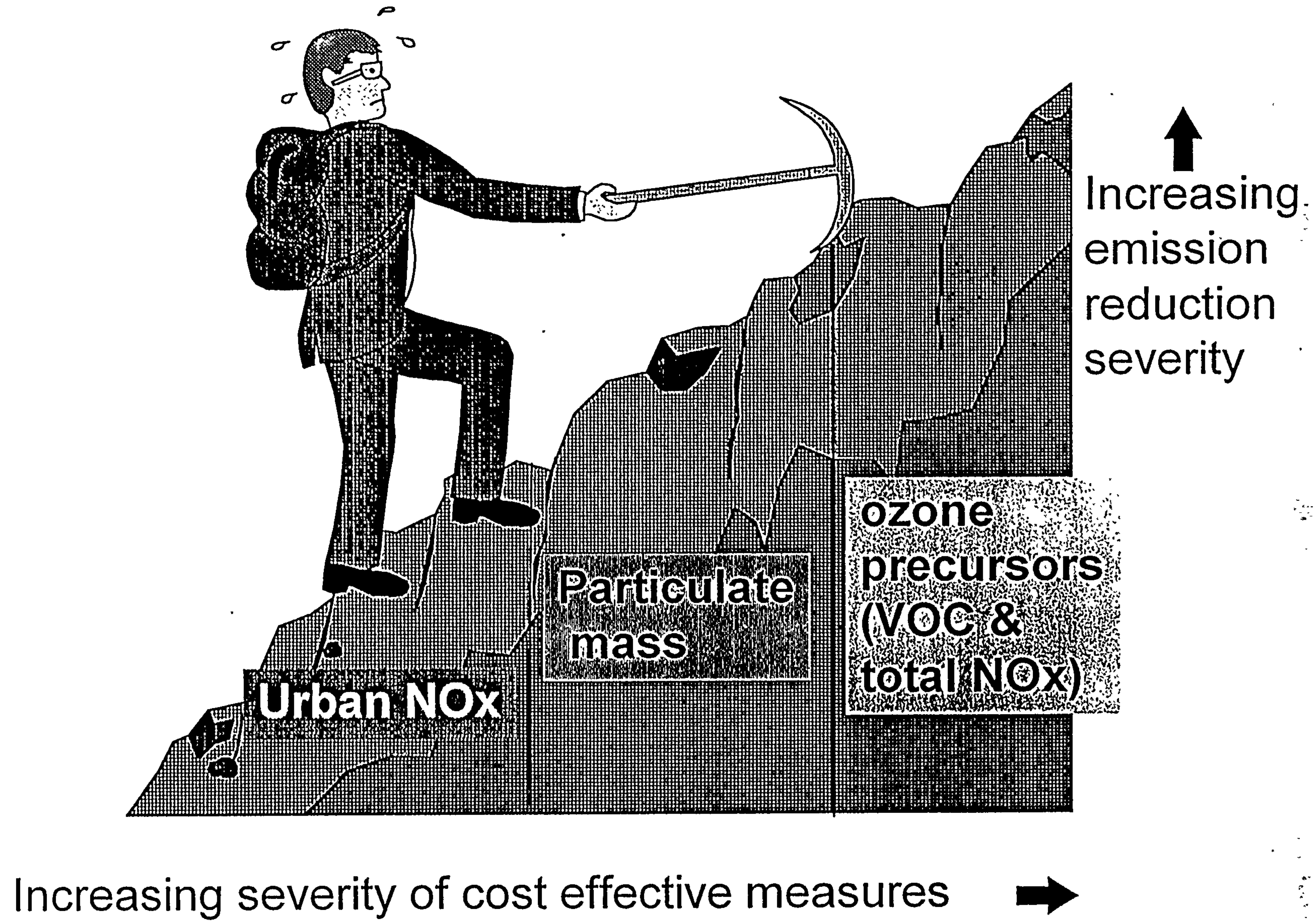
Best option 6% vol olefins using refinery components

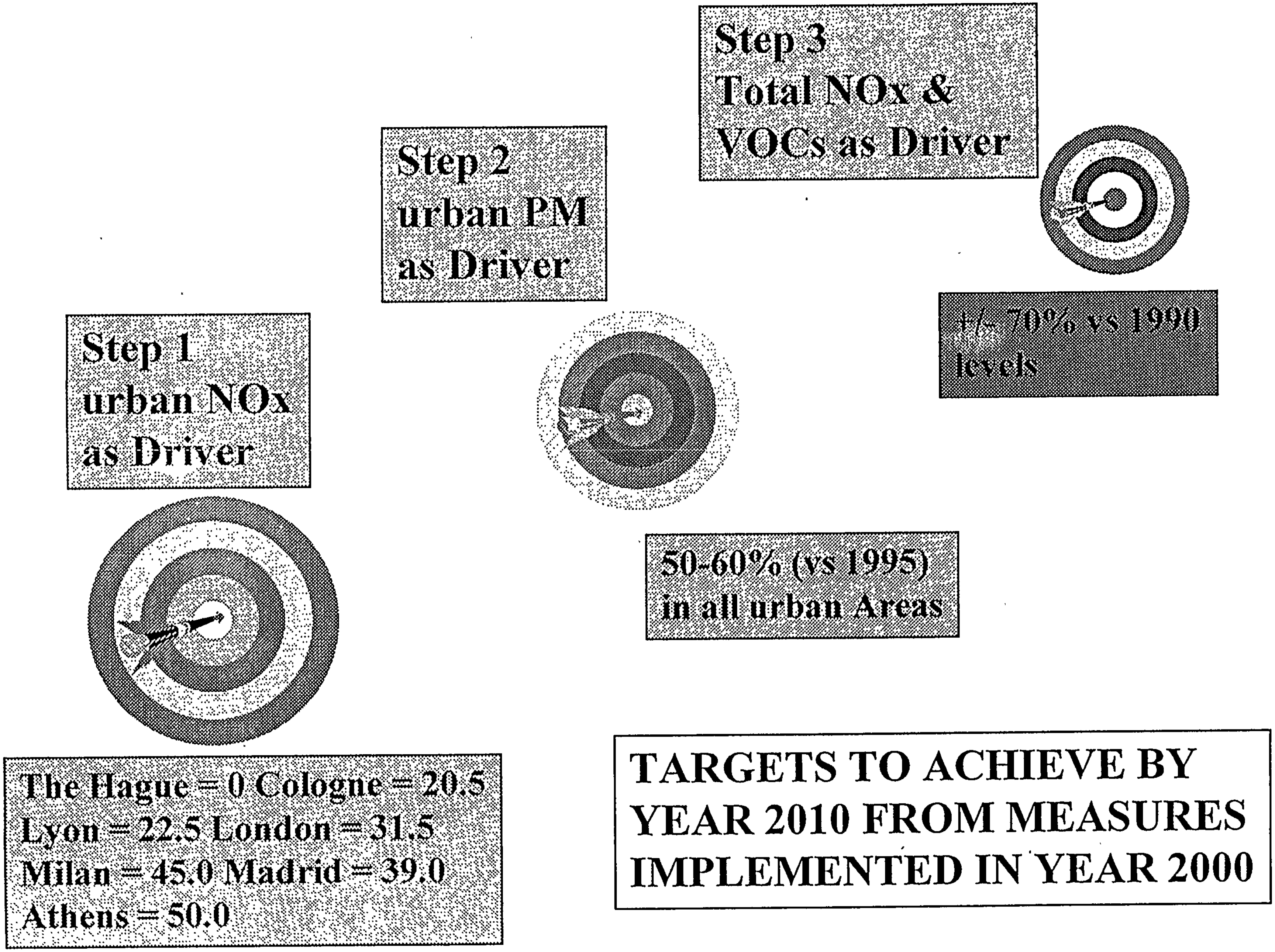


THE EFFECTS OF AROMATICS /E100 ON GASOLINE EXHAUST EMISSIONS

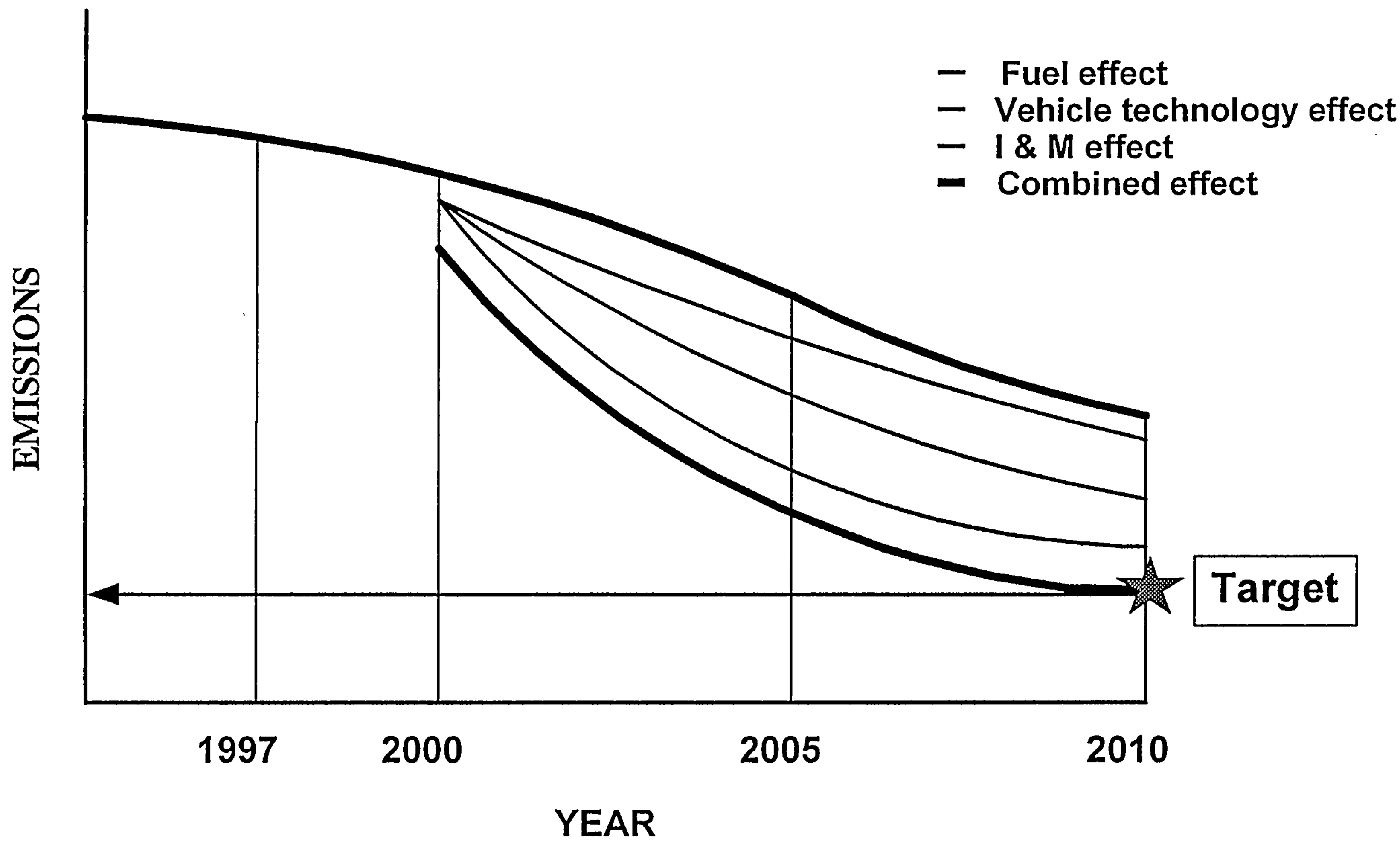
Composite Cycle



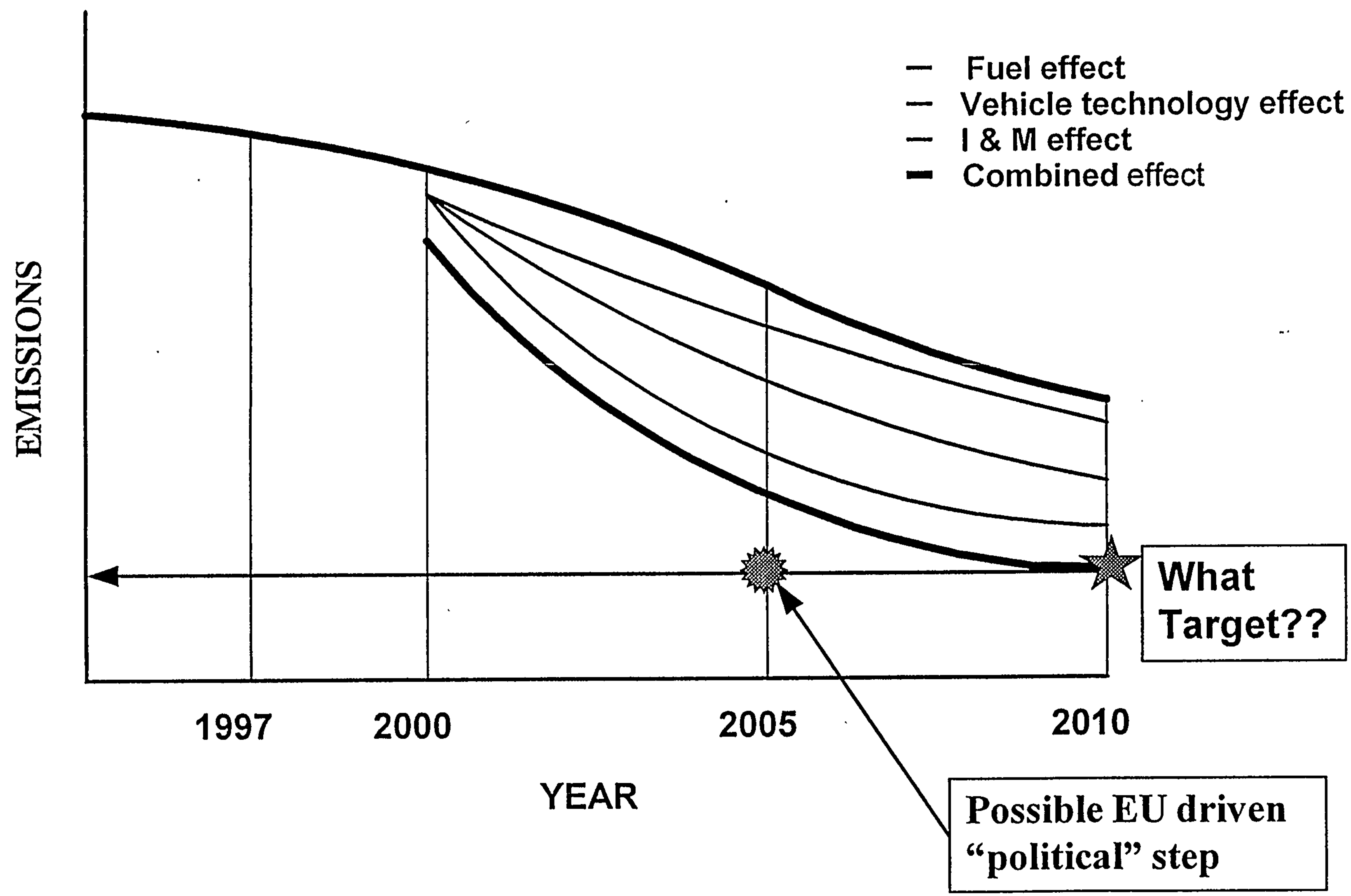

Urban NOx
Particulate mass
ozone precursors (VOC & total NOx)
Increasing emission reduction severity
Increasing severity of cost effective measures


Step 3
Total NOx &
VOCs as Driver
Step 2
urban PM
as Driver
+/- 70% vs 1990
levels
Step 1
urban NOx
as Driver
50-60% (vs 1995)
in all urban Areas
The Hague = 0 Cologne = 20.5
Lyon = 22.5 London = 31.5
Milan = 45.0 Madrid = 39.0
Athens = 50.0
TARGETS TO ACHIEVE BY
YEAR 2010 FROM MEASURES
IMPLEMENTED IN YEAR 2000

Principle of implementation of year 2000 measures



Principle of implementation of year 2000 measures



POTENTIAL FOR FUTURE INDUSTRY-GOVERNMENT AGREEMENTS ON ALTERNATIVE FUELS A PROGRESS REPORT FROM THE NAICC TRANSPORTATION GROUP

Peter Reilly-Roe, Natural Resources Canada

Tony Rockingham, Ontario Ministry of Environment and Energy

Presented at the

1996 Windsor Workshop on Alternative Fuels

June 3, 1996

CCME Recommendation #2 of Oct 1995

The Federal Government in concert with the provinces and other stakeholders through the National Air Issues Coordinating Committee (NAICC):

- **negotiate a memorandum of understanding (MOU) with the auto manufacturing and alternative fuel industries by July 1, 1996 in order to make advanced technology vehicles available for sale in a timely manner.**

- **seek to coordinate and enhance federal, provincial, and auto and fuel industry efforts to support market development of alternative fuels and advanced technology vehicles and report on these efforts to the CCME by the fall of 1996.**

NAICC formed a National Transportation Group (NTG) in December 1995.

The NTG is co-chaired by Natural Resources Canada and Ontario's Ministry of Environment and Energy

It includes broad representation from the fuels and vehicle industries, as well as federal and provincial representatives of energy and environment departments and two ENGOs.

The NTG organized a workshop to:

- **examine the barriers facing alternative transportation fuels and advanced technology vehicles and**

- **to explore areas for possible agreements or MOUs among stakeholders and between stakeholders and governments, that would be useful in overcoming the key barriers.**

The results of the workshop will be reported to the NAICC at its June 17, 1996 meeting.

Workshop Organization

The workshop was held on May 15-16, 1996 in Ottawa.

Prior to the workshop background papers were received from the following organizations:

- Motor Vehicle Manufacturers' Association
- Association of International Automobile Manufacturers of Canada
- Propane Gas Association of Canada
- Canadian Natural Gas Vehicle Alliance
- Canadian Renewable Fuels Association
- Electric Vehicle Association of Canada
- Canadian Oxygenated Fuels Association

ATF Producer Perspectives

- **Although the rationale has changed over the years, there is still a strong public policy justification for supporting the ATF industry.**

- **ATF vehicles still have significant environmental advantages over gasoline vehicles.**

- **The economic viability of the industry depends on the continued and predictable support of government, through tax concessions.**

- **Long term viability depends on the ability to overcome barriers to the marketing of ATF vehicles. Active participation of OEMs is essential.**

- **Cooperation between ATF producers and OEMs to ensure the availability of ATF vehicles.**

OEM Perspectives

- OEMs believe in the advantages of ATFs, but also feel that there have been some unrealistic claims and expectations.

- OEMs have invested a lot in the development of ATVs, but results have been disappointing.

- Obstacles vary between fuels, but the principal common barriers are:

    - lack of range and refuelling infrastructure;
    - perceived erosion of the environmental advantages over gasoline;
    - inherently higher variable costs;
    - poor resale value;
    - long delivery lead times; and
    - lack of customer acceptance.

- **Government resources should be focussed on the most promising opportunities.**

- **Governments must be clear and consistent in terms of policy, regulations and incentives.**

- **Fuel and vehicle standards must recognize the integrated nature of the industry and the importance of the total systems approach.**

- **All parties should constantly think of the needs and expectations of the consumer.**

Federal Government Perspectives

- The Federal Government has supported the development of ATFs for over two decades. At various times, energy policy has highlighted different benefits, including energy security, economic benefits, and environmental protection. An important current priority is Canada's commitment to stabilize greenhouse gas emissions by the year 2000.

- ATFs offer significant environmental benefits, including the reduction of greenhouse gas emissions, however, given new sophisticated emission control systems, the advantages over gasoline cannot be taken for granted.

- **The ATF market has the potential to make an important contribution to the Canadian economy.**

- **The Government understands the importance of tax waivers for the viability of ATFs but is looking for indications that ATFs will eventually be competitive on their own.**

- **Reductions in the cost of ATF vehicles are essential to the long term viability of the industry.**

- **With the exception of propane, the lack of adequate refuelling infrastructure remains an impediment to growth.**

- **The Canadian market will be guided by developments in the larger U.S. market.**

- **The continued growth of the ATF industry will require a comprehensive strategy, led by industry and competitive in the marketplace. Such a strategy should include:**

    - **continuing development of new technologies;**
    - **greater acceptance of ATFs by fleets; and**
    - **greater involvement by vehicle manufacturers.**

- **Government has played a partnership role according to the following principles:**

    - **fuel neutrality;**
    - **environmental integrity;**
    - **government leadership (use of ATVs in government fleets);**
    - **market development and awareness; and**
    - **technology development.**

Provincial Government Perspectives

- **Provincial governments have provided widespread support for ATFs over the past 15 years. Programs have included R&D, procurement and tax relief.**

- **This support has not resulted in significant market penetration.**

- **Gasoline vehicles are demonstrating an increased ability to deliver emission reductions and are challenging ATF claims of environmental benefits.**

- **Given deficit reduction objectives and staff reductions, government's role in the marketplace has changed.**

  In the future, governments will be less likely to intervene directly and may act more frequently as facilitators.

- **The ATF industry will have to identify the issues and the opportunities and develop appropriate strategies.**

Framing Statements for Breakout Groups

1. Improving the economic viability of new or "current" alternative fuels and vehicles

2. Transition from "aftermarket" or demonstration activity to OEM vehicle production

3. Enhancing the contribution of alternative transportation fuels and vehicles to sustainable development

Final Plenary Areas of Agreement

- The success of ATF market development in the short term is critical for the viability of the ATF industry in the longer term.

- Collaboration by all stakeholders is a prerequisite for success.

There is a need:

- to investigate and clarify the environmental benefits of ATFs.

- to better publicize the benefits of ATFs.

- for more effective market research and planning.

- to reexamine the effectiveness of current government and industry incentives for ATFs.

- to review the effectiveness of government policies in relation to ATFs.

Key Workshop Outcomes: Specific Commitments

1. It was agreed that four ATF industry associations (NGVA, COFA, CRFA, PGAC) would form a partnership (MOU to be in place by June 30, 1996).

2. It was agreed that the ATF partnership will explore the development of an umbrella MOU (to be in place by August 1996) with OEMs with the following provisions:

   - government was asked to facilitate the process (perhaps the Co-Chairs of the NAICC Transportation Group);
   - the initial focus will be on marketing; and
   - there may be a need to form sub-groups aimed at specific fuels.

3. **It was agreed that governments be requested to clarify ATF policy through a consultative process aimed at defining the policy rationale for ATFs and integrating ATFs into the broader government policy agendas (energy, environment, industry).**

4. **It was agreed that an industry/government working group be formed to investigate the development of uniform emission and safety standards for aftermarket conversions of gaseous fuel vehicles.**

SESSION 1

PANEL DISCUSSION: ARE THE OEM'S COMMITTED, AND IS THE TECHNOLOGY READY?

Moderator: Bernie James
CANMET, Natural Resources Canada

(Presentations unavailable at time of publication)

SESSION 2

PANEL DISCUSSION: INFRASTRUCTURE ISSUES

Moderator: Peter Ward
California Energy Commission

Presentation - Thomas J. Timbario, EA Engineering Science and Technology, Inc.
Presentation - Zoher Meratla, CDS Research Ltd.

(Other presentations unavailable at time of publication)

Panel Discussion

LEARNING FROM EXPERIENCE:

WHAT HAVE ACTIVITIES UNDER AMFA, EPACT, AND OTHER PROGRAMS TAUGHT US?

Prepared for presentation at

The Windsor Workshop
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by

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WORLDWIDE PUBLIC POLICY DRIVING FORCES UNDERLYING REGULATION OF FUELS AND VEHICLES

- URBAN AIR QUALITY
- OIL IMPORT DEPENDENCE
- GLOBAL CLIMATE CHANGE
- DOMESTIC JOB CREATION
- RENEWABLE ENERGY DEVELOPMENT
- URBAN CONGESTION

OF THESE, URBAN CONGESTION IS NOT RELATED TO ALTERNATIVE FUELS, WHILE ALL THE OTHER DRIVERS HAVE PLAYED ROLES IN ALTERNATIVE FUEL POLICY DEVELOPMENT.

EXPERIENCE TELLS US

FOR VEHICLES/FUELS:

AFVs COST MORE THAN CONVENTIONAL VEHICLES; MANY COST SUBSTANTIALLY MORE.

FUEL COSTS ARE SOMETIMES LESS AND SOMETIMES MORE THAN CONVENTIONAL FUELS.

EVEN WHEN FUEL COSTS ARE LESS THAN CONVENTIONAL FUELS, THE SAVINGS ARE OFTEN NOT ENOUGH TO GET LIFE CYCLE COSTS TO PARITY.

EXPERIENCE TELLS US (CONT.)

FOR INFRASTRUCTURE:

REFUELING INFRASTRUCTURE REQUIRES ADDITIONAL COSTS, WHICH ARE SUBSTANTIAL UNLESS SHARED BY MANY USERS.

MOST FLEETS IMPLEMENTING AFVs ARE LOOKING TO LOWEST SHORT TERM COST FOR REFUELING THEIR OWN VEHICLES, NOT TO ACCESS FOR HIGH VOLUMES OF FLEETS OR PERSONAL AFVs.

VEHICLE STORAGE AND MAINTENANCE FACILITY MODIFICATIONS ARE ALSO OFTEN REQUIRED (FOR SAFETY PURPOSES).

CASE STUDY - CNG TRANSIT BUSES

- INCREMENTAL VEHICLE COSTS HIGH BUT ACCEPTABLE (AND FUNDABLE)
- FUEL COSTS COMPETITIVE
- REFUELING FACILITY COSTS SUPPORTED BY UTILITIES
- MAINTENANCE AND STORAGE FACILITY MODIFICATION COSTS BECOME THE DETERMINANT FACTOR

AFV MANDATES

BY 2010
HOW MANY VEHICLES?
HOW MUCH INFRASTRUCTURE?

Mandate	Likely Range of Vehicles	Estimated No. of Fuel Dispensers Req'd.
Fuel Provider	100,000 to 216,000	1,100
State Fleets	100,000 to 285,000	1,500
Private and Local Government Fleets	450,000 to 1,800,000	9,000
CARB and OTC	2,400,000 (ZEVs) 400,000 (Others)	NA Mostly RFG (?)

FACTORS AFFECTING INFRASTRUCTURE DEVELOPMENTS FROM MANDATES

- FUEL PROVIDERS MUST USE AFs, AND WILL MOST LIKELY ESTABLISH PRIVATE REFUELING FACILITIES.
- STATE FLEETS DO NOT HAVE TO USE AFs, THUS, WILL NOT ADD SIGNIFICANTLY TO DEMAND FOR AF REFUELING FACILITIES.
- PRIVATE AND LOCAL GOVERNMENT FLEETS, IF MANDATED BY DOE RULEMAKING TO ACQUIRE AFs, MAY GENERATE SUFFICIENT DEMAND TO CATALYZE ESTABLISHMENT OF SIGNIFICANT NUMBERS OF PUBLIC AF REFUELING FACILITIES, BUT PROBABLY AFTER 2001.
- CARB AND OTC ZEV IMPLEMENTATION RATE AND DEPTH ARE UNCERTAIN, AND MOST NON-ZEVs WILL PROBABLY USE CLEAN GASOLINE OR DIESEL FUEL

NON-PRICE BENEFITS OF AFV USE

ACCRUING TO SOCIETY: VARIOUS SOCIAL BENEFITS AS MANIFESTED BY "DRIVING FORCES" (SLIDE ONE).

- TO DATE, NOT REFLECTED IN MARKETS OR INCENTIVES.
- UNLIKE LEADED GASOLINE, CATALYTIC CONVERTERS, CLEAN DIESEL, RFG, POLICY BURDENS UNLIKELY EVER TO BE EVENLY SPREAD.

POSSIBLE INDIVIDUAL BENEFITS TO AFV USERS:

- ACCESS TO TRANSPORTATION FUEL IN EVENT OF OIL SHORTAGE. APPARENTLY INSUFFICIENT TO EFFECT SUBSTANTIAL AFV USE.

WHERE ARE WE TODAY?

CURRENT PRINCIPAL POLICY INSTRUMENT IN U.S. IS FLEET MANDATES.

COSTS ARE THE SAME WHETHER MANDATES OR INCENTIVES ARE USED.

COSTS COULD BE REDUCED IF VOLUME THRESHOLDS ARE REACHED FOR SOME FUELS.

CURRENT FLEET MANDATES ARE UNLIKELY TO REACH THE NECESSARY VOLUMES FOR COST REDUCTION FOR FORESEEABLE FUTURE.

WHAT DO WE NEED?

EXISTING POLICY DRIVERS INSUFFICIENT TO OVERCOME COST REDUCTION THRESHOLDS OR ACHIEVE SUBSTANTIAL AFV USE.

WHAT CAN CHANGE THIS PICTURE???

- MORE MANDATES? - HIGHLY UNLIKELY IN SHORT TO MID TERM
- SUBSIDIES/TAX INCENTIVES? - POSSIBLE VIA HIGHWAY TAX
- MARKETS FOR ENVIRONMENTAL BENEFITS/CREDITS? - A REAL STRUGGLE
- MARKET CHANGES IN RELATIVE FUEL PRICES? - UNLIKELY
- SPECTER OF PETROLEUM SHORTAGES? - NO PRESENT VALUE
- CHANGES IN PERCEPTIONS OF INDIVIDUAL BENEFITS? - WOULD TAKE GENERATIONS

LNG FUELING FOR TRANSPORTATION: THE NEXT GENERATION OF LNG FUELING STATIONS

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Abstract

The current state of the art has been reviewed. On the whole, the assessment criteria leading to the selection of liquefied natural gas (LNG) as an alternate fuel have been fairly well developed. However, the technology needs have not been adequately addressed in many instances resulting in demonstration projects less successful than anticipated. Because LNG technology is more complex than that of conventional fuels, such as gasoline and diesel, and because LNG as a transportation fuel is in the early stages of development, the technology needs must be very carefully addressed. The paper presents an overview of a new philosophy for designing LNG fueling stations using a systems approach covering all aspects of an LNG fueling system.

1.0 INTRODUCTION

For the past twenty years, LNG has seen an increasing and broad level of interest as an alternative fuel driven largely by its environmental benefits and other specific attributes including a mileage range comparable to diesel. However, LNG has to compete with other alternate fuels such as, propane, methanol, ethanol, compressed natural gas, gaseous and liquid hydrogen, and other fuels at an early stage of introduction. Based on typical selection criteria, such as, environmental emissions, safety, availability, operating costs, efficiency, ease of developing the infrastructure, weight penalty, mileage range, refueling time and effect on vehicle maximum load carrying capacity, LNG has often come out as the best option in comparison to both conventional and other alternative fuels for many heavy vehicle fleet demonstration projects. The current trend towards high purity liquefied methane together with the inherent clean-up during liquefaction makes LNG the cleanest hydrocarbon fuel.

A review of the experience reported on a large number of LNG fueling projects implemented to date shows that most of these projects have not met all the expectations of the facility operators. Some of the problems encountered include: leaks at nozzles, excessive filling time, icing and difficulty in disengaging the fill nozzle, high boil-off losses, uncontrolled state conditions at the LNG fueling station and on-board the vehicle, unreliable fuel delivery to the vehicle, inadequate metering, lack of proper material balance, uncontrolled emissions to atmosphere, inadequate safety provisions and uncontrolled cooldowns.

Because the LNG industry serving the international trade and the peak shaving facilities is a mature one, with considerable experience in all facets of LNG operations, a close examination of the projects experiencing difficulties indicates that these fueling projects have not been implemented as total systems with a single responsibility from a qualified contractor. The most common omission in the list of evaluation criteria is adequate assessment of technology requirements. Thus, it is not uncommon for fleet operators with no previous experience in LNG to start improvising solutions to problems encountered in the field. This is not considered acceptable. Given the pressure to maintain services, some operators have either slowed the introduction of

LNG or opted for dual fuels or deferred the introduction of LNG in order to avoid these difficulties.

There is another drawback to the current practice. Fleet operating personnel who have to deal with serious teething problems will justifiably develop a perception that LNG is a problem fuel. If this perception is allowed to develop unchecked, the result will be a credibility problem that will make the continued introduction of LNG as a vehicle fuel very difficult.

Thus, a system approach designed by qualified contractors is considered a must if LNG is to play the role it deserves as an alternate fuel.

Most of the issues identified above have been addressed by CDS Research Ltd in a project initiated by the government of Canada through its PERD program.

2.0 ADDITIONAL CONSIDERATIONS FOR SELECTING LNG

In addition to well established evaluation criteria, it is desirable that consideration be given to the following:

1. objective of the project: demonstration only or full conversion
2. given the number of demonstration projects already completed or being implementated, establish the need for another demonstration project, particularly under operating conditions
3. for a large scale conversion effort, develop a total system and identify the potential problem areas so that these are fully addressed and resolved at the design stage. Establish specific performance criteria that have to be met by the design/construction contractor
4. at the outset, insure that safety is given the highest rating. This is not to be construed that LNG is not safe. It simply means that it requires proper design and handling
5. in addressing the economics of LNG fueling, in common with any other industry, scale is an important factor. The conversion cost per vehicle is generally highest for a small fleet. There is a need to consider a central liquefaction facility serving many users, thus permitting certain costs to be spread and creating the volume of vehicles needed to improve the economics of the project. Future LNG fueling growth needs to be assessed and taken into consideration
6. standardization of equipment, such as fuel transfer pumps, fuel nozzles, vapor return, fittings, fuel injection, etc., can improve reliability, safety and costs.

3.0 DESIGN PHILOSOPHY

The implementation of a successful LNG fueling project requires the development of suitable terms of reference. In particular, the following are considered important:

1. sizing the LNG production and/or supply needed for the various phases of the project
2. product specification. For consistency of heating value and to eliminate weathering problems, 99.5% + methane content should be targeted
3. suitable OEM equipment should be available to permit conversion of the targeted vehicles
4. because most of the users, such as transit operators, trucking companies, etc., have little or no experience with LNG, the entire fueling station should be designed for ease of operation and inherent safety

5. it is important to design a coherent LNG supply system. The state conditions of the fuel delivered to the fueling station should meet specific conditions so that when combined with its design residence time, no venting will occur under normal operating conditions. To meet these targets, the insulation system of the delivery tanker and the fueling station need to be selected accordingly. Delivery time should also be taken into consideration
6. the state conditions of LNG loaded into a vehicle should meet specific limits to give the expected residence time and meet the operating requirements. Again the insulation of the vehicle fuel tank must be properly selected
7. given that small LNG plants, of the type needed for LNG fueling, have a high fuel auto-consumption, it is necessary to impose strict limits on the permissible boil-off generated throughout the distribution chain so as to reduce operating costs
8. safety should cover the entire LNG fuel handling chain, including delivery, fueling station facility and vehicle equipment. The siting of the LNG fueling station should take into consideration the local conditions of the site and an assessment of the impact of the design spill
9. security requirements should be carefully assessed
10. the project should comply with existing requirements in the LNG industry for commissioning, operating, maintenance, training and emergency procedures. The fire department having jurisdiction over the fueling station and supply route should have suitable training to mitigate small LNG spill vapor dispersion and radiant heat flux from LNG spill fires
11. all the equipment used in the project should be suitably designed and should comply with the applicable codes and standards
12. the business implications of outages should be carefully assessed to ensure the overall LNG supply system has adequate reliability
13. depending on the location of the facility, a basic public communication program may be necessary to ensure any safety related questions can be quickly and adequately answered.

4.0 SAMPLE LNG FUELING SYSTEM

The following items illustrate some of the features incorporated into the design of an advanced fueling station. (These have all been recently assessed by CDS as part of the PERD program project).

4.1 Control Philosophy

The station is designed to meet the requirements of operators with no previous LNG experience. Under computer control, it integrates a full material balance, continuous monitoring and indication of state conditions, overfill protection, record of LNG transactions, inspection schedule and procedures, maintenance aids and procedures, spare parts lists, operating aids and procedures including troubleshooting diagnostics, safety procedures, training procedures, inhibition of vehicle engine start before fill nozzle disengagement, hands-off filling sequence once the nozzle is properly engaged, automatic correction for the LNG state conditions inside the fuel tank to permit billing where required, multi level custody transfer calculation and checks, interface with vehicle to check on-board instrumentation and effect refueling shutdown at the preset fill level, fill nozzle de-icing sequence, conditioning of the fuel, automatic cooldown of fill line, submerged pump start/stop and condition monitoring, records of venting to atmosphere, enable/disable operation of fueling station, secondary automatic shutdown of transfer operations under confirmed leak or fire event detection, etc.,

4.2 Insulation

Proper specification, design and installation of the insulation on equipment used in an LNG fueling project are very important for controlling operating costs and providing reliable service. In general, conventional insulation systems, including powdered insulation in conjunction with a vacuum space, are well understood and developed. However, superinsulation which provides the longest holding time is still at an early stage of industrial scale application. Within the project referred to herein, the following superinsulation tasks were completed:

1. survey of the current state of the art and short listing of materials approved for LNG service
2. development of detailed specifications and quality control procedures for sourcing both the reflector and separator and for fabrication of the blanket of multi layer insulation
3. development of a computer program written in C++ to compute the required number of layers for a specific design heat flux
4. development of a computer program written in C++ to compute the holding time for any insulation system. The program lends itself to different state conditions in the LNG supply chain. Computed state conditions for a 400 litre fuel tank insulated with superinsulation are illustrated in Figures 1 to 3. The design heat flux is 1 W/m^2 augmented by 15% for the supports. The program allows for the effect of sloshing
5. development of procedures and quality control for packaging superinsulation blankets
6. development of installation procedures including anchoring of the blankets onto the vessel.

Validation of the superinsulation design and installation described above was performed on a substantial liquid hydrogen project.

4.3 LNG Storage

Field erected storage tanks covered by API 620, Appendix Q have benefited from over 30 years of experience and know-how accumulation. The same is true of shop fabricated cryogenic vessels in stationary services.

High frequency service LNG delivery tankers will benefit from additional attention to the design of the supports of the inner vessel and the means to maintain the integrity of the insulation. It is desirable to carry out suitable dynamic proving tests, well established in the automotive industry, on the storage vessel of delivery vehicles and fuel tanks. Apart from assessing the overall structural integrity of LNG containers, the performance of the inner vessel supports, instrumentation and insulation should also be targeted.

The location of the penetrations on a storage vessel or fuel tank will determine the design spill and therefore the safety needs of the equipment or facility.

4.4 Refueling Pumps

External centrifugal pumps require a bottom penetration on the LNG storage vessel at the fueling station. This adversely affects the design spill of the facility since in the event of failure of the bottom penetration the entire contents of the vessel may be discharged. For priming considerations, the external pump will need to be provided with continuous automatic cooldown.

Because of the potential cost penalty associated with the foot print of an LNG fueling station using storage with bottom penetrations, only submerged pumps connected to top penetrations are considered for all tanks and vessels.

Submerged centrifugal pumps have benefited from extensive development work over the past 20 years. When properly specified, a service life in the order of 8,000 hours can be achieved or exceeded. This operating configuration allows the pump to be permanently cooled down and ready for operation.

4.5 Safety

In common with other alternative fuels and technologies, it will take only one serious incident to develop a public perception that LNG is a hazardous fuel. It is this fear that motivated the international LNG trade to treat safety very seriously. The vast quantities of LNG transported between continents over the past thirty years without serious incidents proves that this is a safe fuel when the equipment is designed and handled properly. There is no reason why LNG refueling stations, which are very small in size in comparison to grassroots LNG plants, cannot be designed to the same standards of safety.

Within the design work completed, safety has been addressed for the entire system, from LNG production to the vehicle, including the following specific features:

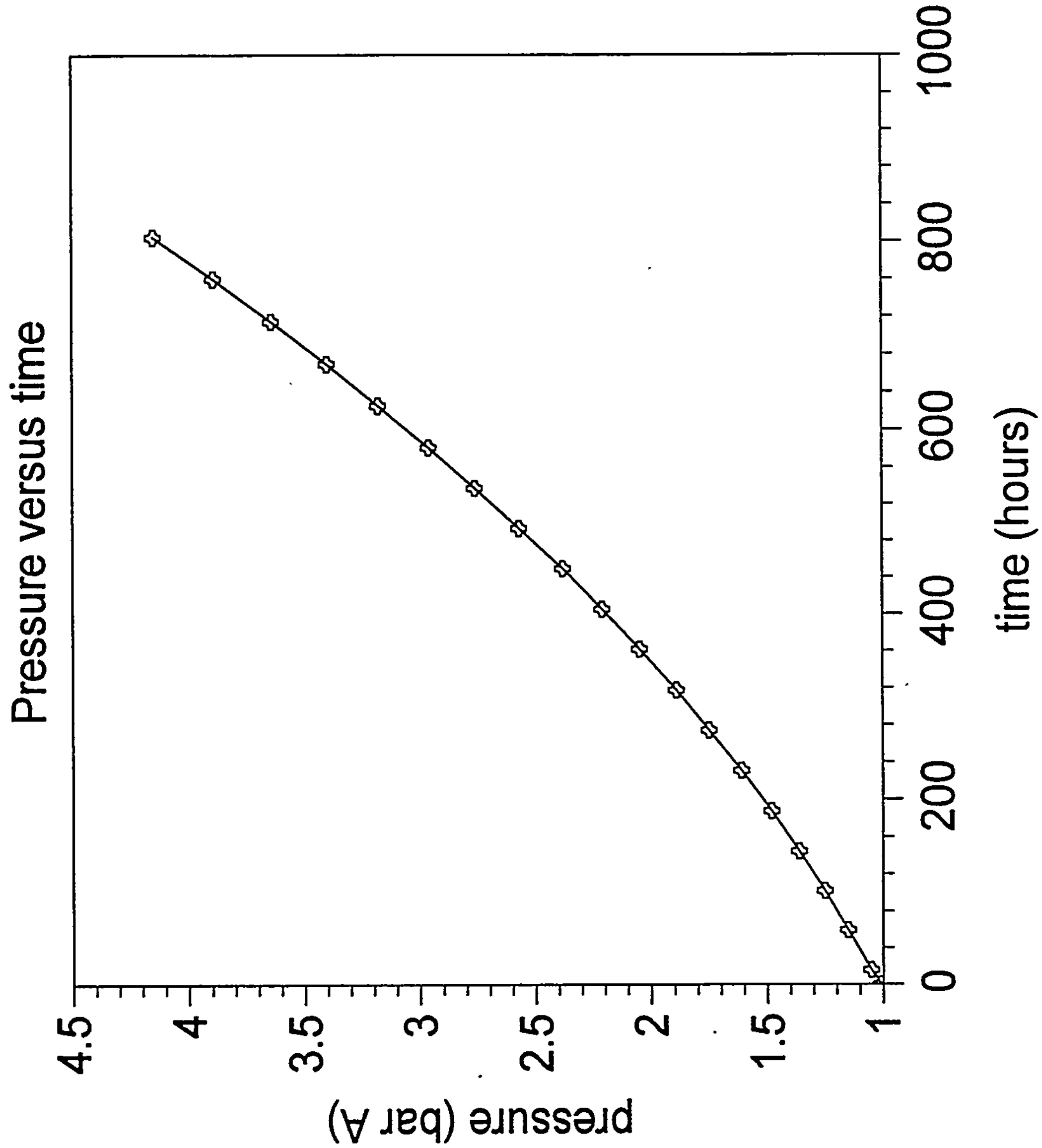
1. a review of incidents in the transportation of refrigerated products indicates that driving away with the fill nozzle still connected is the most common source of accidents. Thus, the refueling system has been designed so the vehicle cannot drive away with the fill nozzle connected
2. based on previous experience in the cryogenic industry, bellows and flexible piping are generally the weakest link in any piping system. To prevent personnel injury in case of failure of a flexible fill line, the refueling sequence is designed for hands-off operation
3. for top penetrations into the LNG storage of refueling station, the design spill is determined by the quantity of LNG that can be discharged whilst the submerged pump is operating. Advanced fast response LNG spill and fire detection systems have been integrated into the automatic emergency shutdown system to minimize the spill size and therefore the secondary safety provisions required. LNG design spill hazard mitigation has been addressed
4. a small design spill requires minimal costs to manage it. There is extensive experimental data for LNG spills on land and water including spills in impoundment systems of the size expected for refueling stations. Therefore, LNG spill vapor downwind travel distance can be readily assessed. Most vapor dispersion modeling tools have been validated over the range of spills expected on refueling stations
5. below an LNG spill pool diameter of 6 m, the mass burning rate of LNG decreases rapidly as the pool diameter is reduced. This feature has been included in the design spill and impoundment system so that radiant heat flux is substantially mitigated by design. Small LNG pool fires can also be extinguished or controlled using readily available technology
6. the means to annunciate when the pre-venting to atmosphere level is reached have been addressed
7. provisions have been made to prevent uncontrolled venting during indoor parking over night in cold climates or during indoor maintenance

8. On and off board vehicle leak detection has been included
9. redundancy has been provided on all critical instrumentation and controls
10. incident specific emergency procedures have been developed.

5.0 CONCLUSIONS

The vast knowledge accumulated in the LNG industry over the past thirty years does not appear to have been fully utilized in LNG fueling for ground transportation. The absence of a system approach based on clearly pre-defined deliverables has hampered the large scale introduction of this fuel. Some aspects of an advanced refueling system are described herein and address a number of issues not fully addressed for on previous projects.

Figure 1 - 400 Litre LNG Fuel Tank



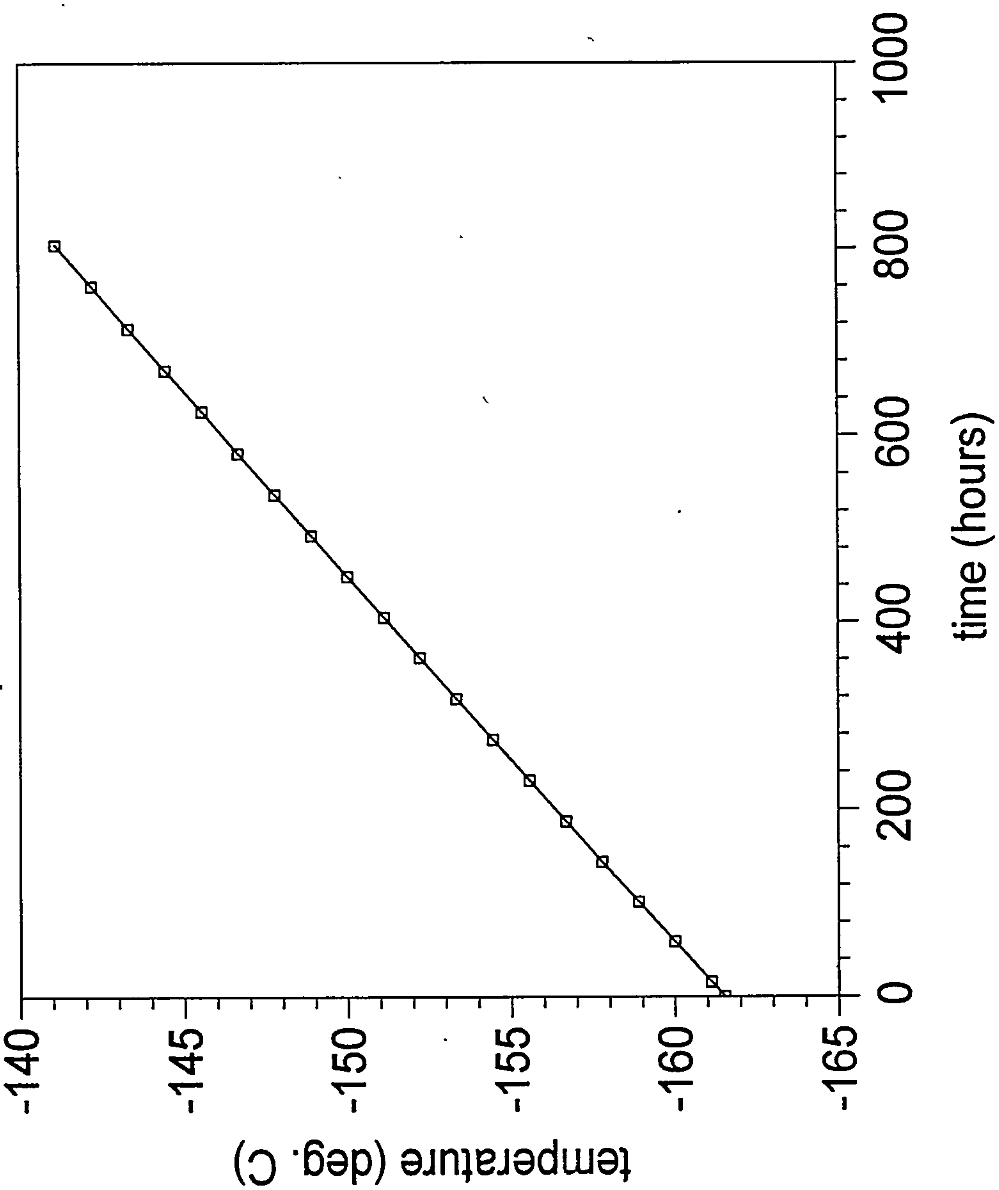
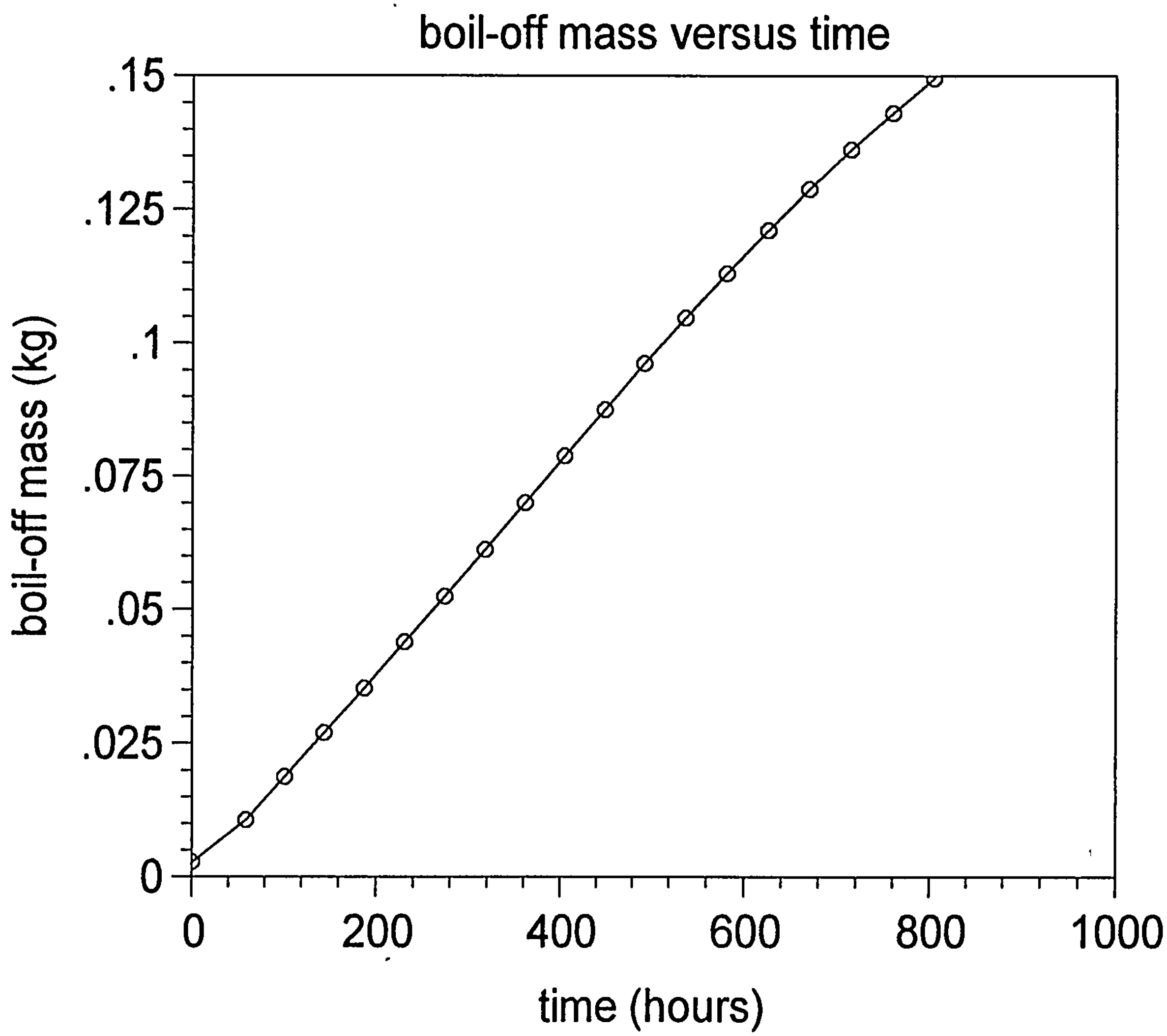


Figure 2 - 400 Litre LNG Fuel Tank
temperature versus time

Figure 3 - 400 Litre LNG Fuel Tank



SESSION 3

INTERNATIONAL LINKS

Chair: **John Convey, ORTECH Corporation**

GFI
Control Systems Inc

MEETING THE EUROPEAN EMISSIONS CHALLENGE

Brett Nelson, GFI Control Systems, Inc.
Glynn Thomas, British Gas PLC
George Tilley, Business Gas

1996 WINDSOR WORKSHOP

SLD520

1996 WINDSOR WORKSHOP

Meeting The European Emissions Challenge

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April 1996

The concern for our environment has never been greater. As a global community, we recognize the importance of providing a clean, safe environment, and as an industry, the automotive sector has a large role to play. Providing alternate fuel powered vehicles is a practical direction for countries throughout the world, but not yet an effortless one.

Industry representatives in North America would agree that the business of converting commercial fleet vehicles to natural gas is fraught with challenges. New vehicle technology creates new hurdles, and understanding, let alone meeting current US legislation can be a difficult process. What we may not realize, from our North American perspective, is that we may have it easy compared to Europe.

By working with European automotive manufacturers, Utilities, and alternative fuel vehicle converters, GFI Control Systems has become an active player in the goal to reduce exhaust emissions in Europe, and understands the extra challenges faced by our European partners. This presentation demonstrates these challenges as they relate to vehicle emissions, describes the strategies used to meet these challenges, and provides a score card of our partner's successes in providing a cleaner global environment.

THE CHALLENGE

GFI Control Systems Inc

SLD526

THE CHALLENGE

THE EUROPEAN EMISSIONS CHALLENGE

- Challenging Vehicles
- Challenging Emissions Cycle
- Challenging Emissions Standards
- Expectations Go Beyond The Standards

To provide Natural Gas powered vehicles as an alternative to petrol or diesel, the European alternate fuels converter must meet and overcome several new challenges, not found in North America. To begin with, the vehicles used by fleets and converted to Natural Gas in Europe are very different than the typical fleet vehicle of North America, and in many cases, these differences create an additional burden on the converter. Secondly, as any student will tell you, some tests are easy, some are hard, and the difference is often reflected in the test results. The test cycle used to measure vehicle emissions also influences the results, and there are key differences between the European emissions test cycle and the American test cycle which make the European test more difficult for Natural Gas powered vehicles. In addition, the legislated emissions standards are quite different for Europe and provide a unique challenge for Natural Gas. Of course, consumer demand does not stop at legislated standards, and expectations placed on alternative fuel vehicles is rightfully high.

THE VEHICLE CHALLENGE
Unique European Opportunities

- Small Displacement Engines
- Electronic Distributorless Ignition System
- Exhaust Gas Ignition

We have been taught that problems should be regarded as opportunities. There are many opportunities for alternative fueled vehicle converters in Europe based on the fact that European vehicles are very different from their American counterparts. To begin with, the typical engine for a European vehicle has a much smaller displacement. Vehicles in the range of 1.3 to 2.0L are the norm for fleet use in Europe, while fleets in North America may start at 2.0L, but are more typically powered by 3, 4, or 5L engines. The smaller displacement engine provides a tougher challenge because conversion to Natural Gas generally results in a small loss in power, which would be instantly felt on the typically inclined roads of Europe.

While engines up to 7.5L have been converted from gasoline to Natural Gas here at home, European trucks with larger displacement engines are most often diesel powered, requiring an added element of complexity to the conversion to Natural Gas.

The technology used in modern European vehicles has also produced some surprises for the vehicle converter. Even on vehicles with manufacturers in both the US and Europe, there are differences in under bonnet equipment. The Ford ignition control system called EDIS was found only on one common engine in North America (the Ford Ranger) in 1992 but was quite prevalent in Europe, being used on a variety of platforms from Escorts to Scorpio's. This ignition system required a completely different approach to timing advance not found on any other vehicle.

There are also variations in electronics and emissions controls which are not likely to be found anywhere in North America. Although extra oxygen sensors in the exhaust are becoming the norm in North America, we are unlikely to see an extra spark plug between two catalysts, which one European manufacturer is calling Exhaust Gas Ignition (Ford Galaxy). Catalysts themselves are newer introductions on European vehicles, and their placement, as well as the placement of the oxygen sensor with respect to the exhaust ports is more variable on European vehicles.

THE EMISSIONS CYCLE CHALLENGE
European Drive Cycle vs Federal Test Procedure

- ECE R15.04 + EUDC
- FTP 75

It can be readily argued that a vehicle's exhaust emissions are strongly dependent on its owner's driving style. Five minutes of high speed, stops and starts would produce very different emissions than a five minute low speed cruise in the same car or truck. For this reason, emissions tests must be performed under tightly controlled and repeatable driving conditions. Unfortunately, North America and Europe have defined two completely different emissions drive cycles to measure vehicle exhaust emissions.

In North America, a light or medium duty vehicle's emissions are measured during a Federal Test Procedure, or FTP, as defined by the US Environmental Protection Agency. The drive cycle used in this procedure is the EPA Urban Dynamometer Driving Schedule or UDDS. The drive cycle itself was developed from the replication of a typical drive in Los Angeles, and as such contains three phases of stops and starts, accelerations, decelerations, and cruise portions, none of which follow a predictable pattern. In fact, the first two phases of the test are commonly known as an LA4. The full FTP test is an LA4, followed by a repeat of the first 505 seconds.

In Europe, vehicles emissions are measured over a very different drive cycle. The European cycle designed for light duty petrol vehicles consists of four repetitions of a basic pattern, called the elementary urban cycle, plus a high speed portion at the end, called an Extra Urban Drive Cycle.

FIGURE 1: Cycle Comparison; ECE Urban Cycle vs FTP 505 Cycle

A comparison of the European cycle over the first 505 second phase of an FTP show the significant differences in driving. Here, vehicle speed in km per hour is plotted vs time in seconds.

Unfortunately, my slide is actually plotted with the FTP cycle in miles per hour, so with my apologies, would you please note that the FTP trace should be 1.6 time higher than illustrated. The top speed of the first FTP hill is 50km/h, and the second hill reaches 90 km/h. I should know better being Canadian, but American road speed always seems slower to me.

One might conclude that the highly variable Los Angeles trip would generate higher emissions than the simple first, second, third gear hills of the European cycle. While this may be true of engine out emissions, it is not the case for tailpipe emissions, which are the critical measured product of the test. Consider for a moment that the best cure for high emissions is a hot catalyst. Note that the Federal cycle starts early with a sustained acceleration, while the European cycle starts much later with short 1st gear and second gear accelerations. The sustained acceleration will provide an early source of high heat into the exhaust, effectively warming the catalyst, while the European cycle waits a full minute before any sustained acceleration takes place. The first hill of the Federal test also reaches a higher speed of 50km/h (or 31 mph as shown in the graph) while the urban cycle does not reach this speed for the first 3 minutes.

Also note that the higher speed cruise is not sustained in the European test, as it is in the second hill of the FTP. Rather, the elementary urban cycle ends at 235 seconds, returning to idle for the next 3 hill cycle to start.

FIGURE 2: Catalyst Temperature During ECE Urban Cycle
- CNG, 2.0L German Ford Transit
- Pre-Catalyst temperature

This repeated return to idle creates a very real problem for controlling emissions on a Natural Gas powered vehicle. As shown by this pre-catalyst temperature plot of a German Transit van, taken over 2 elementary urban cycles, or half of the ECE test, the catalyst temperature drops significantly during each of the idle periods. The impact of the lower speeds is also evident, where the catalyst temperature reaches only 300C in the first hill, 400C in the second hill, and only breaks through 450C in the higher speed, 3rd gear hill. Even after the 50km/h cruise in 3rd, the catalyst temperature drops again to 350C at each idle.

Note that all accelerations are started with a catalyst temperature at or below 350C, and the majority of the test is run with a catalyst temperature below 400C.

Meeting the European Chanllenge

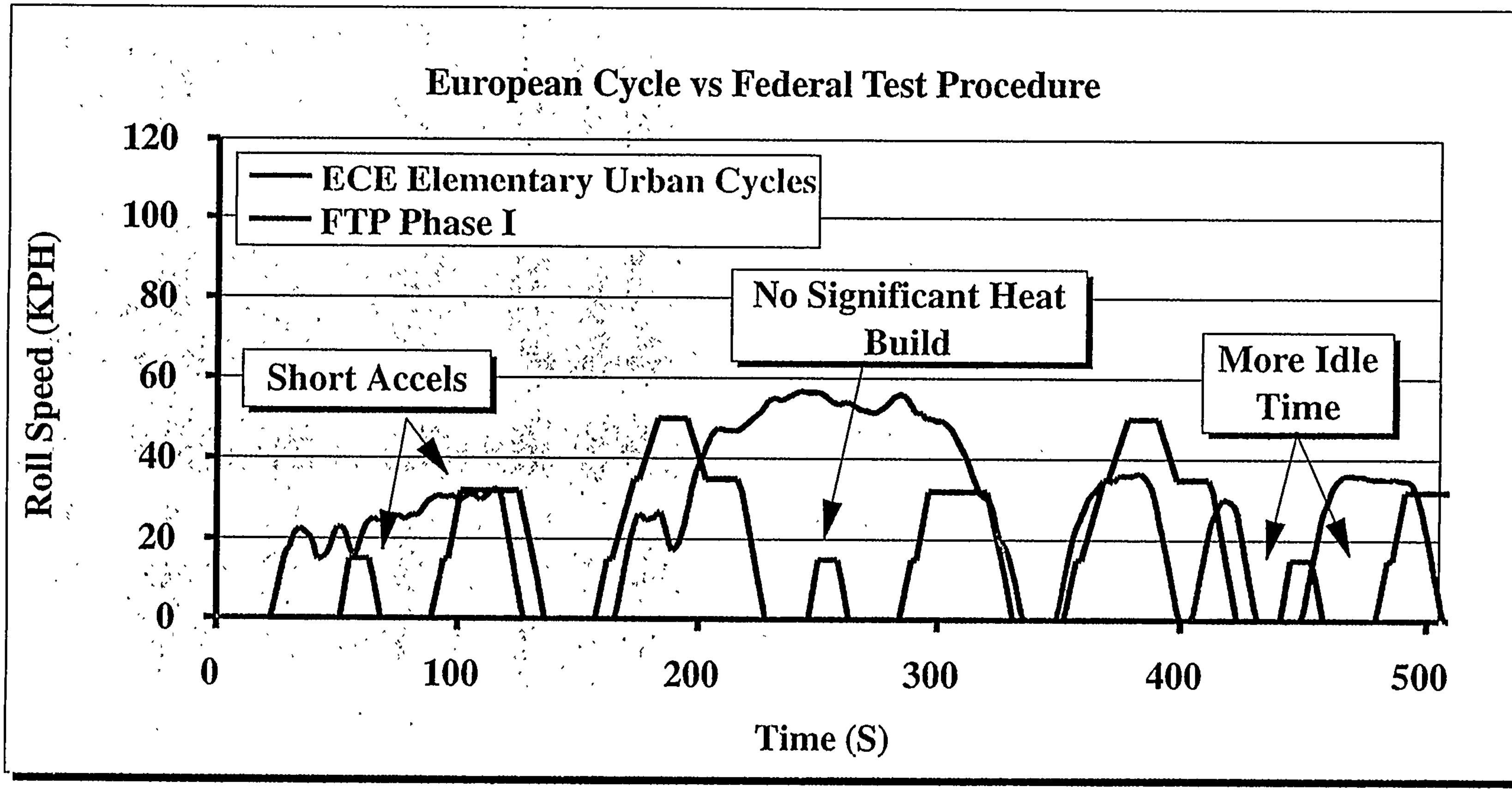

Figure 1

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Meeting the European Chanllenge

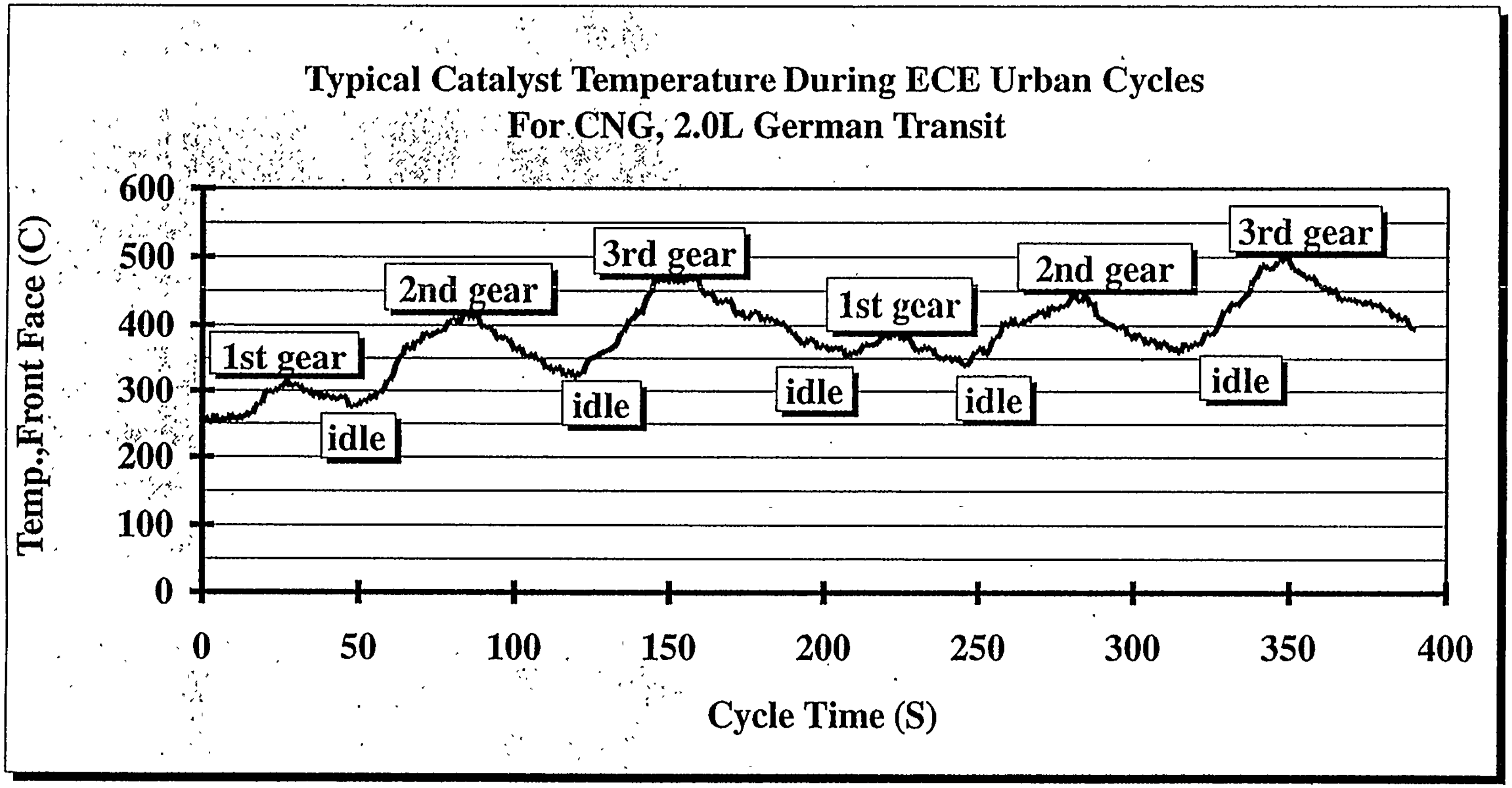

Fig. 2.

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FIGURE 3: Aged Catalyst Efficiency vs Temperature

These temperatures are significant, as shown by this next illustration. The findings of Usmen and McCabe of Ford Motor Company, show the catalyst conversion efficiency for a typical aged automotive catalyst. (Vehicle aging of 50,000 miles.) As demonstrated by their testing, conversion efficiency for CO falls off rapidly below 350C, while HC and NO conversion require temperatures over 500C for effective catalytic reaction. Note the dip in NO converter efficiency around the 400C mark, right where our previous example spent most of its time. This dropout in NO conversion is the result of precious metal sintering common to aged catalysts, and demonstrated by Ford in both Palladium/Rhodium and Platinum/Rhodium beds, typical of commercial vehicle catalysts (Samples from Thunderbird and Crown Victoria.) (4)

FIGURE 4: Cycle Comparison; Full ECE+EUDC vs FTP

Here, a complete European cycle is shown against the same time from an FTP. Note the higher speed portion of the FTP takes place early in the test, providing good light-off heat to the catalyst, while the European cycle places the high speed drive at the end of the cycle, where it can do no good for the rest of the cycle.

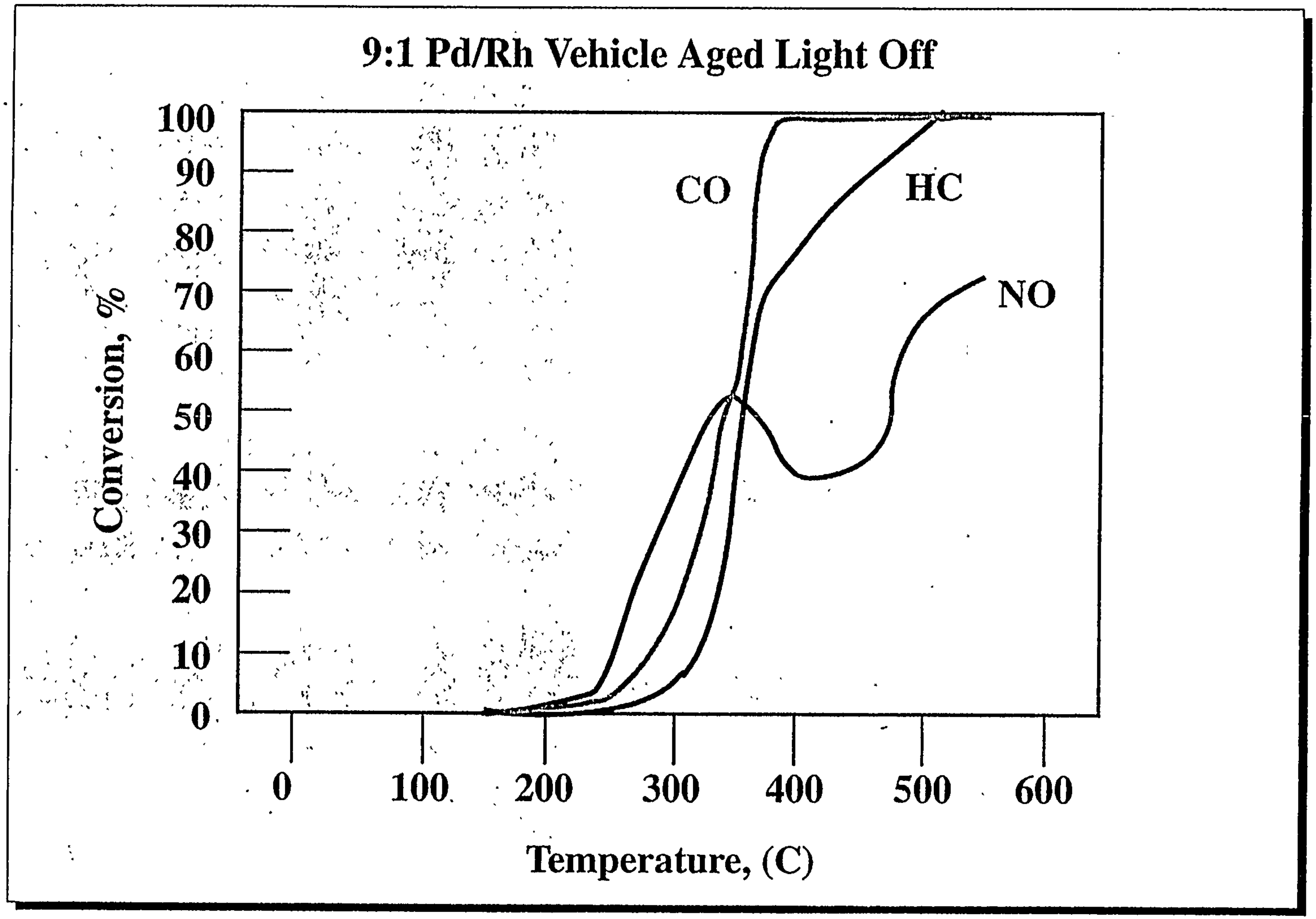
9:1 Pd/Rh Vehicle Aged Light Off
Conversion, %
100
90
80
70
60
50
40
30
20
10
0
CO
HC
NO
0
100
200
300
400
500
600
Temperature, (C)

Fig 3.

Meeting the European Chanllenge

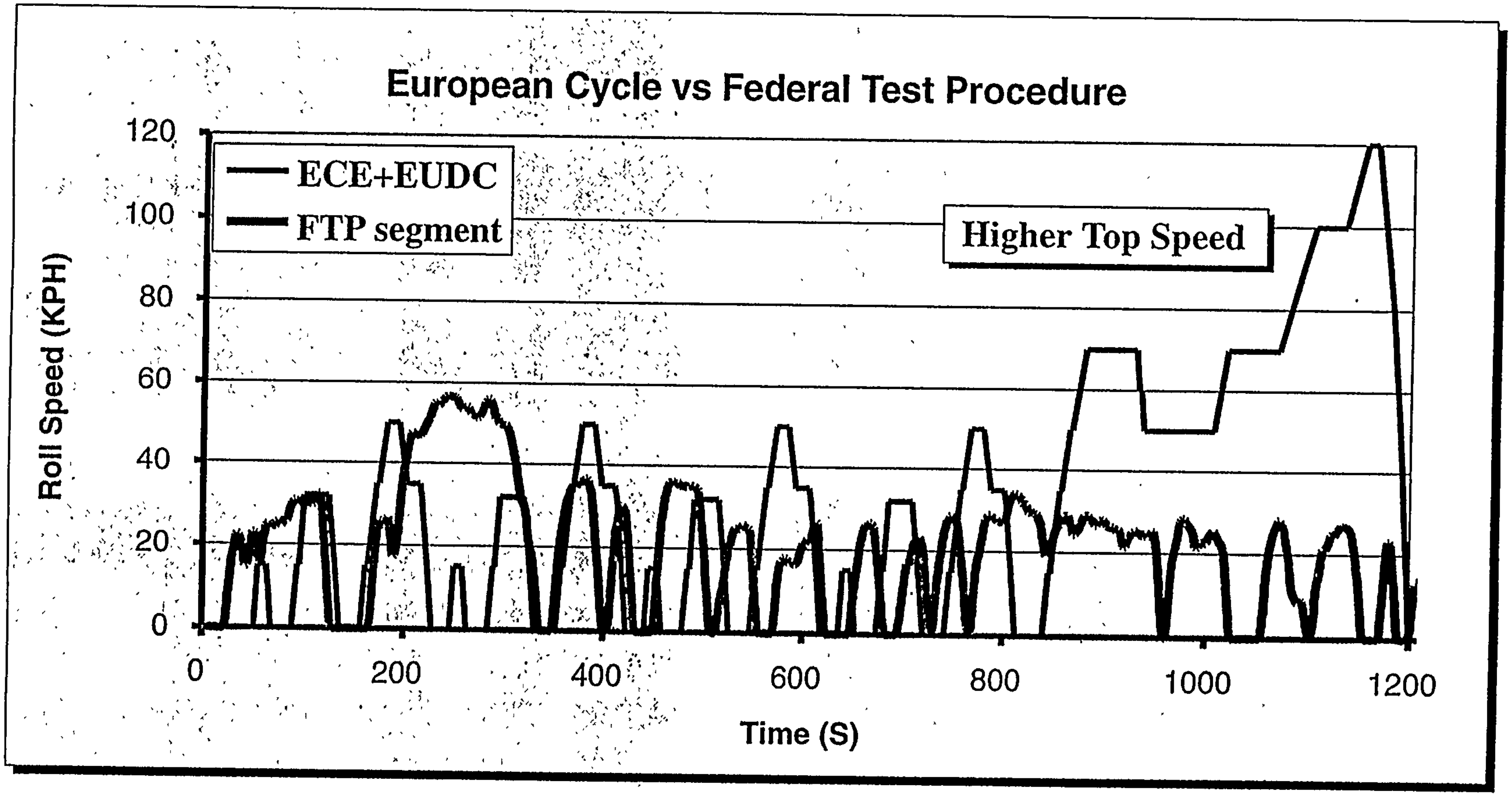

Fig 4

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FIGURE 5: Catalyst Temperature, ECE+EUDC vs FTP
- Lower Exhaust Temperature Demonstrated While Running Natural Gas
- Up To 150C Cooler During AMA Cycle

The end result of a European cycle versus the American FTP is shown by this next plot. Here, pre-catalyst temperatures are once again plotted against time. Both plots are for the same vehicle, a typical small displacement Van converted to run CNG. The early, high speed hills of the FTP are clearly effective at raising the catalyst temperature to over 500C, where the maximum converter efficiency is found. Contrast this with the slow climb in converter temperature under the European ECE cycle. Here, catalyst temperature reluctantly climbs to 500C after 10 minutes of driving. These are 10 painfully long minutes for a European emissions calibrator.

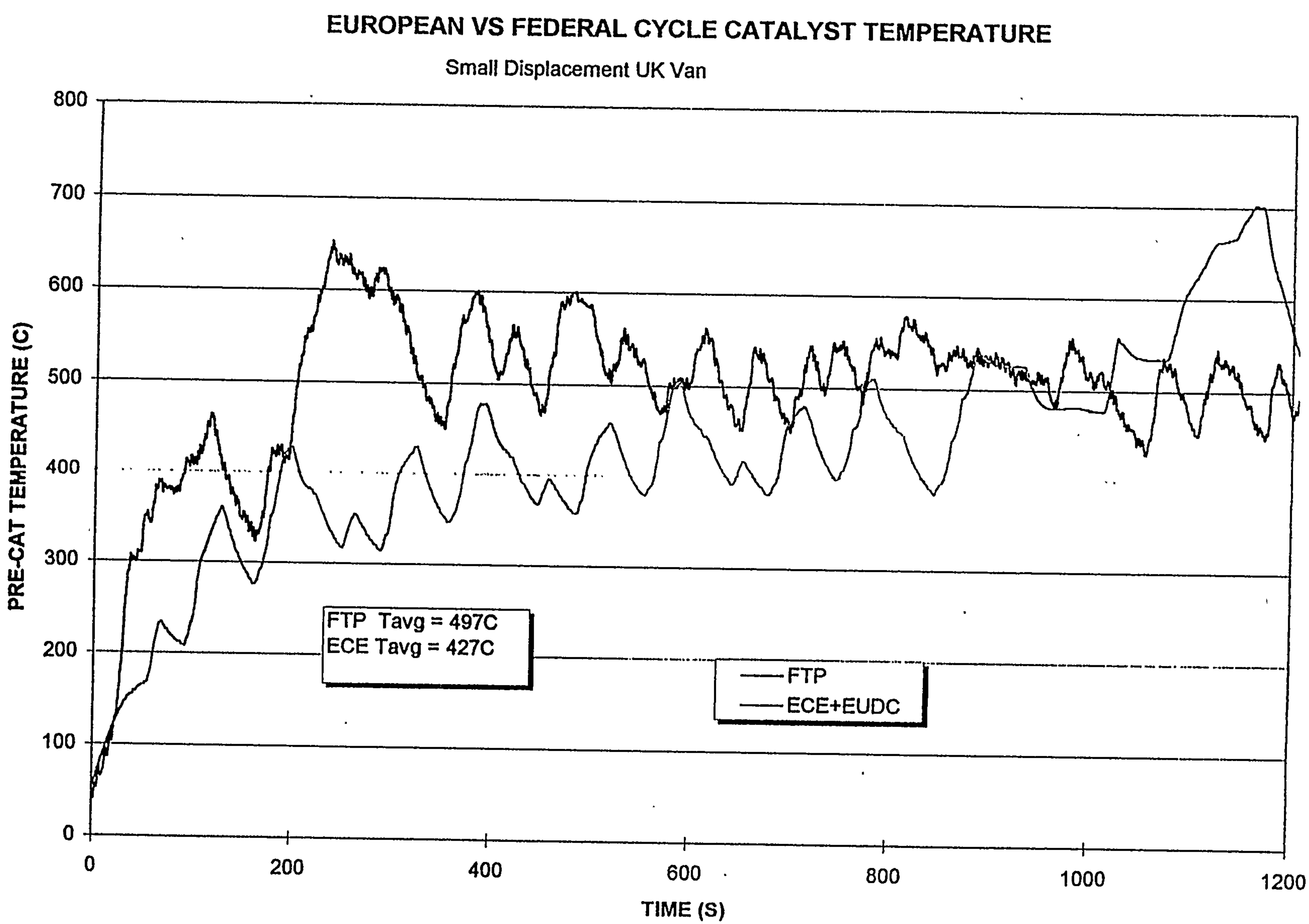
The real heat is finally generated in the Extra Urban Drive Cycle, placed at the end of the test.

Overall, the front face catalyst temperature averages 497 degrees C during the FTP, which places it just on top of the catalyst efficiency curve, whereas the ECE+EUDC cycle average catalyst temperature for the same vehicle is well down the curve, at 427 degrees C.

Why is this question of temperature so important? Surely any test is fair as long as it is consistent. The problem with the European test when used to measure Natural Gas emissions is not shown here, but has been demonstrated by repeated tests with our Bi-Fuel vehicles. Catalyst temperature traces during European emissions cycles, Federal cycles, and AMA mileage accumulation tests have shown that a vehicle running Compressed Natural Gas has a lower catalyst temperature than the same vehicle running gasoline. In fact, temperature drops of 100 to 150C are not uncommon.

Re-examine the FTP and European cycle temperatures shown here and imagine a shift upwards of 100 to 150 degrees. This shift would take the FTP temperatures to 600C, and more importantly, move the ECE+EUDC temperatures safely over the 500C high catalyst efficiency band. Under these circumstances, the European cycle becomes more evenly matched to the Federal test; but, unfortunately for Natural Gas conversion suppliers in Europe, this European emissions cycle remains a challenge.

Chart1



EUROPEAN VS FEDERAL CYCLE CATALYST TEMPERATURE
Small Displacement UK Van
PRE-CAT TEMPERATURE (C)
800
700
600
500
400
300
200
100
0
TIME (S)
0
200
400
600
800
1000
1200
FTP Tavg = 497C
ECE Tavg = 427C
FTP
ECE+EUDC

Fig5

THE EMISSIONS STANDARDS CHALLENGE

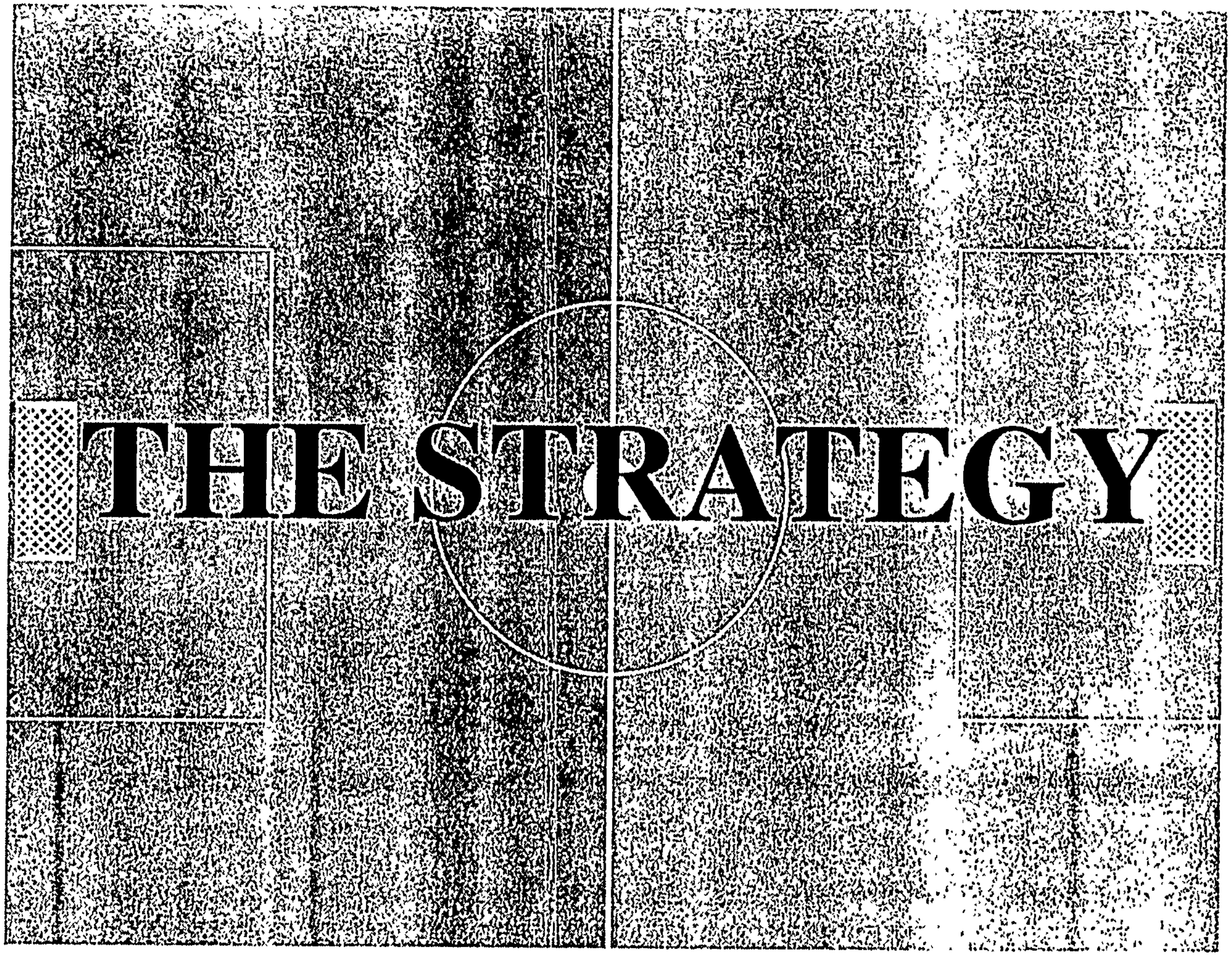
- Federal (North American) Regulated Emissions
- *CO, NOx, NMHC*
- European Regulated Emissions
- *CO, THC+NOx*

On top of the European cycle, the European emissions standard provides an additional challenge for CNG conversions. The two most difficult Natural Gas emissions compounds to reduce through standard catalytic conversion are combined into one legislated number.

Catalytic converters on today's automobiles are designed for petrol exhaust. It is now widely recognized that methane, the principal component of CNG, is harder to oxidize than the longer chain molecules of petrol. Because of its higher bond strength, unburned natural gas travels through a standard automotive catalytic converter relatively unscathed, whereas the unburned hydrocarbons in petrol exhaust with their longer chain, higher carbon molecules, are more readily oxidized. This results in a higher total hydrocarbon emission from a vehicle running natural gas through a standard catalytic converter. The hydrocarbons emitted from a natural gas powered vehicle are generally at least 85% methane, but the European legislation does not differentiate between methane and non-methane hydrocarbons as the newer American standard does, in recognition of the fact that methane has a considerably lower environmental impact than the higher carbon compounds.

To magnify the problem in the Europe standards, Oxides of Nitrogen are added to the Total Hydrocarbons count to produce one legislated number. For petrol based emissions, this is not as big an issue, but with Natural gas conversions, NOx emissions can be difficult to control. NOx is typically produced any time the air fuel ratio in the combustion chamber goes lean. This occurs most often during accelerations, where the air flow into the engine rises sharply, and the fuel system must react quickly to provide the matching fuel. For a modern petrol fuel injection system, this task is made easier with a combination of sensors tied into the fuel control system, which may detect the extra air intake directly, or indirectly through a throttle position change or speed density change. Once detected, the petrol fuel system also has an advantage over an aftermarket conversion in that it has been provided with the best position for fuel injection, at the inlet ports, whereas an alternate fuel conversion must typically inject fuel further upstream.

To minimize NOx emissions, especially when combined with Total Hydrocarbons as it is in Europe, it is important for the alternate fuel converter to carefully chose a conversion system which can react quickly to these accelerations, and maintain accurate fuel control throughout the emissions cycle.



GFI Control Systems Inc

SLD527

THE STRATEGY

VEHICLE CONVERSION STRATEGY
CNG Conversion System
• Gaseous Fuel Injection (GFI) System
• Commercially Available and Proven
• Electronically Controlled
• Single Point Fuel Injection
• Closed Loop Stoichiometric
• Interfaces with OEM Electronic I/O
• Provides Electronic Spark Advance and Dwell Control

GFI's business partners in Europe have chosen the GFI fuel system for several reasons. As an electronically controlled single point fuel injection system, GFI can make rapid adjustments to fuel delivery, and provides precise metering of fuel under all conditions. The GFI system interfaces with OEM electronic signals, allowing rapid detection of transients, and long term stability of air fuel ratio. In addition, GFI provides the ability to intercept and control spark advance and dwell, an important factor in successful European conversions.

VEHICLE CONVERSION STRATEGY
Diesel Conversions
• Converted to CNG by Modifying Engine
• Pistons Machined to Reduce CR to 12.3:1
• Injector Holes Drilled for Spark Plugs
• Valve and Valve Seats Replaced
• Ignition System Fitted
• Throttle Body Fitted
• GFI Fuel Injection System Fitted

As noted earlier, it is much more common in Europe to encounter medium to heavy duty truck fleet vehicles running diesel instead of petrol. This list shows the extra work involved in converting a Leyland DAF Roadrunner to CNG, as performed by British Gas for their UK market. As seen here, this effort is fairly significant, and fairly rare for North American converters given the common availability of large displacement gasoline powered engines here.

EMISSIONS CYCLE STRATEGY Calibration Tuning • Engine Mapping Allows Precise Fuel Control • Transport Delays Programmed • Lambda Targets and Biases Used For Optimization

For all engines, the critical step in providing a successful conversion, is the matching of the conversion system to the vehicle. The GFI system provides a full suite of calibration parameters which enable a qualified calibrator to map out the fuel demand of the engine over its entire range of loads and speeds. This allows precise fuel control over the full operating range of the vehicle. To provide the best overall fuel control, including THC minimization, the transport delays of the system are also measured and fine tuned. This provide the best transient control, especially important for the frequent stopping and starting experienced during a European emissions cycle. Two key transport periods measured are the fuel delivery time from injection point to intake, and the exhaust port to oxygen sensor feedback. For NOx control, it is important to maintain stoichiometric or slightly rich operation under accelerations. The GFI system provides lambda target tables and fueling biases to allow the system calibrator to enrich or reduce the amount of fuel under many different sets of conditions, including accelerations, cruises, and decelerations.

The best combination of rich, lean, and stoichiometric fueling is dependent on the base vehicle design, so no one strategy is best for all cases.

Once programmed, the GFI fuel system will provide repeatable and accurate fuel delivery, allowing the calibrator a greater degree of confidence that performance and emissions results will be consistent from test to test, over the life of the vehicle.

EMISSIONS CYCLE STRATEGY Calibration Tuning • Spark Timing Advanced • Selected for Best Catalyst Efficiency • Selected for Best Performance

A key feature of the GFI control system, unique for NGV conversion systems, is its programmable spark advance system. In North America, this feature is used most commonly to recover power lost by conversion to the less energy dense natural gas. Given the catalyst temperature problems encountered in the European emissions cycle, spark advance and even some spark retard, provides an additional strategy for conversion suppliers to meet their emissions challenge. By providing a limited degree of spark retard on start-up, it is possible to generate some additional exhaust heat to promote early catalyst light-off. This strategy is used sparingly, to avoid performance problems or wasted energy in the combustion process.

THE SCORE

GFI Control Systems Inc

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THE SCORE: VEHICLES
European Conversions

Italy	290 000
Germany	1 100
France	603
The Netherlands	600
Great Britain	370
Belgium	116
Sweden	108
Ireland	34
Austria	18
Spain	11
Denmark	9
Total	292 969

Approximate, As of August 1995

The conversion to natural gas is a difficult one, nonetheless, over a quarter of a million vehicles have been converted to this clean fuel. British Gas, working closely with GFI Control Systems, has successfully converted over 400 vehicles since 1991 in the UK. Given the challenges faced by European natural gas vehicle converters, these are impressive statistics.

THE SCORE: VEHICLES

- Both Petrol and Diesel Converted
- CNG a Commercially Viable Alternative
- Minimal Power Loss From Petrol
- Excellent Driveability
- Bi-Fuel Operation Maintained

Both petrol and diesel vehicles have been converted, proving that CNG is a commercially viable alternative to these fuels. Testing at the British Gas Research Centre has shown that power loss is minimized with conversions to Natural Gas using the GFI fuel control system. Driveability is maintained, as well as the vehicle's gradeability, or ability to restart on a hill, an important measure in the UK. In all cases of single point gaseous fuel injection, petrol operation is maintained with no impact on torque or power, a common demand by consumers of Natural gas powered vehicles.

7.5L Diesel Conversion Results

	Original Diesel	Gen 1 CNG Conversion	GFI CNG Conversion
Max Power (kW)	86	84	92
Max Torque (n.m)	370	371	427

NOx	11.64	11.69	2.75
CO	5.44	2.33	2.33
HC	1.75	1.63	1.84
Pm	0.42	0.05	n/a
CO2	762	713	484

Emissions measured over ECE49 (13 mode) test

Power and Torque corrected to ISO 1585

British Gas has also demonstrated their ability to successfully meet the challenge of converting diesel equipped vehicles. Using a generation 1 style system, power and torque were maintained at 86kw and 370 newton.metres respectively, while reductions in CO, particulate matter, and CO2 emissions were obtained. By implementing the more sophisticated strategies available with the GFI system, power was actually increased to 91 kw, and torque increased to 427 newton metres. Original CO reductions were maintained, while NOx was brought down by an impressive 76%. Additionally, CO2 emissions are 36% lower on the alternate fuel

European Emissions Summary

	THC+NOx Reduction	NOx Reduction	CO Reduction
1.4l Ford Escort Van	56%	85%	40%
2.3l Mercedes 210 Van	37%	63%	50%
1.3l Ford Escort Van	14%	33%	68%
2.0l Peugot Boxer	6%	25%	74%
2.2l Renault Trafic	0%	0%	0%

Values show percent reductions in emissions from CNG conversion as compared to petrol

Emissions measured over ECE+EUDC Cycle

In the case of petrol vehicle conversions, using GFI for natural gas fuel injection, British Gas has shown that the emissions challenge, which is very real in Europe, can be met by the right combination of skill and strategy. This chart not only shows that European emissions legislation can be met, but further reductions in emissions over petrol can be realized. Even the challenge of THC+NOx can be overcome on these commercial applications, without compromising Carbon monoxide emissions. Even with the Renault Trafic, which represents an optimized engine build for petrol can be successfully converted and the emissions held well below EU limits, within 0.01 grams per km of the original petrol emissions.

THE NEXT MATCH

THE NEXT MATCH
Leveling The Playing Field

- NEW VEHICLES
  - *Designed For CNG*
  - *Methane Tuned Catalysts*
  - *Appropriate Emissions Controls*
- NEW EMISSIONS CYCLE
- NEW EMISSIONS STANDARD
  - *Non-Methane Organic Gases*

In any fair contest, teams compete both at home and in "away" games. Gasoline has had a long standing "home team" advantage, with natural gas as the consistent "visiting team." The playing field; the vehicle, is designed for gasoline combustion, and reduction of gasoline combustion byproducts. Emissions cycles provide unique challenges for natural gas, and emissions standards weigh against the methane based gaseous fuel. Natural Gas can and does meet these challenges, but the next match may be played on a more level playing field. Vehicles can be optimized for natural gas combustion, using higher compression ratio engines, and emissions controls designed for the gaseous fuel. Use of methane tuned catalysts alone will significantly reduce the challenges faced by natural gas powered vehicles, allowing new demonstrations of the potential of this clean future fuel.

Figure 6: ULEV Results from Small Displacement Passenger Car

The possibilities have already been demonstrated by this small displacement vehicle manufacturer, using the GFI fuel system, and a natural gas friendly catalyst. The ultimate goal of Ultra Low Emissions is achieved here, with room to spare, on Natural Gas. The ULEV challenge, not enforced until 1997, and phased in over several years, can already be met with natural gas, on nothing more complicated than a level playing field.

Can the challenge be met? Yes! It is being met today, by strategists all over the world, using the fuel of the future, natural gas, and the GFI gaseous fuel injection system.

THE NEXT MATCH

GFI Control Systems Inc

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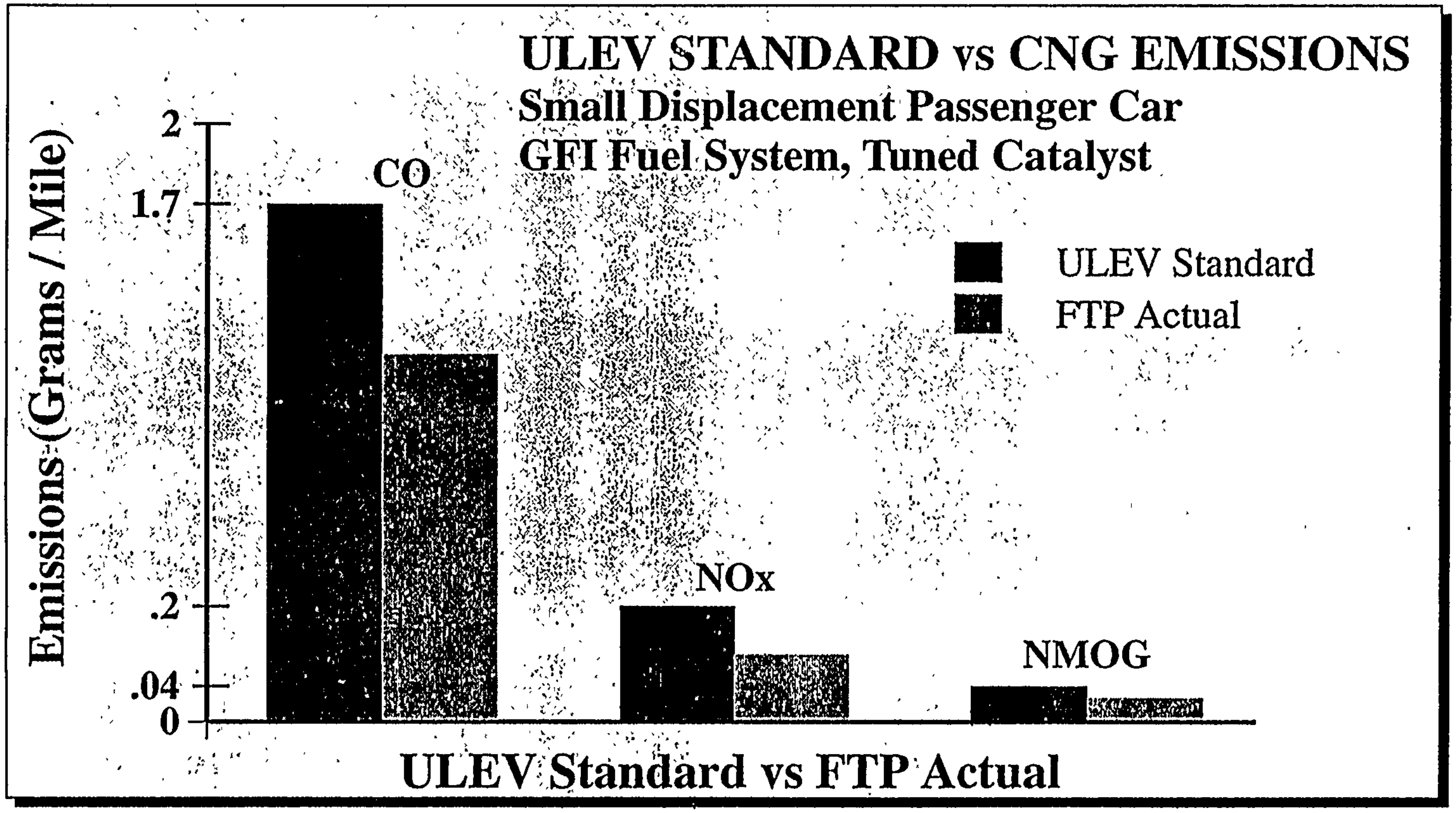
Meeting the European Emissions Challenge



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TNO-paper
VM9605

Stoichiometric and Lean Burn Heavy-Duty Gas Engines - A Dilemma between Exhaust Emissions and Fuel Consumption?

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Introduction

The main objective for today's engine development is to comply with the more and more stringent emission legislation. Already for a very long time, research has been carried out in the field of alternative fuels. Emission legislation is one of the main reasons for the fact that alternative fuel engines are a viable product on today's market. The technology is being developed reapidly to meet with the legislative measures for cities or the so-called *non-attainment areas.*

An engine and vehicle manufacturer has many options to consider when making clean engines (figure 1). Of course, the conventional diesel engine and clean exhaust gas technology (EGR. deNOx-catalysts) developed for this engine type will remain an interesting option for the future. Liquid alternative fuels (methanol, ethanol, etc.) have been tested and a number of demonstration projects all over the world have demonstrated that this could be a feasible option. Most of the current development work both in Europe and North-America, however, is directed towards the use of gaseous fuels (natural gas and propane/LPG). Furthermore, in Europe, an increasing number of Original Equipment Manufacturers of light-duty and heavy-duty engines are putting alternative fuelled engines on the market. Besides, although in a quite early stage, the rather new fuel DME looks, at least from a technical point of view, a promising alternative for diesel engines.

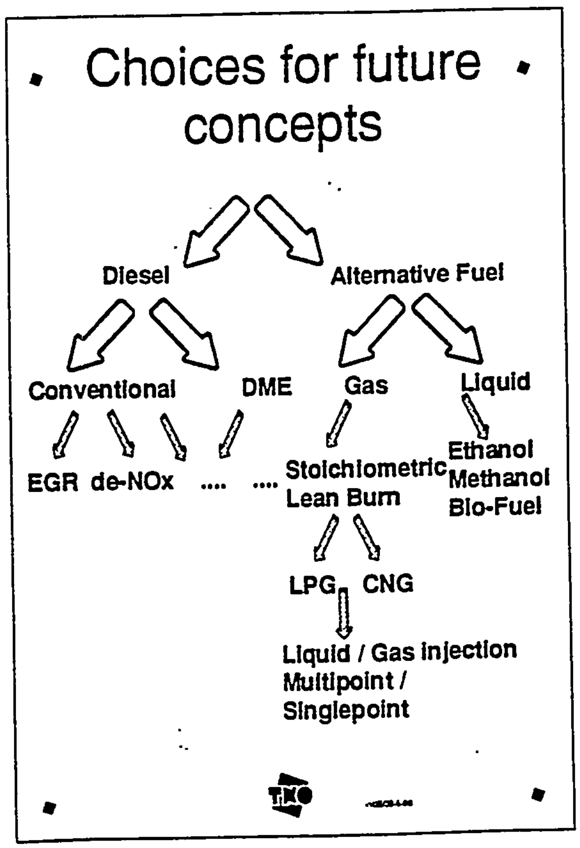

Figure 1

Gas engines can be divided into two major groups. One the one hand, OEMs direct their research into stoichiometric engine technology. The main reason for this is the extremely clean exhaust gases that can be achieved by using a closed-loop controlled three-way catalyst. On the other hand, engine manufacturers opt for lean burn technology, as these engines have a lower fuel consumption with respect to their $\lambda=1$ counterparts.

This paper compares stoichiometric with lean burn technology for heavy-duty gas engines (natural gas and LPG) and demonstrates that there is a future for both engine concepts on the multilateral global market. Emission limits in Europe as expected in the near future will facilitate both engine concepts. Which of the two concepts is the most viable depends on a number of factors.

Emission standards

Due to the introduction of the three-way catalyst the emission production of light-duty vehicles has been reduced considerably. The contribution of heavy-duty vehicles into the total emission production has, therefore, increased. This has resulted in considerable political pressure to reduce the pollution from these vehicles. Figure 2 shows, as an example, the situation in the Netherlands with respect to NO_x-productions. Without any measures the NO_x emission from heavy-duty vehicles would soon be extremely high. The legislator has imposed stringent emission limits for the coming years, mainly focused on the further reduction of NO_x and, to a lesser extent, of particulate matter (figure 3) [1]. Depending on the technology an engine has to be tested in the future according to a 13-mode like steady-state test or a transient test (EURO III). Gas engines will have to be tested according to a fully transient cycle (FIGE test) as well as the steady-state test.

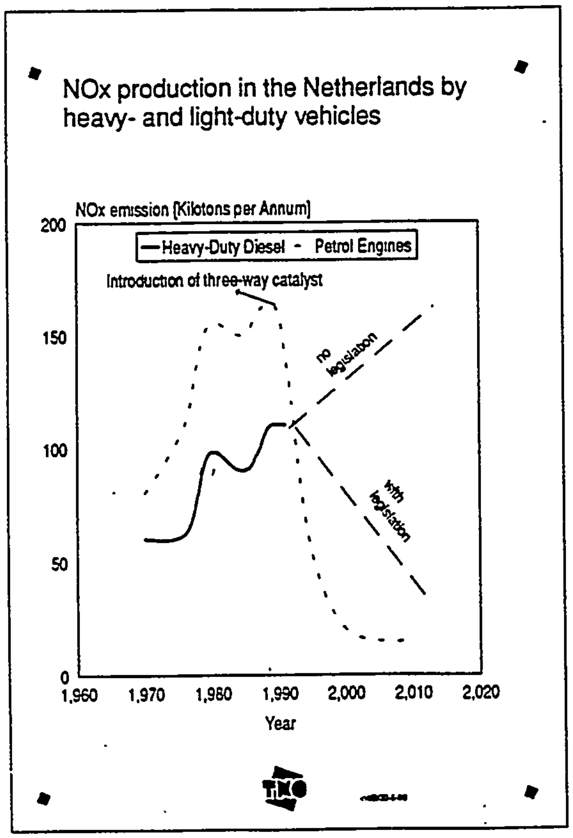

Figure 2

European Emission Limits in g/kWh

Heavy-Duty Engines
European 13-mode test

	EURO-I 1992	EURO-II 1995	EURO-III 1999	EURO-IV 2004
NOx	8	7	<5	<3
CO	4.5	4	2.5	1
HC	1.1	1.1	0.7	0.5
PM	0.36	0.15	<0.10	<0.10

Euro-III and Euro-IV: expected introduction date
Possible change in weighting factors and/or test procedure

Figure 3

Improvement of air quality is one of the major issues within the European Union (EU). The EU is convinced that a substantial improvement is only possible and economically feasible with clear and uniform measures throughout all its member states. This awareness has resulted in a cooperative study by the automobile industry (ACEA), the oil industry (Europia) and the EU-commission. A project was started to predict the air quality situation in urban agglomerations in the year 2010 under different scenarios. Preliminary results demonstrate that there are big differences in the reduction necessary for the different regions (cities) in Europe. In the different scenarios the influence of improved technology, different fuels and different composition of the vehicle fleets is simulated. In some cities the air quality required can never be achieved by technical measures alone, while in other cities this can be achieved by relatively simple measures [2].

In the Netherlands there is already a long history of alternative fuels. CNG but mainly LPG is a well accepted fuel. About 12% of all the kilometres driven in the Netherlands is on LPG. A study carried out by TNO has revealed that a proper fuel-mix (one-third diesel, one-third gasoline and one-third LPG) has overall the biggest positive effect on the regional and global environment [3]. The Dutch government has made clear its intention to reduce also the CO_2 emission. The objective is to reduce this greenhouse gas by 3% in the year 2000 with regard to the emission level of 1990. The Dutch Ministry of Environment has announced its policy to decrease the emission of CO_2 in different sectors (traffic, transport, industry etc.) by aiming at the use of 10% renewable energy and a 33% reduction in energy consumption in 2020 [4].

Equipped with the latest technology and properly adjusted, natural gas and LPG engines are able to produce very little emissions. In that respect, the stoichiometric engine with a three-way catalyst has the clear advantage over the lean burn engine. The latter, however, potentially has a better fuel consumption. The reason for buyers has mainly to do with these aspects. Although rather similar from the outside, there is a clear difference in the development efforts of both engines.

The above clearly shows that under these circumstances there will be a good potential for alternative fuelled vehicles. Many countries in Europe (the Netherlands, France, England, Germany etc.) have decided or are considering to stimulate the use of alternative fuels by adopting tax incentives.

Development targets

As already stated, the single most important issue is the emission legislation. In 1999 the EEV-emission limits will come into effect in Europe. EEV stands for Enhanced Emission Vehicles and the adopted limits concern heavy-duty city-vehicles. The EEV-limits are:

Component	Limit [g/kWh] ([g/bhph])
NOx	2.5 (1.87)
HC	0.6 (0.45)
NMHC	0.25 (0.19)

The EEV-emission limits still leave enough room for the lean burn heavy-duty gas engine to come onto the market. Moreover, it is possible that locally more stringent emission legislation will come into force, based on the best available technology (NO_x < 1g/kWh). Apart from this boundary condition, the ability of the engine to meet the emission legislation, there are other important factors which decide which engine type is the most viable.

In Europe, where some of the public transport companies are state-companies, the decision is sometimes made in favour of the stoichiometric engine for public image reasons. One of the motives for most of the European manufacturers to produce closed-loop three-way catalyst λ=1 engines.

First of all, the manufacturer will decide on the basis of production and development costs which engine type is the most attractive to produce and sell. As gas engines are still built in rather small volumes, the development costs play a considerable role in the sales price of an engine. Of course, as production volumes increase this factor will loose importance.

Apart from the above, at the end of the day the user of the engine (client) decides which engine is bought. The main motive for commercial users is without any doubt the costs in use. An urban transport company will never buy any vehicle running on alternative fuel that is economically less attractive than a vehicle with a conventional diesel engine with which it is very familiar. Factors that will influence the costs in use are for example the fuel price level, maintenance costs and taxes. Furthermore, investments that are necessary to run on alternative fuels (safety adaptations to garages, installation of filling stations) will influence the decision. Besides, there are less business economics related considerations. In North-America the decision is mostly made looking at the so-called *total package* and, therefore, most, if not all the engine manufacturers are producing and selling lean-burn engines.

In view of this equivocality it is worth looking at the technical aspects which determine the feasibility of both engine concepts.

Technical Aspects

Traditionally, a typical engine for a European city bus applications has a displacement of 10 to 12 litres and a power output of 160 to 200 kW, depending on the area of use. The current development trend is clearly towards smaller engines with a somewhat higher power output. The increase in specific power output will improve the part load efficiency, but has its consequences for engine development, as it will certainly increase the working temperature of the engine.

Emissions

As already stated the stoichiometric engine has a clear advantage with respect to the emission output. Figure 4 shows the comparison between the NO_x emission of a stoichiometric and a lean burn engine. With a suitable control strategy, which among others takes care of enough CO in the exhaust gas, the three-way catalyst is capable of reducing the NO_x-emission to less than 1 g/kWh. With increasing load the lean burn gas engine will produce more and more NO_x. In order to reduce the emission of nitrogen oxide the ignition timing has to be retarded. The effect of this retardation on efficiency is limited for, in this case, the 2.5 g/kWh NO_x-calibration. However, aiming for 1 g/kWh will have its effect on fuel consumption and, moreover, on the running stability of the engine, as the ignition timing has to be additionally retarded. It is important to emphasize that the 1 g/kWh NO_x limit is presently difficult to reach with a production engine.

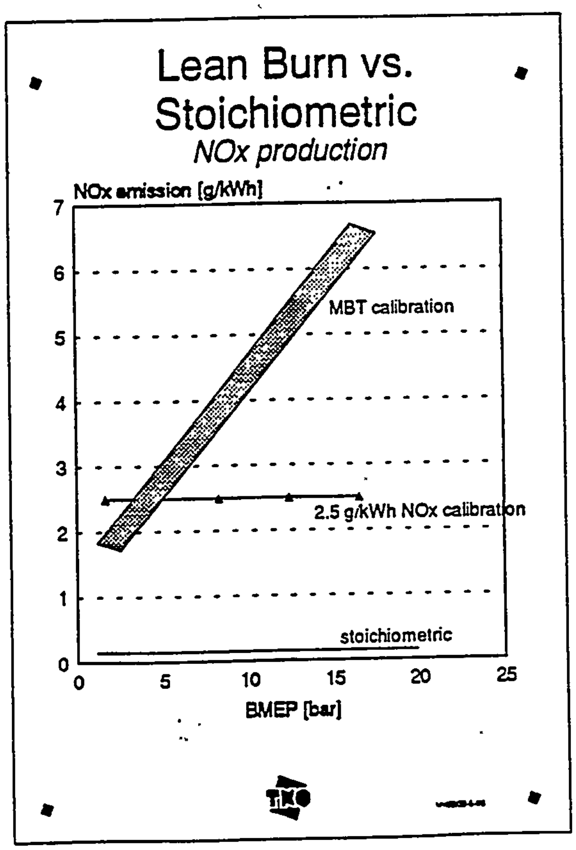

Figure 4

An other important emission component, perhaps more important than NO_x, is the hydrocarbon emission. The stoichiometric engine will reach the EEV emission values without too many problems. The lean burn version has considerably more difficulty to reach the 0.6 g/kWh HC (figure 5). Main issues are here the light-off temperature and the conversion efficiency of the inevitable oxidation catalyst. A great amount of research has been carried out to improve these two crucial characteristics of this type of catalyst. Current tests demonstrate conversion of 80..95% over the lifetime of the catalyst.

During the past years TNO have put a considerably amount of effort in combustion chamber research. A number of different combustion chamber configurations was tested. Figure 6 graphically demonstrates an example of test results with a compact and an open chamber. It turned out that very good results can be obtained with relatively combustion chamber configurations. A compact chamber, having a higher swirl ratio, has a more stable ignition behaviour. However, the open chamber has, at the same λ-value, a lower NO_x-emission. The choice of the swirl and squish ratio, the position of the spark plug etc. is crucial to obtain the best engine performance for lean burn engines. As can be seen in the same figure, the current ignition systems on the market limit the possibility to use compact combustion chambers.

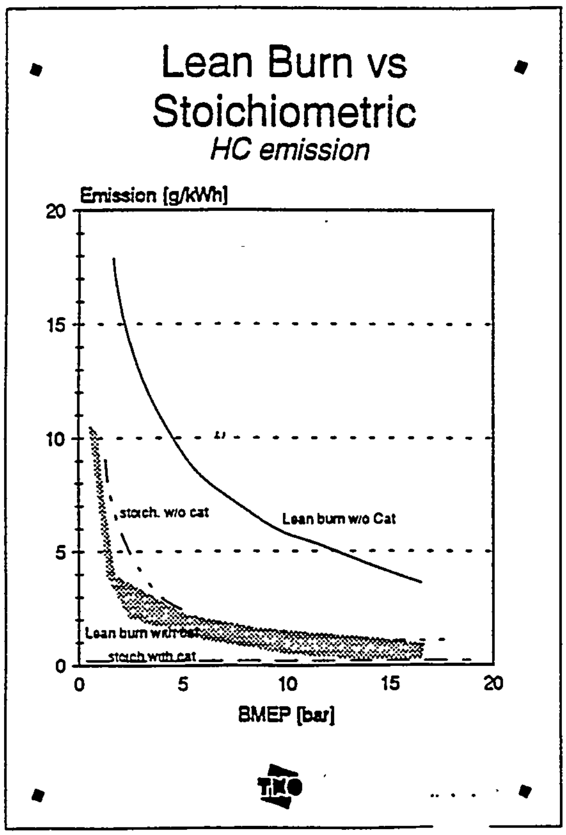

Figure 5

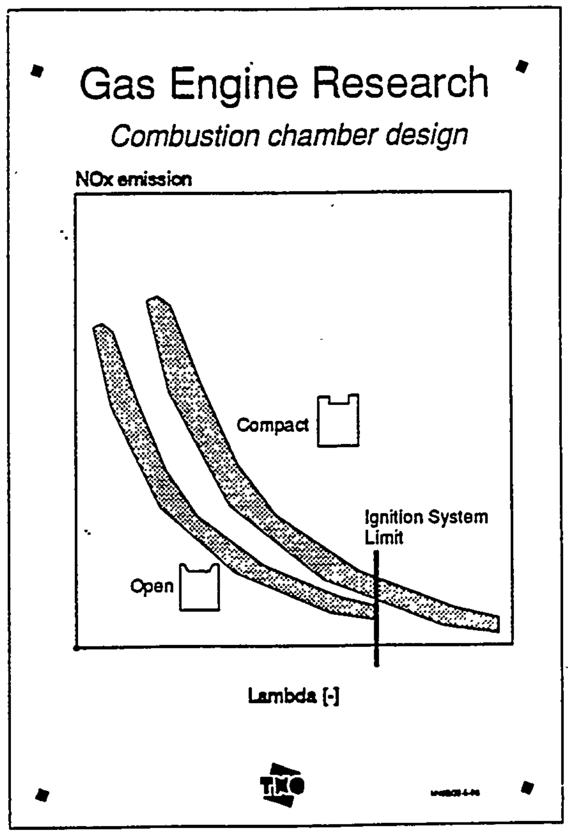

Figure 6

Ignition systems

The point raised in the previous paragraph, a suitable ignition system (including the spark plug), is currently a major concern for the effective development of lean burn gas engines. As the charge density in a lean burn engine is higher than in a stoichiometric engine, the voltage required is also considerably higher. Striving towards lower NO_x-emissions the λ-value will increase, too. Basically, the perfect ignition system would be one with the combined advantages of the different available ignition systems, i.e.: the quick rise-time of the capacitive system, the long spark duration of the inductive system and the very high energy of the plasma ignition system. Knowing, that during transients and due to wear of the spark plug the ignition voltage required becomes higher it will be clear that the development of a well performing lean burn gas engine for more and more stringent emission limits is an ordeal. Figure 7 shows the ignition voltage required at different engine loads for a stoichiometric engine, a lean burn engine with different λ-values, spark plugs and spark plug gaps, as well as the effect of transients, wear and fouling. Figure 8 schematically demonstrates the difficulty with spark plug gaps. At full engine load (high charge density and temperature) a small spark plug gap is required, whereas at idle speed (low charge density and temperature) a bigger spark plug gap is required. The figure shows the ignition capability of a spark plug with a certain spark plug gap.

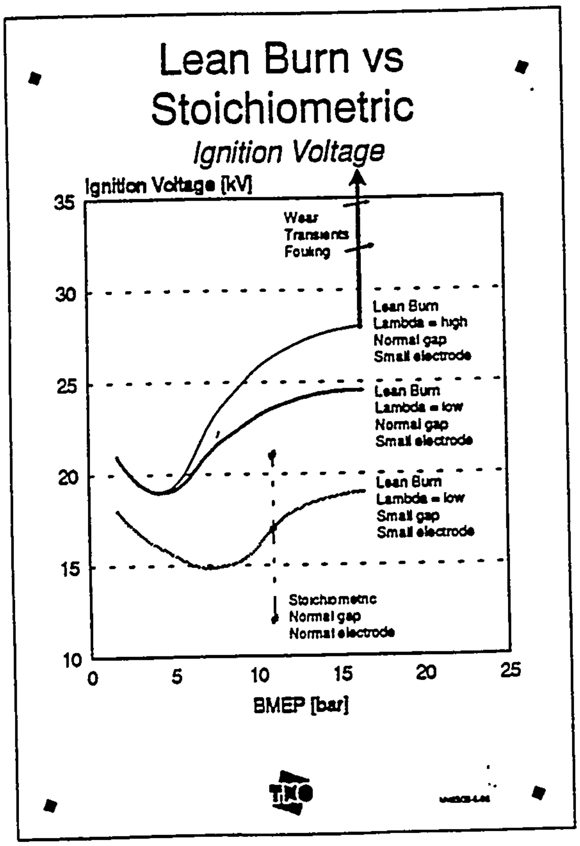

Figure 7

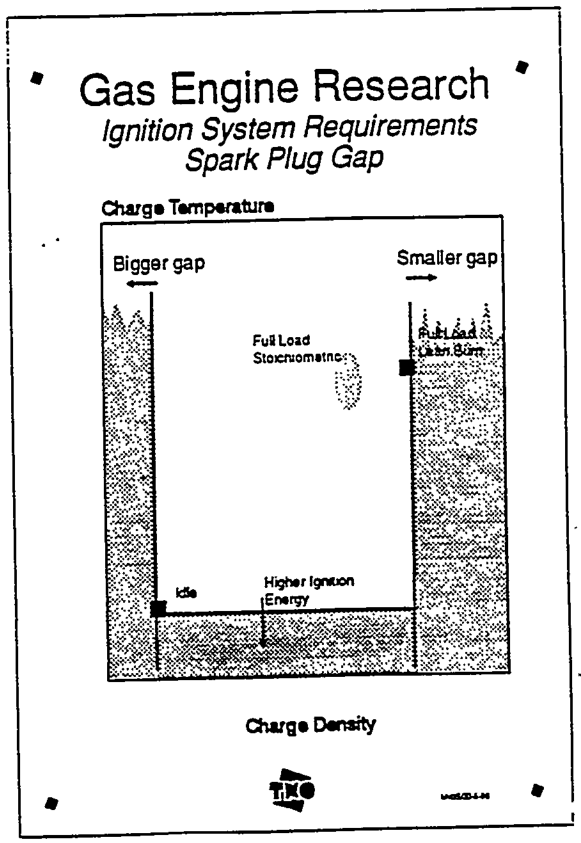

Figure 8

Mechanical and thermodynamical constraints and driveability
Due to the higher air-fuel ratio of the lean burn engine, the charge density of this engine is higher. This results in a higher in-cylinder maximum pressure. As current gas engines are more or less derived from a diesel engine this will normally not cause too many problems. Another effect of the higher air-fuel ratio is the higher boost pressures required. Firstly, this imposes certain properties to the turbocharger. Although these kind of boost pressures are almost the same as for the diesel engine, due to the fact that the gas engine is an otto engine the compressor map should be wider at those high pressures. Figure 9 shows an example of an application where the working line of the engine at full load is very close to the surge line and the choke line of the compressor. Secondly, a good driveability of the engine is more difficult to obtain. For the same transient response the time t_1 and t_2 (in figure 10) should be the same. Besides an appropriate control strategy in combination with drive-by-wire control, one could choose to use a turbocharger with a variable geometry for driveability reasons only.

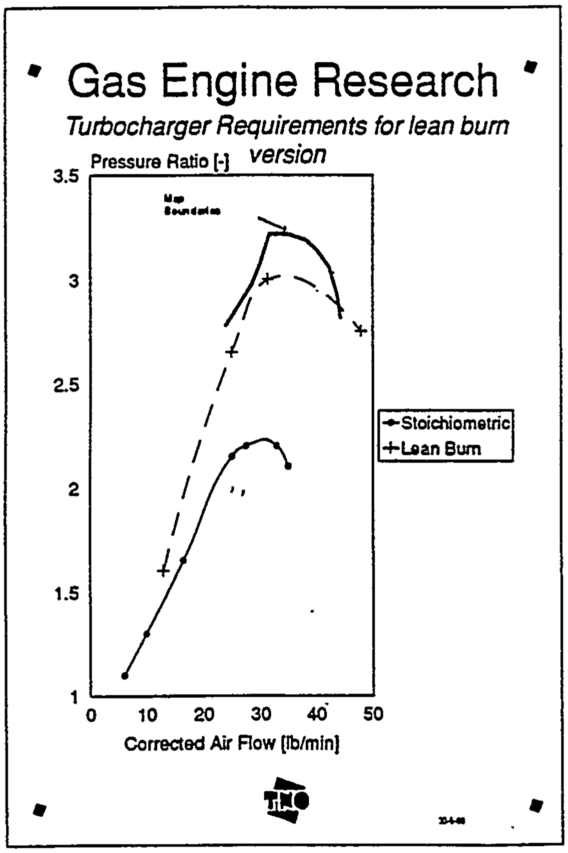

Figure 9

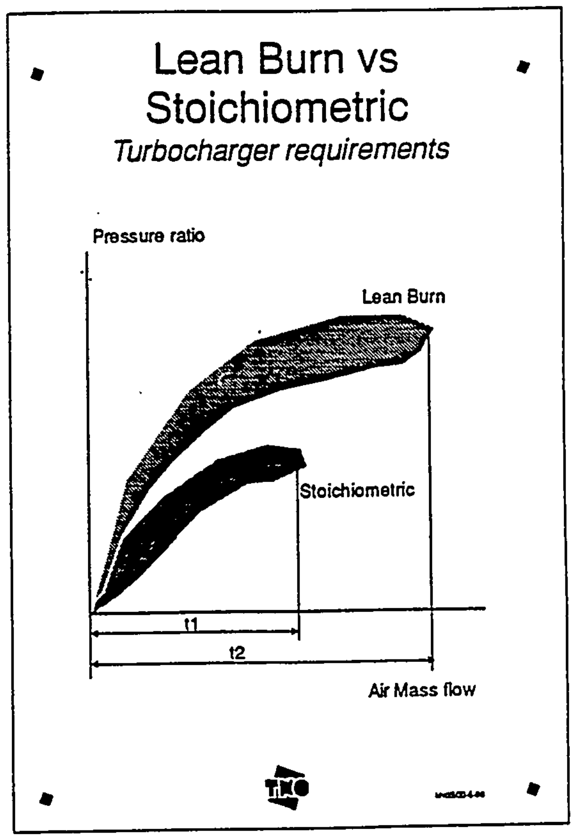

Figure 10

It is well known that the thermal loading of the stoichiometric engine is considerably higher than of the lean burn version. Figure 11 shows an example of pre-turbine exhaust temperatures measured on a number of engines running at maximum torque. It shows that the temperatures before the turbine are approximately 150 to 200 °C higher in the $\lambda=1$ engine. Temperatures at rated speed are even higher (50..100 °C). In the laboratory extreme values in the neighbourhood of 1100 °C were recorded. One of the options to reduce the temperature in the stoichiometric engine is the use of EGR (Exhaust Gas Recirculation). Tests were carried out to demonstrate the possibility to reducing the thermal loading of the engine by using EGR. Figure 12 shows the effectiviness of EGR compared with the lean burn engine. It turns out that by using 25% EGR the temperature can be reduced by 80..120 °C. The lean burn engine, however, running with an air excess of about 60% is much more effective in reducing the exhaust gas termperature (approximately 250 °C). Besides, using the recirculated exhaust gas to reduce the overall engine temperature, it is also very effective to reduce the NO_x emission. Research has demonstrated that 25% EGR can reduce the NO_x emission by 80% (figure 13) without penalizing the HC emission too severely. Further research has to prove whether a stoichiometric engine with an EGR system and a suitable EGR strategy could be able to reach future emission limits with only an oxidation catalyst, instead of a more expensive three-way catalyst.

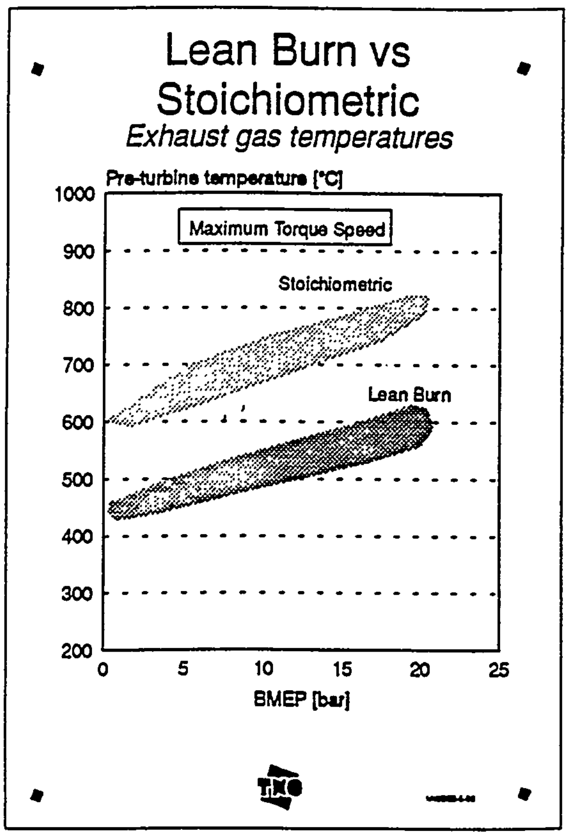

Figure 11

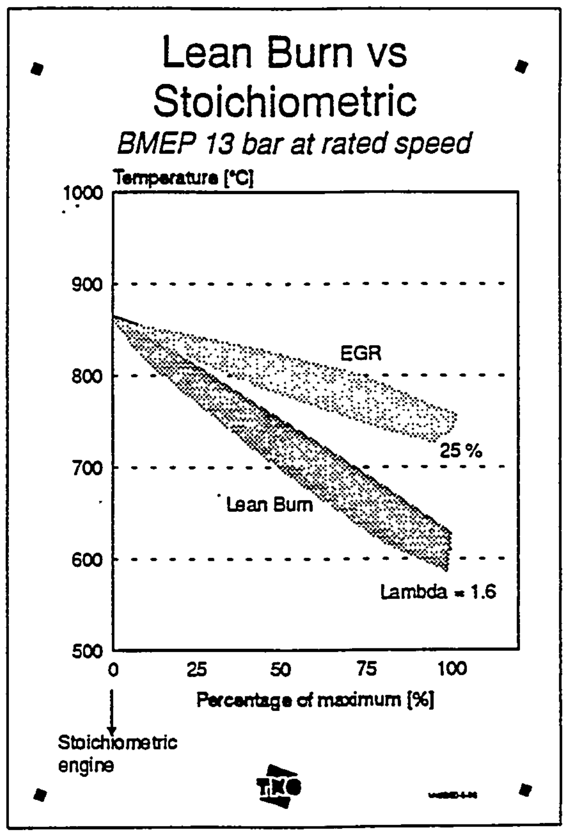

Figure 12

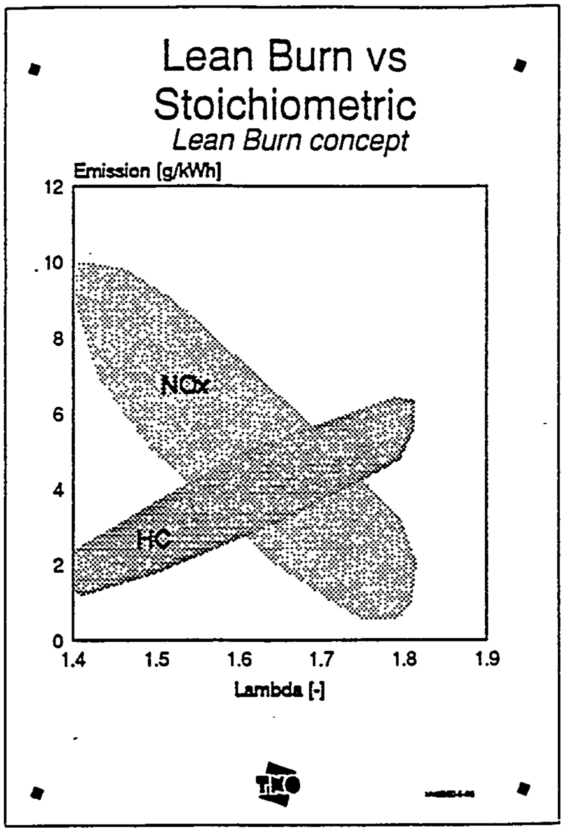

Figure 13 a

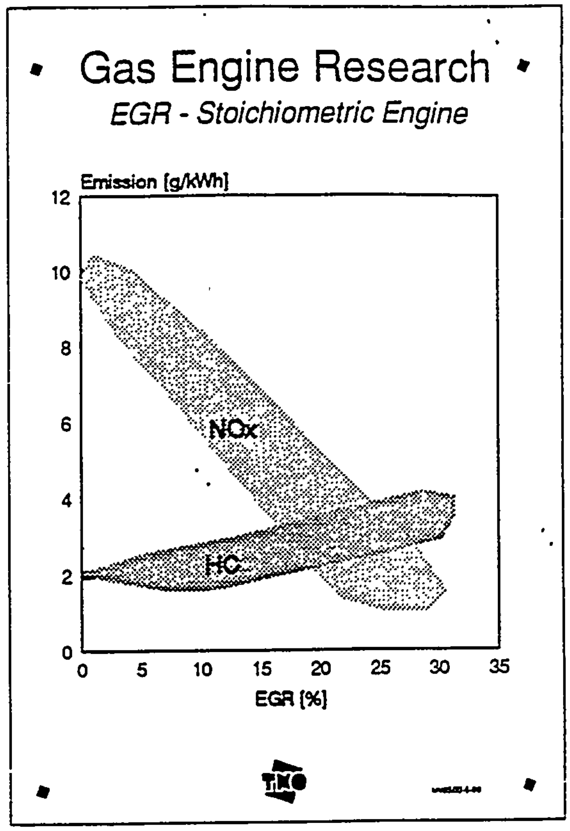

Figure 13 b

Considerations and Conclusion

It is clear that there are many issues to consider while making the decision for lean burn or λ=1 engine development. This paper demonstrates that technical feasibility is not the main item: both engine type can be made to comply with the current emission legislation and the emission legislation of the near future. The EEV standards currently under discussion allows lean burn engines to be developed. Only if exhaust emission values of less than 1 g/kWh NO_x are required the stoichiometric engine with a three-way closed loop controlled catalyst will be necessary. The lean burn engine has still a considerable advantage from the total efficiency point of view. Stoichiometric engines in practice still show an up to 30% higher energy consumption than their diesel twins. Although the lean burn engine has a clear efficiency advantage, from the driveability point of view the stoichiometric engine has it easier. The latter's higher temperature level of the combustion and of the exhaust gases is the reason that a more expensive catalyst or an EGR system has to be used, as well as other cost increasing equipment like a knock detection system and/or water-cooled turbine housings etc. On the other hand, the lean burn engine needs a more advanced ignition system and with its higher boost pressures a bigger (more expensive) turbocharger (if not a variable geometry turbocharger and a drive-by-wire control system).

No doubt, research to be carried out in the coming years will improve fuel consumption of the stoichiometric engine and emission performance of the lean burn engine. In the end, development and production costs and the costs of the engine in practice will determine the most viable engine concept. Costs in use depends of course, on the one hand, from durability and reliability of the engine (maintenance costs), but on the other hand from a favourable pricing of the fuel and concerned taxes. The industry, research companies and government have to work closely together in order to prove the technical feasibility of the use of alternative energy sources in the field and to take care of the economical application of the technology in the market.

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Paper Presented at the Windsor Workshop on Alternative Fuels , Toronto, June 1996

A Low Pressure Natural Gas Vehicle Storage System

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C. Komodromos British Gas plc.
D.F. Quinn Royal Military College of Canada
S. Ragan Sutcliffe Speakman Carbons Ltd.

Abstract

A complete low pressure natural gas adsorbent storage system is described. This work was carried out by the Atlanta Gas Light Adsorbent Research Group, (AGLARG), and co-funded by the US Department of Energy.

The objective of the project was to install in a vehicle an adsorbent storage system capable of delivering 150 V/V from a fill pressure of 3.5 MPa (500 psi) at ambient temperature.

Three breakthroughs with this system are reported. First, a carbon adsorbent in a form capable of storing greater than 170 V/V was developed and produced. Secondly, a new design of flat tank to contain the adsorbent has been made. This has two principal advantages, it allows for more acceptable installation in the vehicle than cylindrical vessels and it greatly improves the adsorptive heat problem. Thirdly, a guard bed system has been used which prevents storage capacity loss due to non-methane components in the natural gas being irreversibly adsorbed on the carbon adsorbent.

This system has been installed in both a van and a light truck where pressure, temperature, flow and demand can be remotely measured in real time.

Introduction

Natural gas has become entrenched as an alternate vehicular fuel, particularly in countries where gasoline prices are high. Emission control legislation in other countries may also encourage further use of natural gas as a fuel. Currently Argentina leads with about 340,000 vehicles and there are about one million operating worldwide,(1).

As a fuel, natural gas ranks as one of the best, with its clean burning and low emission characteristics, but it suffers from a major drawback, it is difficult to store. Presently, it is predominantly stored as compressed natural gas, (CNG), at pressures about 20 MPa, (3000 psi) and even higher pressures have been suggested. Only, perhaps, a thousand vehicles are operated using liquefied natural gas, (LNG), this being limited mainly to heavy duty vehicles operating nearly continuously, twenty-four hours a day.

An alternative to these storage methods is an adsorbent storage system, usually referred to as adsorbed natural gas, (ANG). Here the natural gas is adsorbed by a porous material where the storage density of the adsorbed methane is greater than that of the gas phase at the same pressure. This provides an enhancement in the storage capacity.

To be a commercially viable system, it is generally considered that a delivered gas volume at STP, 150 times greater than the storage volume, 150 V/V, is necessary. This can be achieved relatively easily using existing carbon adsorbents by either cooling the adsorbent below ambient or by using fill pressures in excess of 7 MPa, (1000 psi). However, cooling cannot be considered practical and the use of pressures greater than 7 MPa creates similar problems to those of CNG.

Recognizing this, the US DoE co-funded a research program by a consortium of oil and gas utility companies and a carbon manufacturer, collectively known as AGLARG, (Atlanta Gas Light

Adsorbent Research Group). The target of this research program was to produce an ANG system capable of delivering 150 V/V from a fill pressure of 3.5 MPa, (500 psi), at 298K. This was considered to be a demanding but possibly achievable goal. However, this storage capacity was not the only objective of the program. The system as a package was to use advantageously the attractive properties of ANG while at the same time addressing some of the problems known to exist with ANG storage.

The Storage System

Gains in gas storage density by adsorption occur at pressures less than 10 MPa, (1500 psi), but if simplicity and ease of use is considered, then the pressure should be limited to that achievable by using only single stage compression, less than 5 MPa. This pressure is about gas trunk line pressure and so in some places recompression could be avoided. However, the de facto value, somewhat arbitrarily chosen, has been 3.5 to 4 MPa. Thus an adsorbent material, with properties which optimize storage capacity at this pressure, had to be developed. Secondly, design of a storage vessel for this material had to be undertaken.

This relatively low pressure does not mandate the use of cylindrical shaped vessels, and so other shapes for the storage vessel could be considered. With limited available space, an alternative to a large gas cylinder appears attractive.

Earlier work on ANG storage has shown that the storage capacity gradually reduces with repeated refueling. For a successful ANG storage system, this problem has to be overcome, and so the AGLARG group examined the use of a guard bed to protect the adsorbent from the undesirable higher hydrocarbons, minor components of natural gas, which are mainly responsible for this reduction.

The complete storage system therefore comprised of a new type of carbon adsorbent maximizing storage density, a new design of storage vessel taking advantage of the relatively low pressure and a guard bed to ensure no reduction in storage capacity on repeated refueling.

The Adsorbent

Presently, carbon adsorbents would appear to be the best for natural gas. What kind of carbon is required to achieve 150 V/V delivered ?

For delivery of 150 V/V, it will be necessary to store about 175 V/V since some methane remains adsorbed at less than 0.1 MPa, (1 Bar). This is equivalent to 117 grams gas per liter of storage volume.

Since adsorption only takes place in micropores, pores of less than 2 nm, the micropore volume of the adsorbent should be maximized.

Parallel slit pore models suggest that a maximum density of 170 g methane per liter of micropore occurs in pores of 0.78 nm width, (two methane molecules wide), at 298K and 3.5 MPa,(2).

To store 117 grams, 0.69 liters of ideal micropore, (0.78 nm width), will be needed.
Only 0.31 liters per liter of storage volume will remain for the skeletal carbon atoms.

Using a graphite density of 2.2 g/mL, 0.31 liters of carbon atoms will weigh 690 grams.

So, 690 g carbon with 690 mLs of ideal micropore per liter of storage volume will be necessary to achieve 150 V/V delivered. (Carbon density 0.69g/mL, 1.0 mL micropore per gram.)

The next questions then become, "How do we make a carbon with these properties ?" , and, "How do we know how close we have come to this ideal structure ?"

The direct measurement of storage capacity by packing a vessel with adsorbent and measuring methane delivery, is not always practical when creating adsorbent carbons. Often only a few grams of carbon are made. Characterization measurements on these materials can be carried out and methane isotherms measured using less than one gram quantities. However, no reliable method for obtaining a pore size distribution, (PSD), of these carbons is available. Using the methane isotherm at 298K, a new method was developed for the assessment of PSD,(3). This provides a "picture" of any prepared carbon, which enables us to see how close the prepared carbon is to the "ideal" structure. Any change in preparation conditions can be monitored against any change in the PSD. Figure 1 shows the 298K methane isotherms for two carbons prepared in the same way but at different temperatures and Figure 2 shows how this change in preparation conditions altered the PSD of the carbon adsorbents,(4). The carbon used in this present study had a pore volume of 1.30 ml/g, 37% of which was in the ideal pore size region.

The Storage Vessel

With adsorbent storage, large diameter cylindrical tanks are not necessary and indeed are undesirable. They are difficult to pack the carbon into, and are not efficient in removing heat from the carbon during filling, (adsorption), or supplying heat during fuel use, (desorption). In practice a 25 - 30 cm diameter densely packed, carbon filled vessel can take many hours to return to an equilibrium state after one fill-empty cycle.

Cylindrical tanks are also space intrusive, in that, nearly always, they are placed in areas which otherwise would be used for passengers or baggage. Also, the space occupied by these is, in reality, greater than their simple geometric volume.

The design of an ANG tank should therefore consider several factors.

It should

(a) take advantage of the lower pressure used in ANG
(b) minimize heat effects
(c) be easy to fill with adsorbent
(d) be space efficient and easier to locate into the vehicle
(e) be relatively light in weight
(f) be easy to manufacture
(g) must be safe and certifiable as a pressure vessel

Figure 3 shows the design chosen for this study. The twenty-two cell aluminum single step extrusion with welded end caps incorporates all of the above criteria in its design. Its low flat profile offers a great deal of flexibility for incorporation into any vehicle, and it can be of any length without requiring any redesign or retooling. The profile and interior web aids greatly in the heat management during filling and emptying. It is relatively lightweight, although this is fully offset by the weight of the carbon adsorbent. These vessels were designed to meet the British Standard , BS5500 safety code using extensive finite element analysis. A program of pressure fill-empty cycle testing on sample tanks was carried out to establish fatigue life and safety factors. After 380,000 cycles from 0.5 to 4.5 MPa, a pinhole leak developed at a weld. A sample tank split close to a weld at 21.5 MPa, (3200 psi), during a burst test, giving a factor of safety of at least five . An adsorbent filled vessel will not immediately depressurize on rupture. Rather, there will be a relatively slow loss of pressure as the adsorbed methane desorbs over a few seconds. Further slowing the evolution of gas from the adsorbent is the considerable cooling associated with rapid desorption.

For test purposes, both on the vehicle and also on a stationary fill-empty cyclic test-bed, tanks were filled with granular carbon and with monolithic blocks. Presently extruded carbon pieces are being prepared and will be tested in the near future.

The Guard Bed

The problem of deterioration of storage capacity using adsorbents is largely due to the cumulative adsorption of the higher hydrocarbons, C5 and above, which are present in small amounts in natural gas. These are continually adsorbed by the highly microporous carbon adsorbent, but because of their higher adsorption potential, unlike methane, are not desorbed during fuel use. Thus they gradually fill micropores which otherwise would be available to methane. Other components in natural gas, such as nitrogen, carbon dioxide or the lighter hydrocarbons, C2 - C4, are desorbed as the pressure is reduced. Table 1 shows a typical natural gas composition and the potential for uptake of each of the components. Possible odorants are also included in this table. It is clear that the only odorant likely to be retained by the storage carbon would be diethyl sulfide. Other odorants would odorize the complete system but would be desorbed as the tank is emptied.

For rapid filling of a storage tank, the gas flow rate through an adsorbent guard bed is very high, making the capture of small amounts of C5+ hydrocarbons difficult. Thus a narrow micropore carbon structure somewhat similar to the storage carbon structure is favored. However, since facile desorption of C5+ hydrocarbons from the guard bed carbon is required to prevent retention, a carbon with a more open pore structure is desirable. Evaporative loss control devices, (ELCD's), used for the control of gasoline emissions, use an upper micro, lower mesopore type of carbon. This type of carbon appears to be suitable for use in the guard bed.

Presently, a three liter cylindrical shaped guard bed packed with granular carbon is being tested. The guard bed is placed in line just in front of the main storage tank. On filling the storage tank, gas must pass through the guard bed, where the C5+ hydrocarbons are adsorbed, before entering the main storage tank. The guard bed has built in electric heaters. During fuel use, (desorption), these heaters are switched on and gas from the storage vessel again passes through the guard bed. The C5+ hydrocarbons are desorbed from the heated granular carbon in the guard bed and swept along in the gas stream for consumption in the engine.

Results and Conclusions

Small scale experiments, with vessels of less than one liter, gave deliveries in excess of 150 V/V using packed granular carbon. However, difficulty was encountered in packing the granular carbon into the full size tank to a sufficiently high density to obtain a delivery of 150 V/V.

This same carbon was then briquetted as shaped monoliths to fit the cell dimensions, avoiding wasted void space. In its briquetted form, the carbon had a higher density than the packed granular material, and in this form has been consistently delivering in the low 140 V/V on both the stationary test bed and on the vehicles. The tests, to date, indicate that the guard bed is doing its job and that no deterioration in storage capacity has been observed.

The tank design has given flexibility for fitting within the frame of a Dodge "B" van. In the past few weeks, four tanks have been fitted to a Dodge Dakota truck bed, a protective false bed has been placed on top of the tanks raising the bed by about five inches.

The goal of delivering 150 V/V has not been met to date using a flat tank, but 94% of this goal has been achieved. It is felt that over the next few months, briquettes of higher density will be produced so that this 150 V/V delivered target can be met. Extrusion forming, which is just underway, could also help in reaching this goal.

It is important to bear in mind that this study was undertaken as a "proof of concept". The tank design is sound but will no doubt be further refined. The guard bed is effective. The carbon used for this study is only a development carbon. It is not yet available for commercial application and a further objective is to be able to commercially produce a carbon with these properties at a competative price.

Acknowledgment

AGLARG wishes to thank the US Department of Energy for co-funding this study. DFQ thanks AGLARG for their continued support for carbon research.

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Figure 1

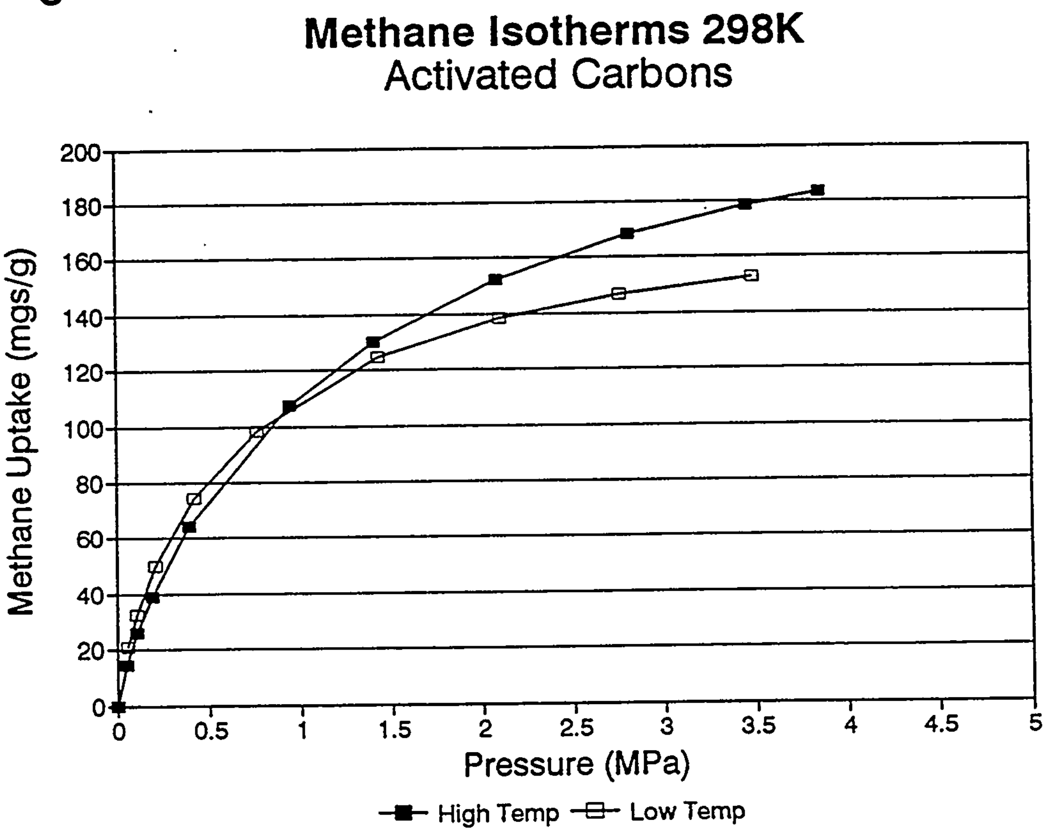

Methane Isotherms 298K
Activated Carbons
Methane Uptake (mgs/g)
200
180
160
140
120
100
80
60
40
20
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Pressure (MPa)
High Temp
Low Temp

Figure 2

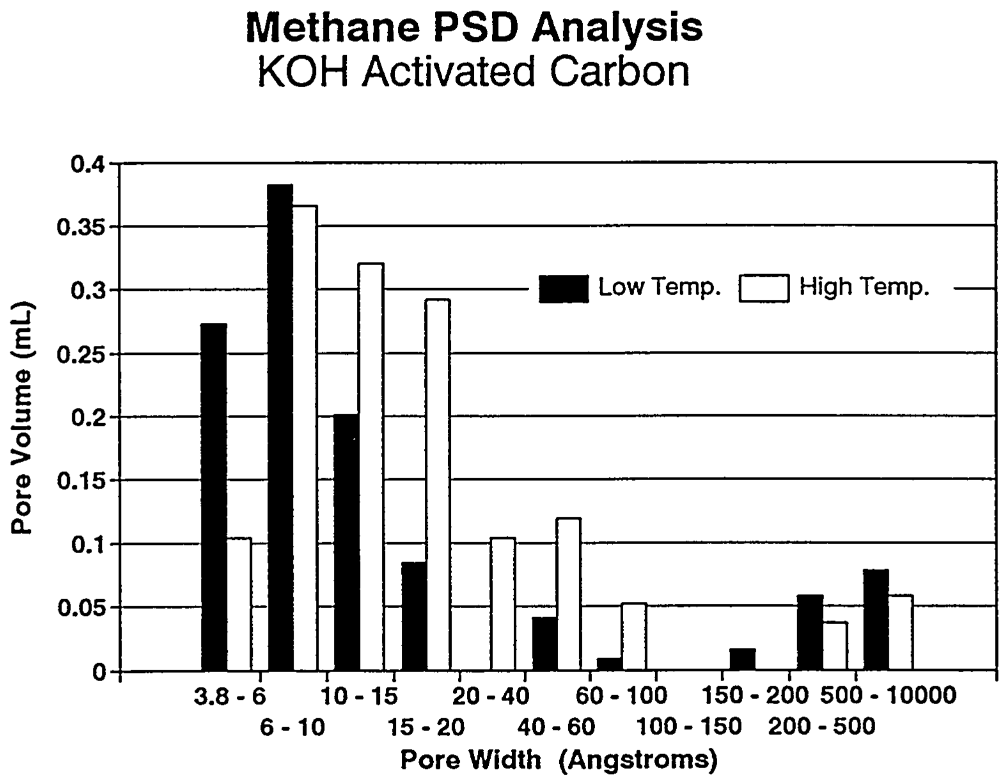

Methane PSD Analysis
KOH Activated Carbon
Low Temp.
High Temp.
Pore Volume (mL)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
3.8 - 6
6 - 10
10 - 15
15 - 20
20 - 40
40 - 60
60 - 100
100 - 150
150 - 200
200 - 500
500 - 10000
Pore Width (Angstroms)

Figure 3

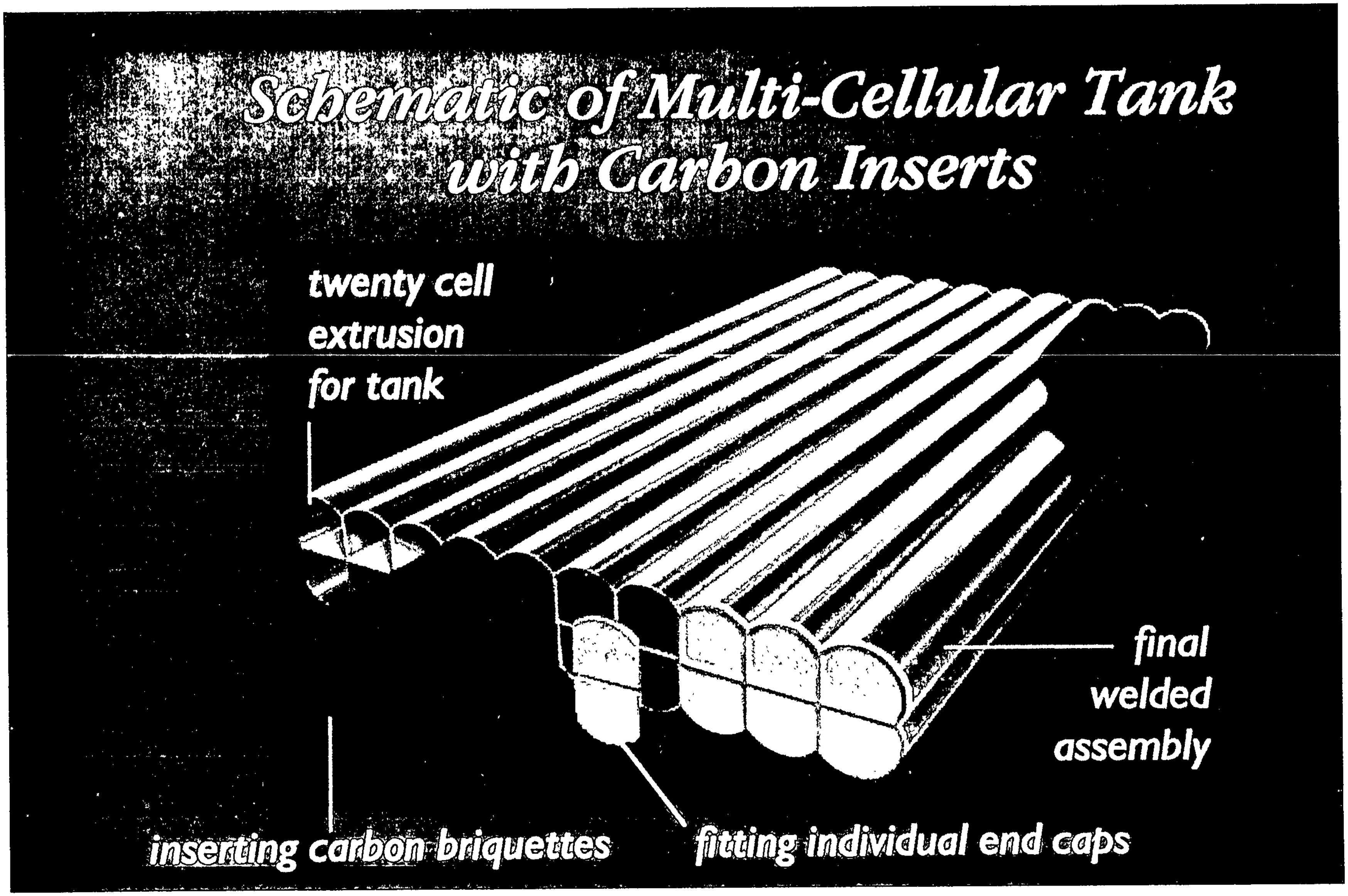

Schematic of Multi-Cellular Tank
with Carbon Inserts
twenty cell
extrusion
for tank
final
welded
assembly
inserting carbon briquettes
fitting individual end caps

TABLE 1
Typical Composition of Natural Gas (Bacton Terminal)

Component	Concentration vol.%	Relative Pressure	Potential Uptake g/g
Carbon dioxide	0.25		
Nitrogen	3.17		
Hydrocarbons			
Methane	92.81		
Ethane	2.84	7.320E-04	
Propane	0.58	2.350E-04	0.019
Butane	0.20	9.480E-04	0.068
Pentane	0.067	1.370E-03	0.127
Hexane	0.032	2.240E-03	0.176
Heptane	0.017	3.970E-03	0.232
Octane	0.007	4.800E-03	0.259
Nonane	0.001	2.220E-03	0.262
Benzene	0.022	2.960E-03	0.127

Odorants			
Diethyl sulfide	7.00E-04	1.160E-04	0.143
Methyl ethyl sulfide	6.00E-05	4.260E-06	0.029
Ethyl mercaptan	6.00E-05	1.180E-06	8.600E-04
Tert. butyl mercaptan	1.20E-04	8.500E-06	0.079

DETROIT DIESEL SERIES 50 PROPANE DEMONSTRATION PROJECT

James A.Gray

Detroit Diesel Corporation

(Presentation unavailable at time of publication)

SESSION 4

PROPANE

Chair: **Bob Larsen, Argonne National Laboratory**

PROPANE (LPG) VEHICLE TECHNOLOGY - PRESENT & FUTURE

Shawn Yates
Propane (LPG) Program Coordinator
Chrysler Canada Ltd.

1996 Windsor Workshop on Alternative Fuels
Toronto Colony Hotel
Toronto, Ontario
June 4, 1996

SLIDE 1: INTRODUCTION LABEL

Good morning. My name is Shawn Yates and I work in the Product Development & Engineering Group at Chrysler Canada. I would like to thank the organizers of this propane session for allowing me to be here with you. This presentation is a brief overview of two main areas of propane or LPG vehicle technology; fuel metering and fuel storage; from both a traditional and future technology perspective.

SLIDE 2: PROPANE CHARACTERISTICS

Propane, as a member of the hydrocarbon family, can exist as either a liquid or a vapour, depending on the pressure or temperature surrounding it. Propane is usually stored and transported as a liquid under pressure. Under atmospheric pressure conditions, propane vaporizes becoming a gas at -44°F.

SLIDE 3: GASEOUS FUEL METERING #1

Almost all presently available propane fuel systems meter fuel in the gaseous state. The majority of these systems operate at low fuel delivery pressures but the emergence of higher pressure gaseous metering systems has begun. Shown in this slide is a traditional gaseous metering system. Whether it is low pressure or high pressure metering, liquid propane is first delivered from a fuel tank by natural flow to a fuel shut off device. The liquid propane then flows through a regulator or vaporizer, to reduce the fuel pressure and vaporize the propane by allowing the propane to absorb heat from its surrounding area. If there is not enough heat available to satisfy the vaporization requirements, some propane will not change state and could enter the metering system as a liquid and cause engine flooding. In a more traditional gaseous fuel metering approach, propane is then delivered to the engine in a gaseous state at low pressure, through venturi or air valve mixers mounted above the throttle blades. In the venturi system, properly sized metering jets and openings at the throat area of the venturi nozzle are used to control the flow of fuel in response to the differential pressure signal created in proportion to the air flow. The air valve system uses a fuel metering valve that opens in proportion to the intake air flow. For a given air flow, the air-fuel ratio is primarily controlled by the contour of the metering valve. Systems like this are normally designed to operate at very low fuel delivery pressures which considerably extends their low temperature capability compared to other systems. These low pressure systems have also been in existence for many years, but without the use of electronic control systems to improve the accuracy of fuel metering characteristics, fuel economy and performance can be sacrificed.

SLIDE 4: GASEOUS FUEL METERING #2

Design activity aimed at producing higher pressure gaseous propane fuel systems have begun. The benefits of high pressure metering are largely based on the improved control possible with a high speed solenoid valve or fuel injector and the associated control electronics. Fuel injector response would have to be fast enough to give predictable flow characteristics down to millisecond pulsewidths and opening and closing rates, in order to ensure adequate performance at high engine speeds. Also, the required increase in operating pressure to the injectors, may seriously affect the low temperature (below 32°F) operating capability of the system. This would not be as much of a problem in the southern United States as it would in Canada. Other factors such as injector lack of lubricity, durability and noise characteristics would have to be assessed to ensure the fuel system performance would be unaffected.

SLIDE 5: LIQUID FUEL METERING #1

The primary incentive for attempting to produce a liquid propane fuel metering system, is associated with the power benefit derived from the cooling effect of vaporizing liquid fuel in the intake air stream. Another incentive is the potential enhancement of cold start ability of propane vehicles at temperatures approaching -20°F. The higher charge density and the resulting power increase creates the potential to operate a standard gasoline engine, without a loss in power. Electronic control and a pressure sensor are essential to provide optimum mixtures to the engine with liquid fuel metering. Single-Point Metering or Throttle Body Metering usually meter fuel with an intermittent opening and closing of a calibrated orifice above the throttle blades. Operation of the control system would be quite similar to that of present gasoline electronic control systems which are usually engine mapped based systems, with manifold vacuum and engine speed as the primary factors used to determine the fuel requirements. Feedback control would be essential to provide the required mixture consistency and accuracy to compensate for component variations or wear.

SLIDE 6: LIQUID FUEL METERING #2

Multi-Point liquid fuel metering systems offer the same advantages as single-point fuel metering and feature a few unique advantages of their own. Improved cylinder-to-cylinder fuel distribution is possible with multi-point systems. Engine packaging requirements, closely resembling gasoline fuel metering systems, are also an advantage of multi-point liquid fuel metering systems.

The most obvious problem associated with liquid propane metering is the fuel's tendency to change state as a result of an increase in the local temperature anywhere in the fuel lines, or at the fuel injectors. The only way to avoid this problem is to ensure that the fuel is metered as saturated liquid by using a pump to boost the delivery pressure beyond the fuel's accompanying boiling point. This system would basically require a fuel pump in place of a vaporizer in the gaseous fuel metering systems.

SLIDE 7: TRADITIONAL PROPANE FUEL STORAGE

All current motor fuel tanks are designed and manufactured to standards set by the ASME code and usually involve cylindrical steel construction or a combination of cylindrical steel construction. The fuel tank on a propane vehicle has a system of valves and safety features to fill the tank, remove fuel from the tank for delivery to the engine, measure how much fuel is in the tank, and relieve the tank should the pressure increase excessively. The problem with the traditional fuel storage is to optimize capacity using cylindrical shapes in a rectangular envelope that is usually allocated for gasoline fuel storage.

SLIDE 8: GASOLINE FUEL STORAGE

Gasoline fuel storage systems of today usually utilize light weight "blow molded" plastic technology to optimize fuel capacity within a given envelope. The fuel tank attaching methods used on gasoline fuel tanks are very "simple"; straps are usually used to hold the tanks in place. As well, gasoline fuel storage systems must meet the corrosion, environmental resistance and safety standards as specified by federal regulations. Corrosion and environmental resistance, durability, and weight, become main issues with traditional propane fuel tanks, especially when they are mounted external to the vehicles structure.

SLIDE 9: CONFORMABLE PROPANE FUEL STORAGE

Design activity aimed at the development of "conformable" propane fuel storage systems has begun. As discussed earlier, weight reductions, improved materials selection, capacity increases and corrosion and environmental resistance benefits are potentially available with conformable designs. Plastic or composite propane fuel storage systems, that further resemble gasoline fuel storage systems, are still a few years away.

SLIDE 10: PROPANE VEHICLE CHALLENGE

As you have just heard, advanced propane vehicle technologies have emerged this past week, as thirteen colleges and universities from across North America competed in the 1996 Propane Vehicle Challenge.

SLIDE 11: PROPANE VEHICLE CHALLENGE #2

Gasoline powered 1996 NS Chrysler Minivans were modified, totally at the discretion of the school, to operate on dedicated propane fuel systems. Almost all of the technology I have discussed was displayed at the Challenge, even with the time constraints imposed on the schools. Gaseous carburetion and high pressure metering was used by many schools. Liquid fuel injection technology was also displayed at the competition, but there are still many areas of improvement available for next year.

SLIDE 12: PROPANE VEHICLE CHALLENGE #3

Maybe next year we will see more advanced fuel storage systems, but I am sure we will experience closer resembling gasoline equivalent vehicles. Students, your experiences and efforts have been so valuable in preparing you for "real world" problem assessments.

SLIDE 13: CONCLUSION

Whenever new technology is discussed it should be kept in perspective. The cost of a propane fuel system is a big factor to fleet customers analyzing their potential payback. Emission performance is also a big factor to fleets, as they are becoming more regulated. Gasoline vehicle technology is improving every model year and propane vehicles have a lot of catching up to do. The competition to propane is not other alternative fuels like CNG, but it is gasoline. Without the advancement of propane vehicle technology, the industry will lag behind gasoline and any "perceived advantages" of propane over gasoline will simply not be true.

I think this years' Propane Vehicle Challenge has gone a long way to advance propane vehicle technology and keep the propane minivans rolling down in Texas next year.

Thanks for your attention, good luck to the schools and participants in this years' Challenge and thanks again for the opportunity of being here today.

Injected Heavy Duty Propane Engine

1996 Windsor Workshop on Alternative Fuels

G. Campbell Perry, Bibi Ursu	BC Research Inc.
Tony Filetti	Mogas Sales Inc.
Doug Yip	Digicon Engineering

BCRI

Introduction

- **Project Objectives**
- **Project Team**
- **Technical Approach**

BCRI

Project Objectives

- To Develop and Demonstrate Low Emissions Truck Engine
- Use a Spark Ignition Cummins C8.3 Engine
- Phase 1: Engine Development
- Phase 2: Vehicle Demonstration

BCRI

Project Team

- BCRI
- Mogas
- Digicon Engineering
- Cummins Engine Company
- ICG Propane
- Inland Kenworth/Paccar

Technical Approach

- Spark Ignition Version of C8.3 Engine
- Lean Mixture Operation
- Liquid Propane Injection

BCRI

Engine Description

- Cummins C8.3
- 6 Cylinder In-Line
- Turbocharged-Aftercooled
- 8.3 L Displacement
- Diesel Power Ratings
  157-224 kW (210-300 HP)

BCRI

Lean Mixture Operation

- Reduction of NOx Emissions
- Simplified Emissions Control
- Reduced Thermal Stress on Engine

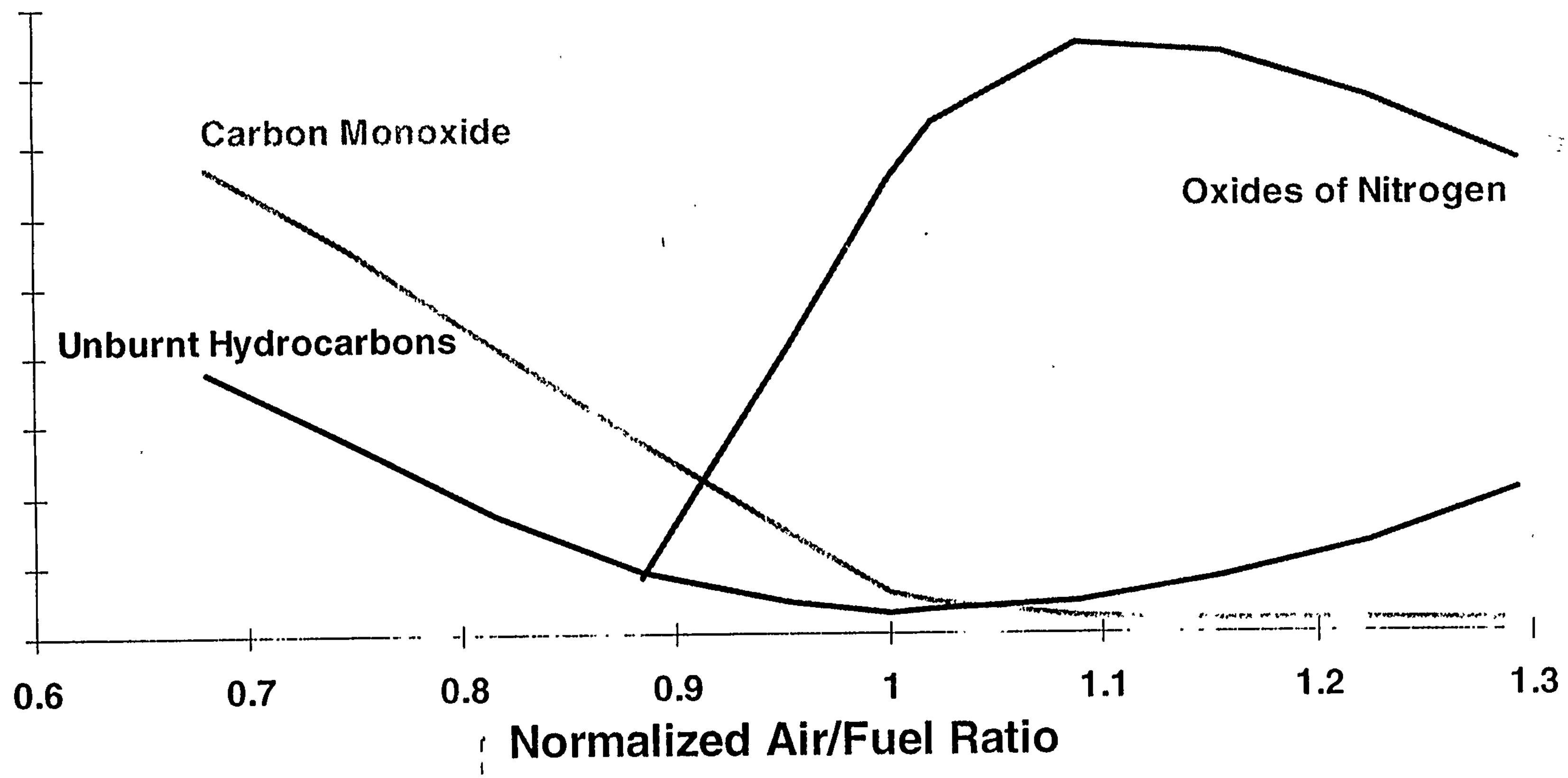
BCRI

Lean Mixture Operation

- Reduction of NOx Emissions
- Simplified Emissions Control
- Reduced Thermal Stress on Engine

BCRI

Emissions vs Normalized Air/Fuel Ratio



BCRI

Liquid Propane Injection

- Consistent Fuel Properties
- Reduced Cold Start Difficulties
- Additional Charge Cooling
- Good Mixing

BCRI

Engine Modifications

- Spark Ignition Head
- Pistons with Special Combustion Chamber
- Throttle Body
- Turbocharger
- Ignition System

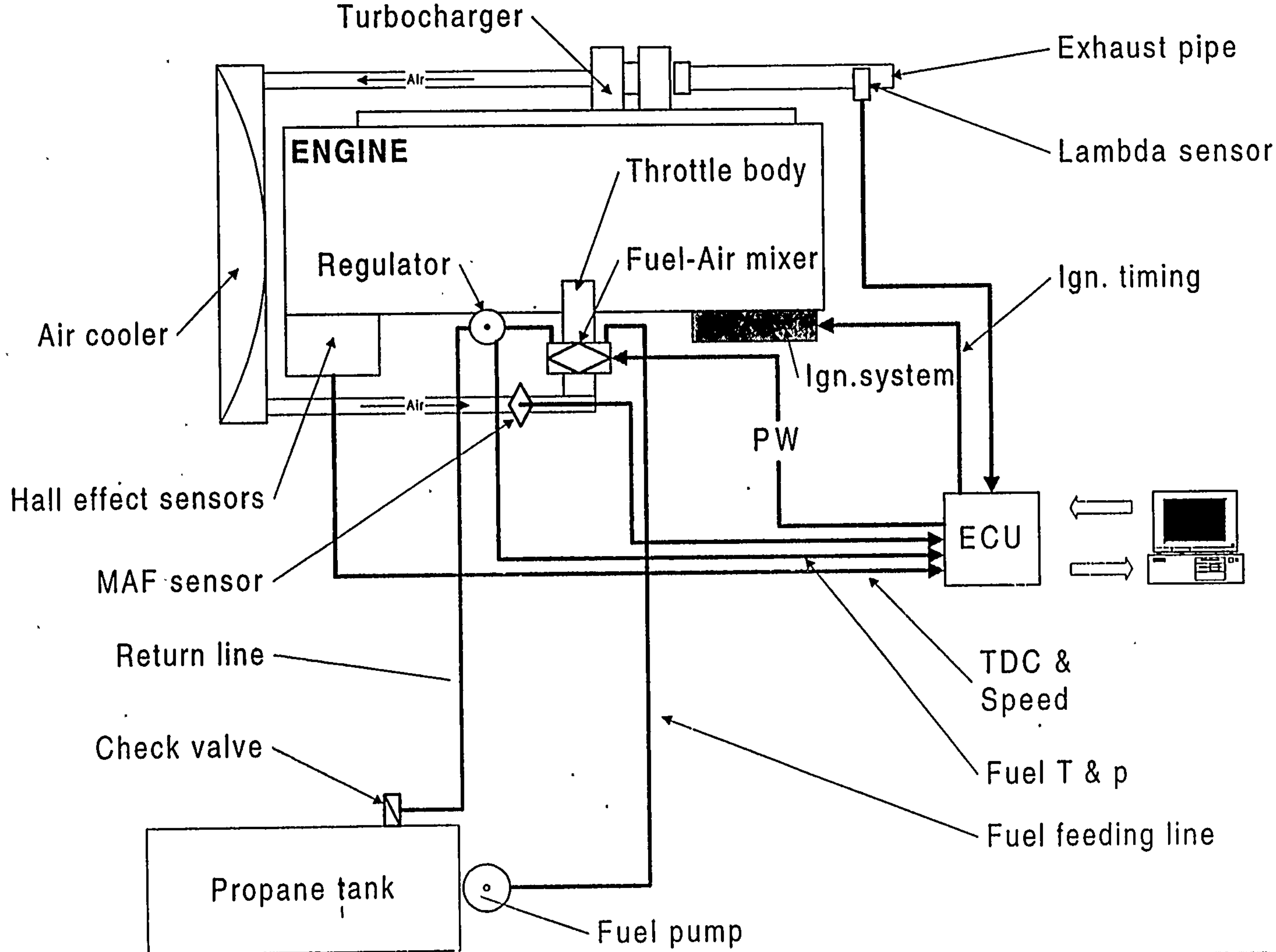
BCRI

Conversion System

- Microprocessor Controlled
- Feedback with Lambda Sensor
- Electronic Injectors Designed for Liquid Propane
- Single Point Injection

BCRI

Fuel System Schematic



BCRI

Fuel System

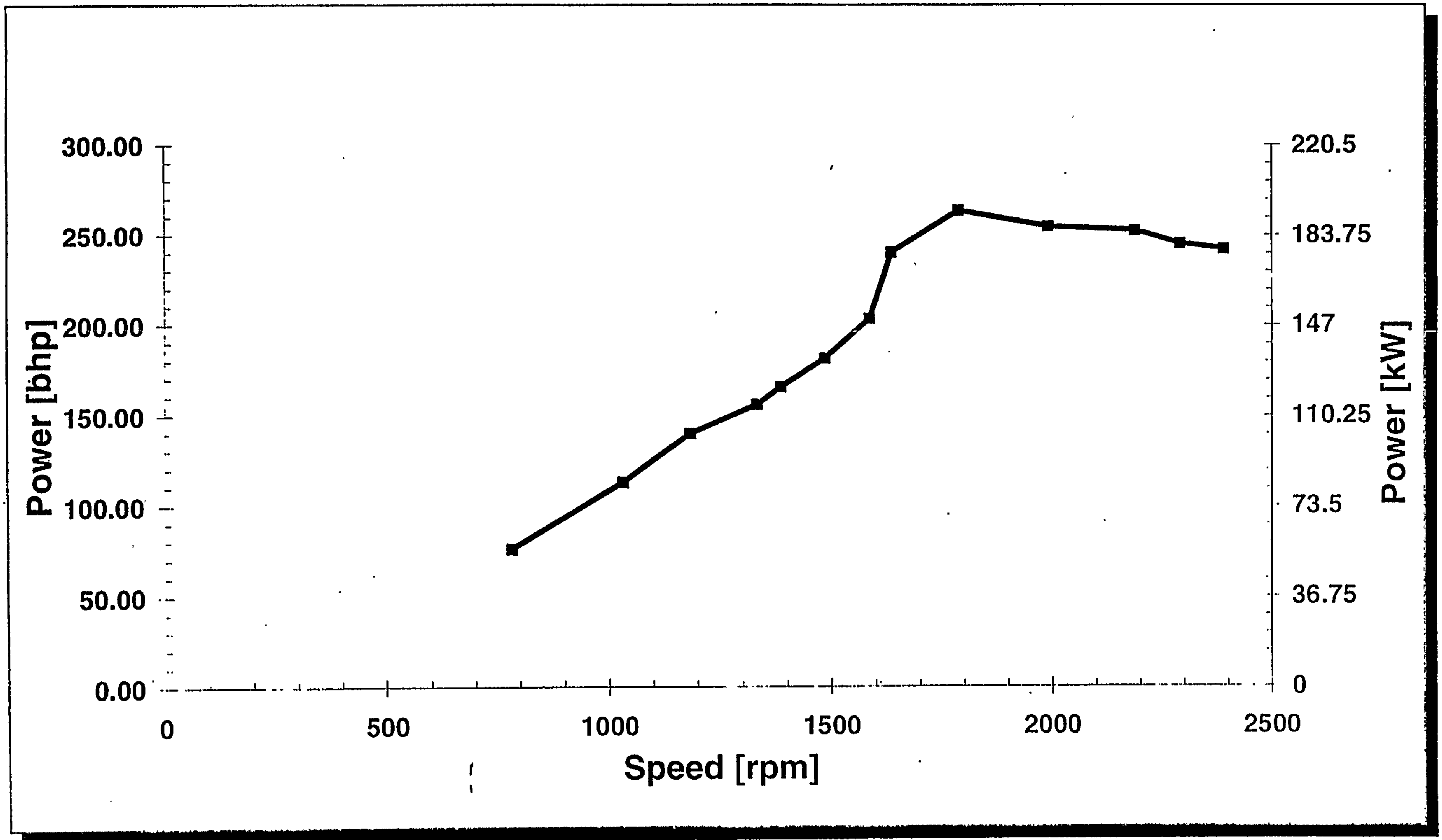
- Liquid Propane
- Siemens Injectors
- Electric Pump
- Single Point Injection

Ignition System

- Timing and Dwell Controlled by ECU
- Hall Effect Triggering
- Single Spark

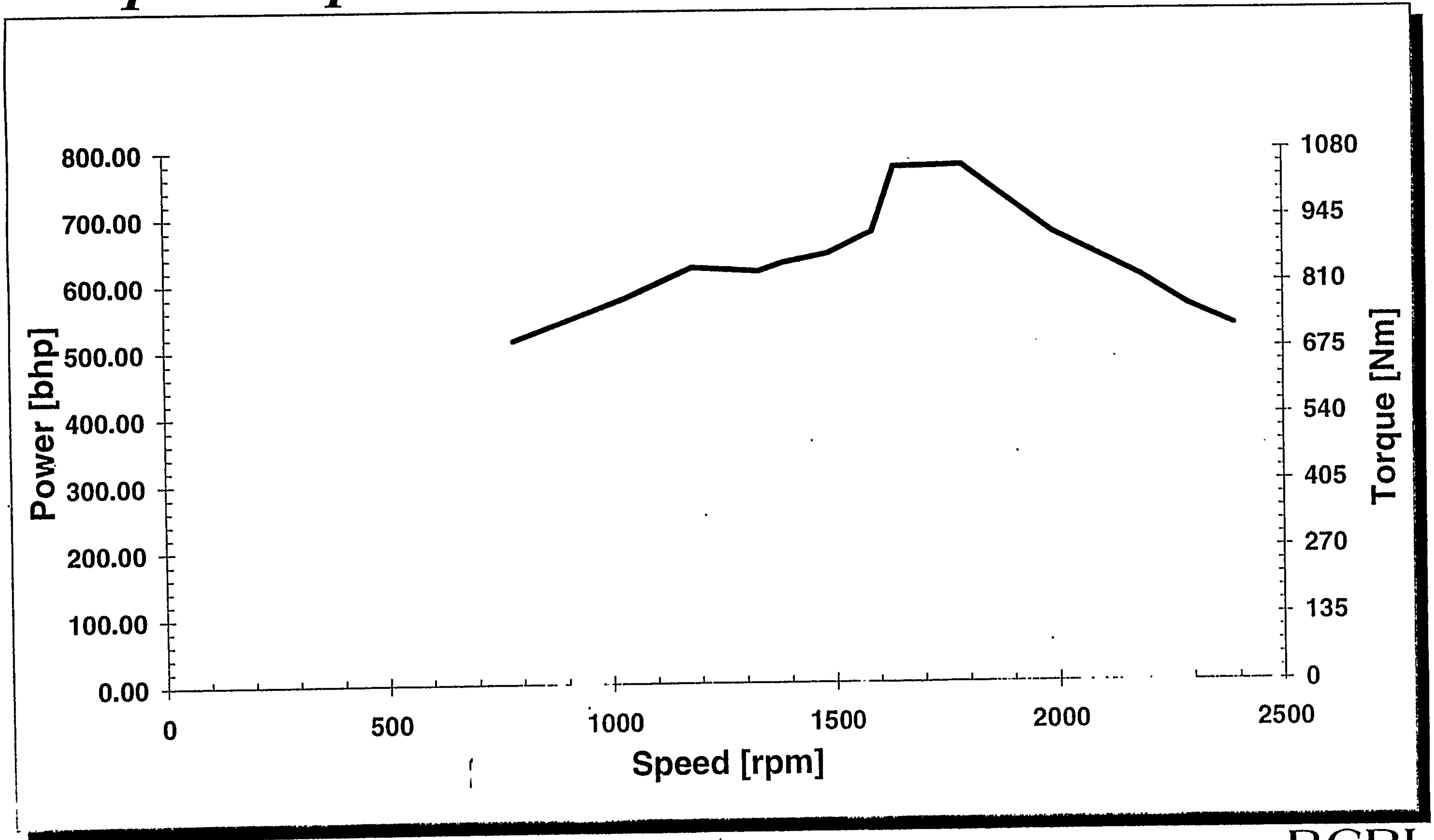
BCRI

Power vs Speed



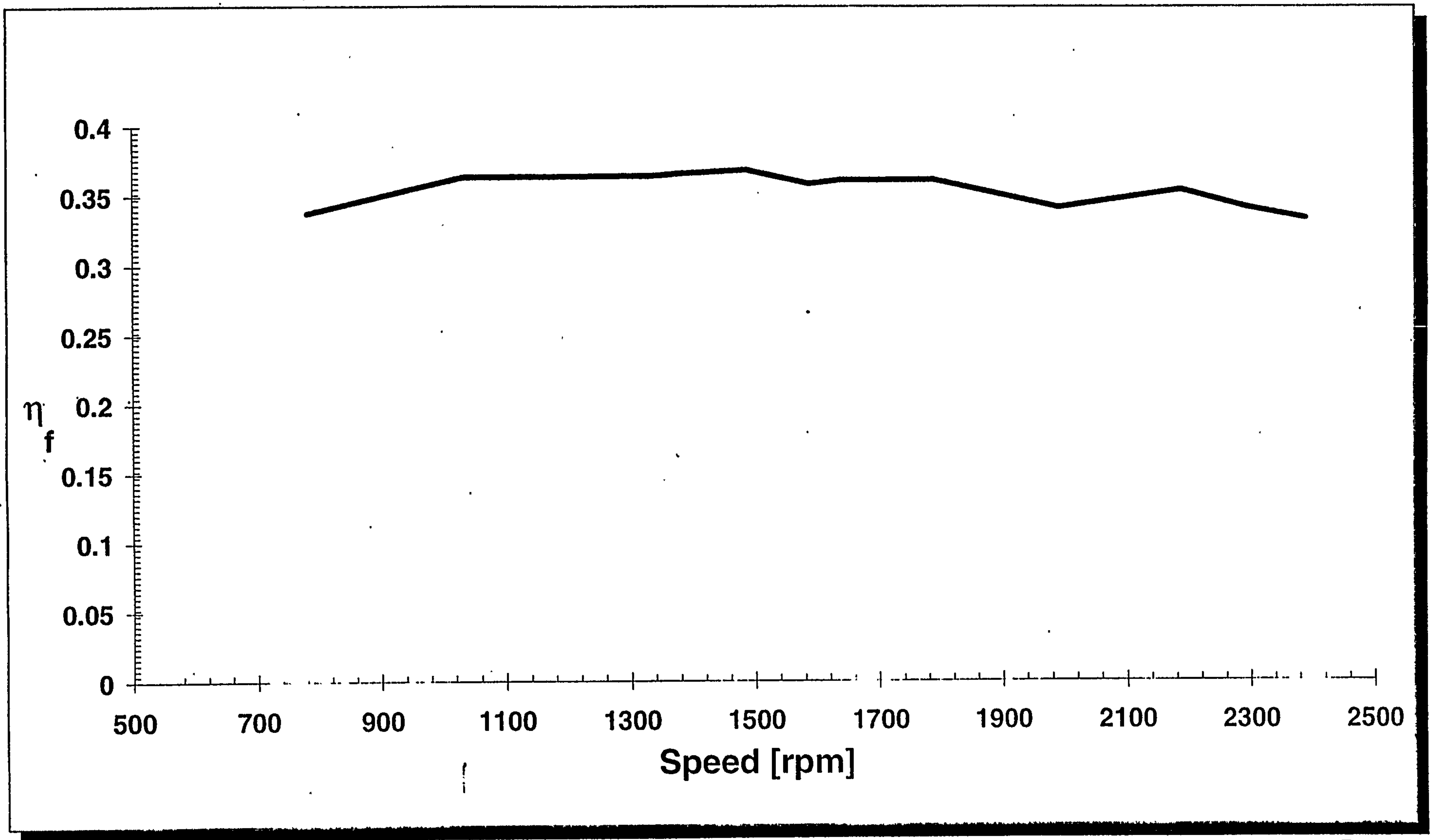
BCRI

Torque vs Speed



BCRI

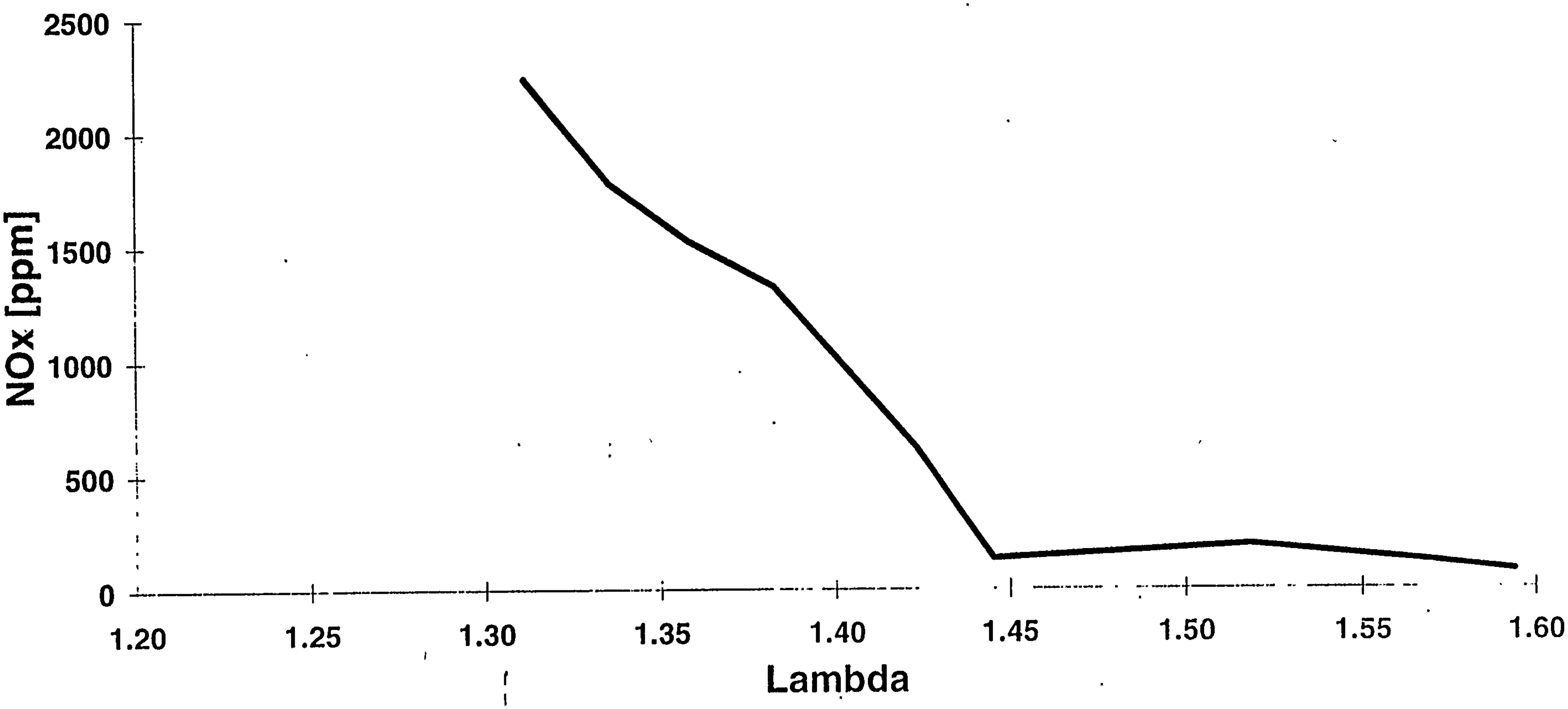
Thermal Efficiency vs Speed



BCRI

NOx vs Lambda

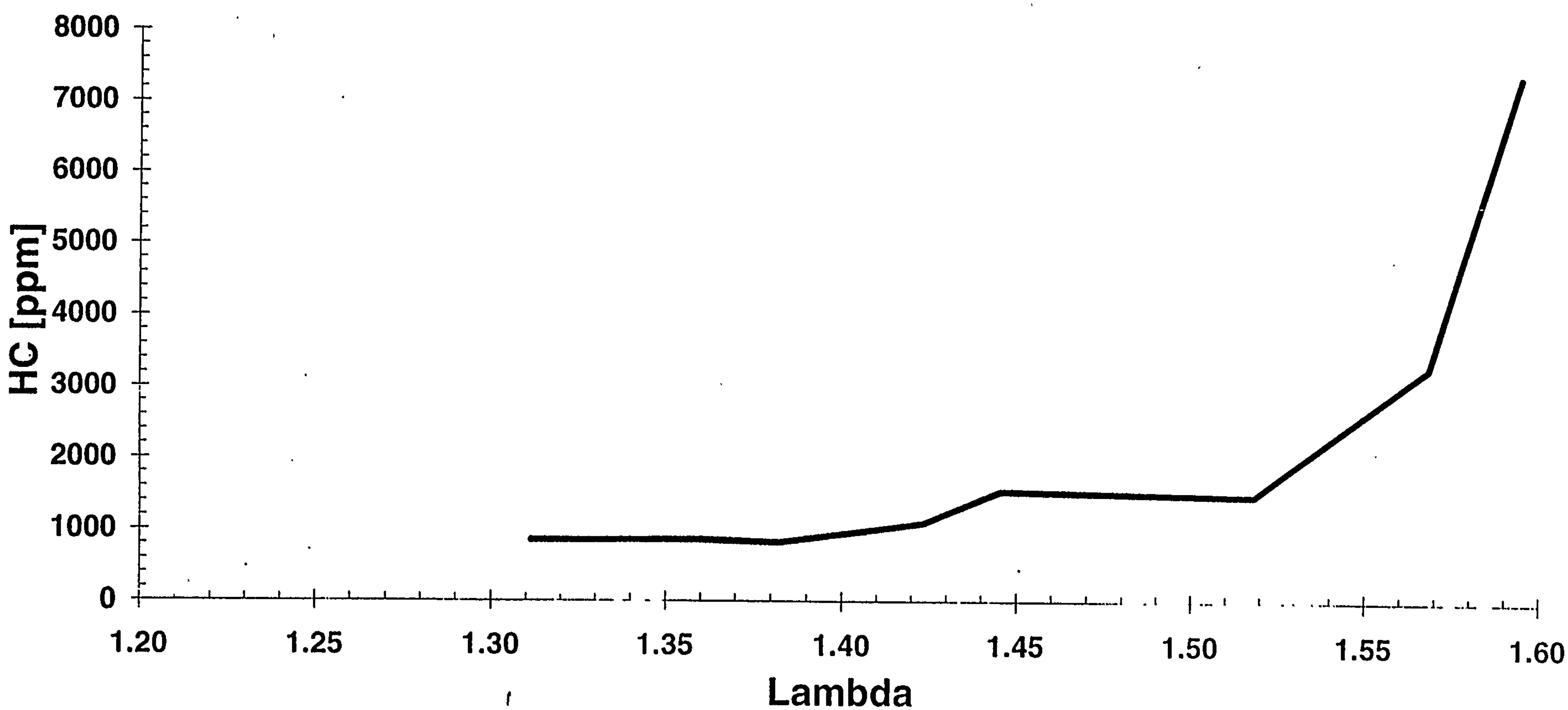
1600 RPM Max Load



BCRI

HC vs Lambda

1600 RPM Max Load



BCRI

Conclusions

- Liquid Propane System Promising
- Emissions on Target
- Feedback Control Essential for Low Emissions

BCRI

Funding

- Natural Resources Canada (CANMET)
- Science Council of British Columbia

BCRI

SESSION 5

ENGINE DEVELOPMENTS

Chair: Wendel Goetz, ORTECH Corporation

Design & Development of a Novel Fuel Injection System for Dimethyl Ether

Natural Gas Engine, Vehicle & Fuel Technology TOPTEC,
May 6, 1996

AVL Powertrain Engineering

Scope

- Background
- DME Properties & Characteristics
- Engine Test Results Summary
- Common Rail Injection System Concept
- Computer Modeling/Simulation Results
- Bench Test Methodology/Initial Results
- Summary

AVL Powertrain Engineering

Background

- Ultra-Low HD Emissions Needed
- Diesel Technology Stalled Above ULEV
- Alcohols/Natural Gas Fuels- Problems!
- Dimethyl Ether (DME) Evaluated:
  - Ultra-Low Emissions Capability Established
  - Fuel System Requirements & Design Identified
- NREL/DOE Sponsoring DME Fuel System Development & Emissions Demonstration Program

AVL Powertrain Engineering

Alcohols/Natural Gas Fuels

...Problems...

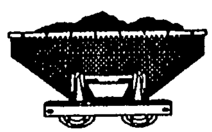
- Alcohols
  - Low Cetane-Ign. Aids Required
  - Corrosive/Toxic (Methanol)
- Natural Gas
  - Thermal Efficiency Low (Otto Cycle)
  - Fuel Storage Complex/Expensive

Neither Fuel Suitable for Compression-Ignition

AVL Powertrain Engineering

DME Characteristics

- Evironmentally Benign, Non-Toxic
- Liquid at 5 Bar...Like LPG
- Moderate Energy Density
- ~60 Cetane, Sootless, Visible Flame
- Abundant and/or Renewable Feedstocks

  - Natural Gas 
  - Coal 
  - Biomass 

Powertrain Engineering

Relative Merits

...Alternative Diesel Fuels...

Characteristic	DME	Natural Gas	Methanol
Cetane	Excellent	Poor	Poor
NOx Emissions	Excellent	Excellent	Excellent
HCHO Emissions	Excellent	Excellent	Poor
Noncorrosive	Excellent	Excellent	Poor
Fuel Quality Sensitive	Excellent	Poor	Good
Retrofittable	Excellent	Poor	Poor
Fuel Efficiency & Range	Excellent	Poor	Good
Fuel Availability	Poor	Good	Poor
Engine & Vehicle Costs	Excellent	Poor	Poor

AVL Powertrain Engineering

Engine Test Results

- Naviatar 7.3L DI V-8
  (HEUI Injectors)

- AVL 1 Cyl. Research Engine
  (2.0L, 4 Valve DI)

Powertrain Engineering

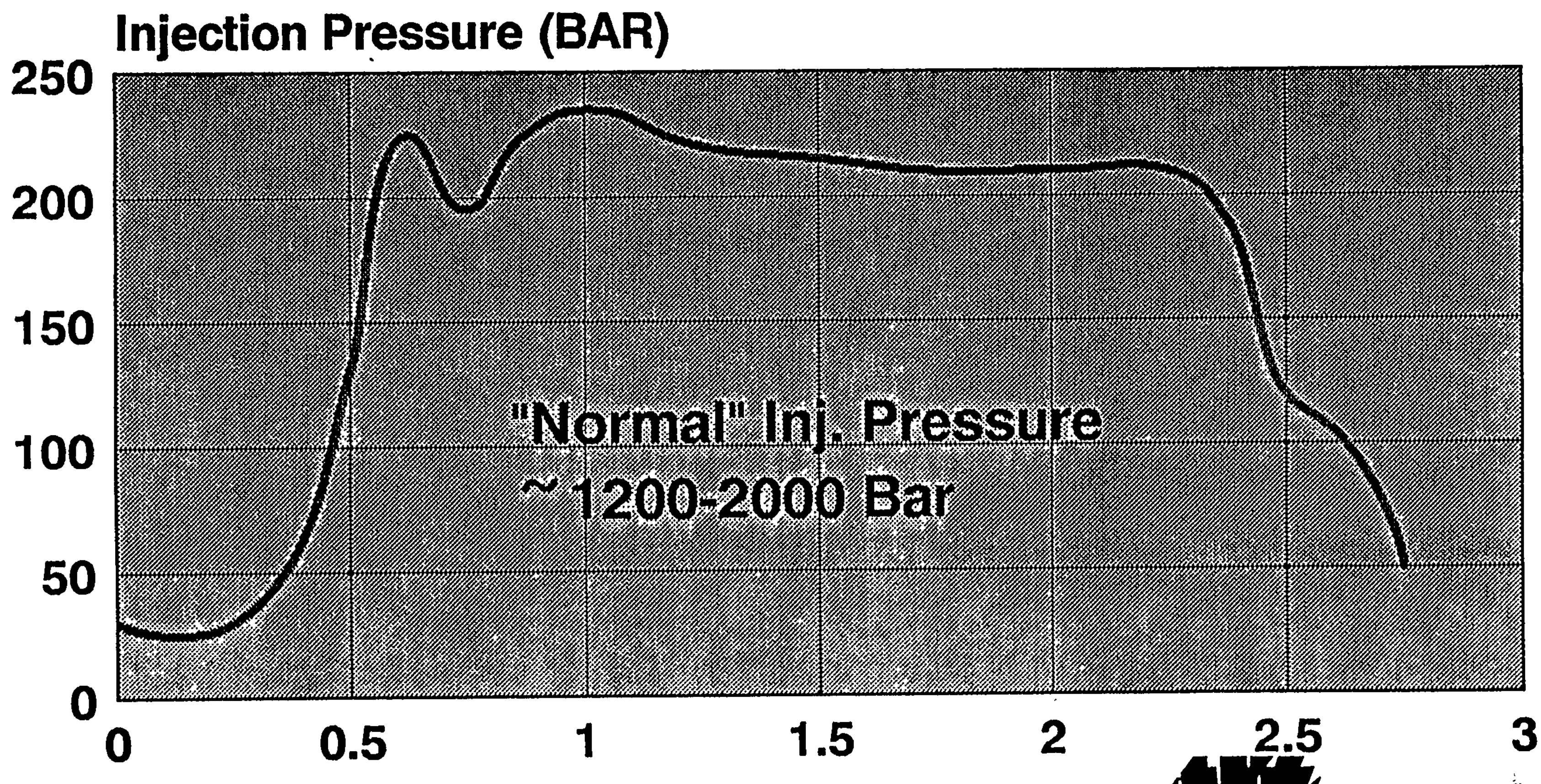
Navistar 7.3L V-8 DI Truck Engine

...Test Program Summary...

- No Basic Engine Design Changes Req'd.
  - Modified Injectors (Plungers, Orifices)
  - Optimized Timing, EGR, Inj. Press. (220 Bar)
- Mapped Emissions & Performance
  - Energy Efficiency = Diesel
  - Totally Smokeless
  - Very Low NOx, CO, HC & HCHO
- Simulated HDD Transient Emissions
  - Surpassed ULEV Requirements

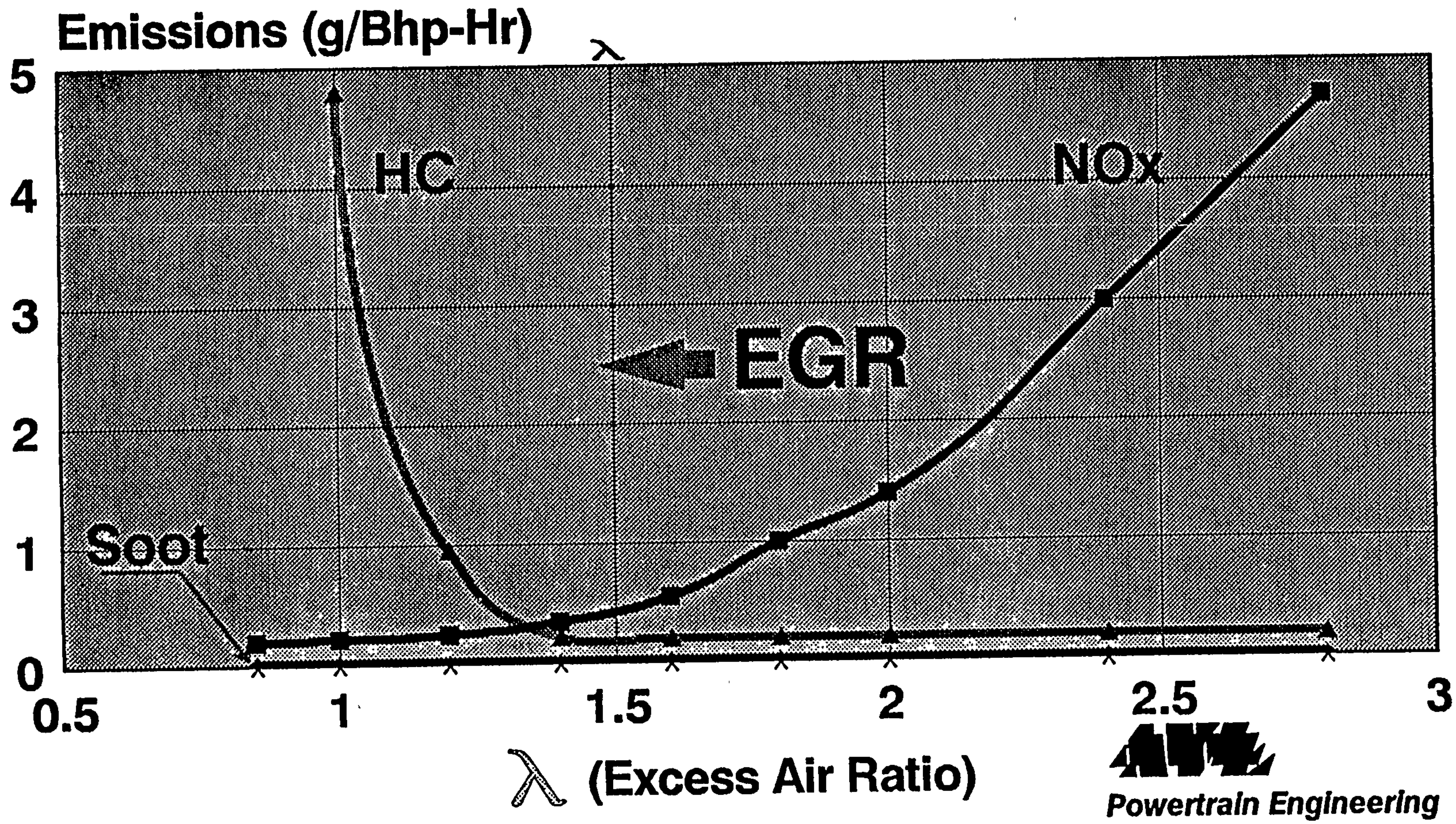
AVL Powertrain Engineering

Full Load Injection Pressure

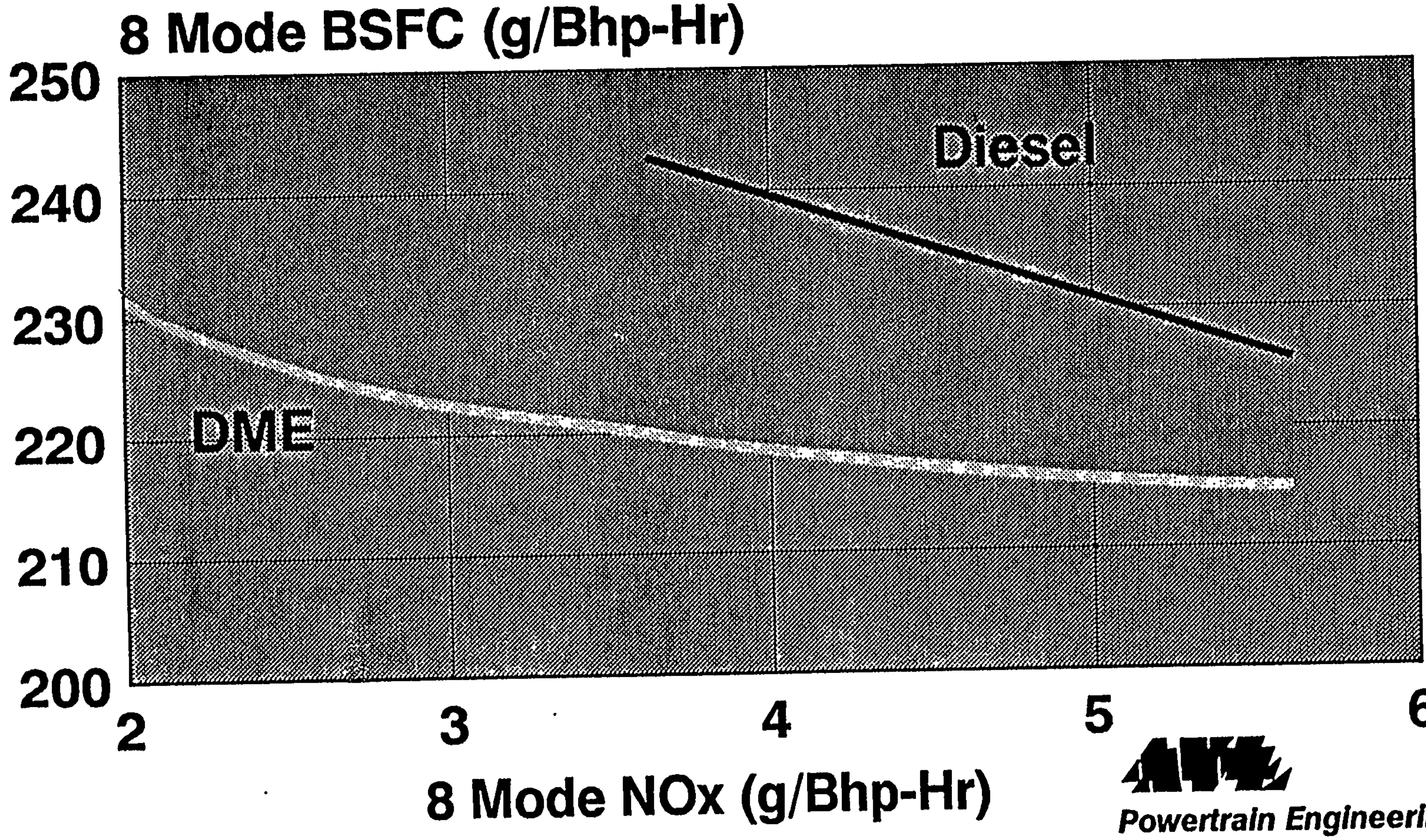


Powertrain Engineering

Effects of Lambda on Emissions



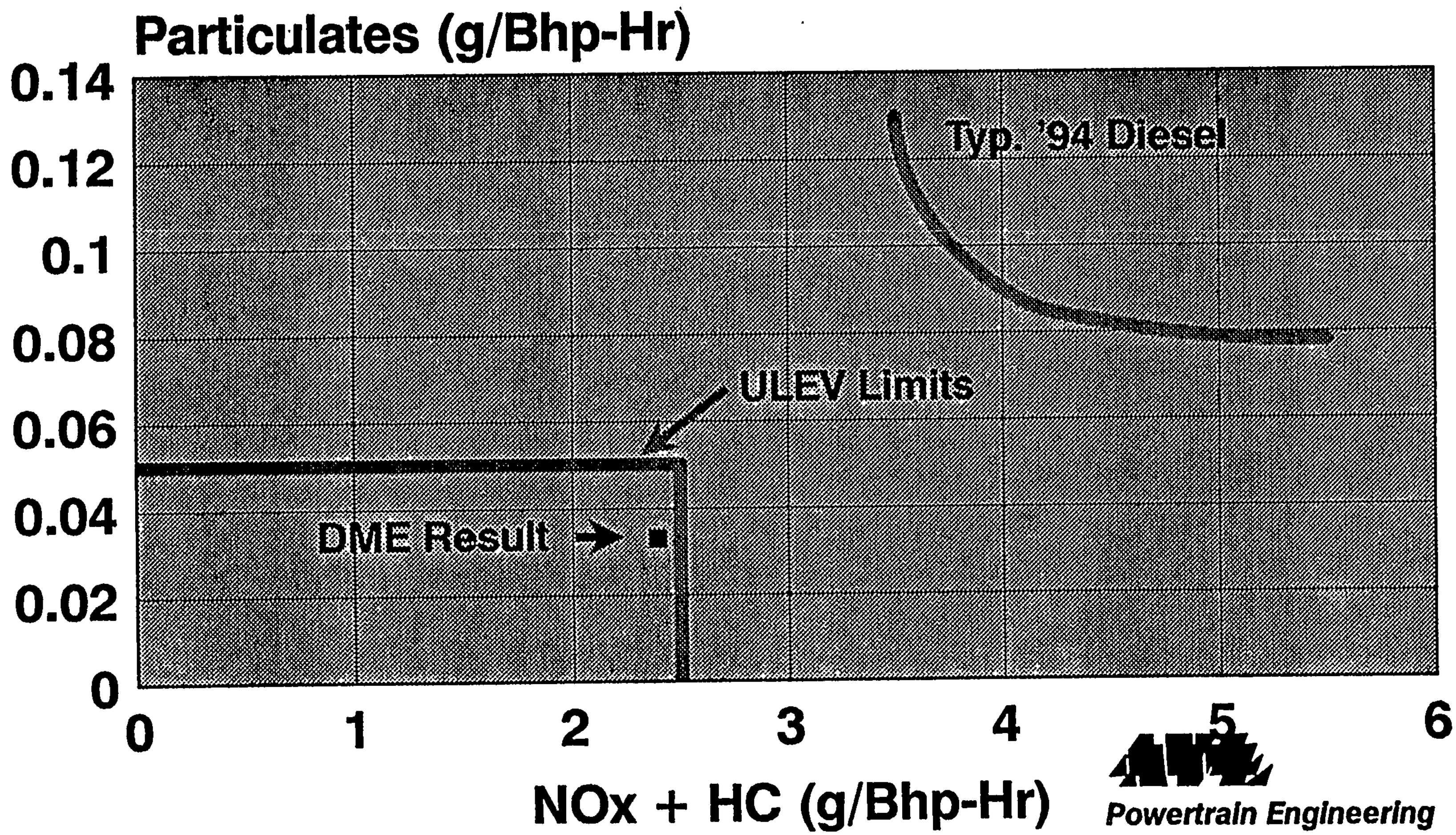
NOx/BSFC Tradeoffs
(Diesel Equivalent BSFC)



Powertrain Engineering

HDD Transient Cycle Emissions Simulation

...AVL 8 mode Test With DME...



Powertrain Engineering

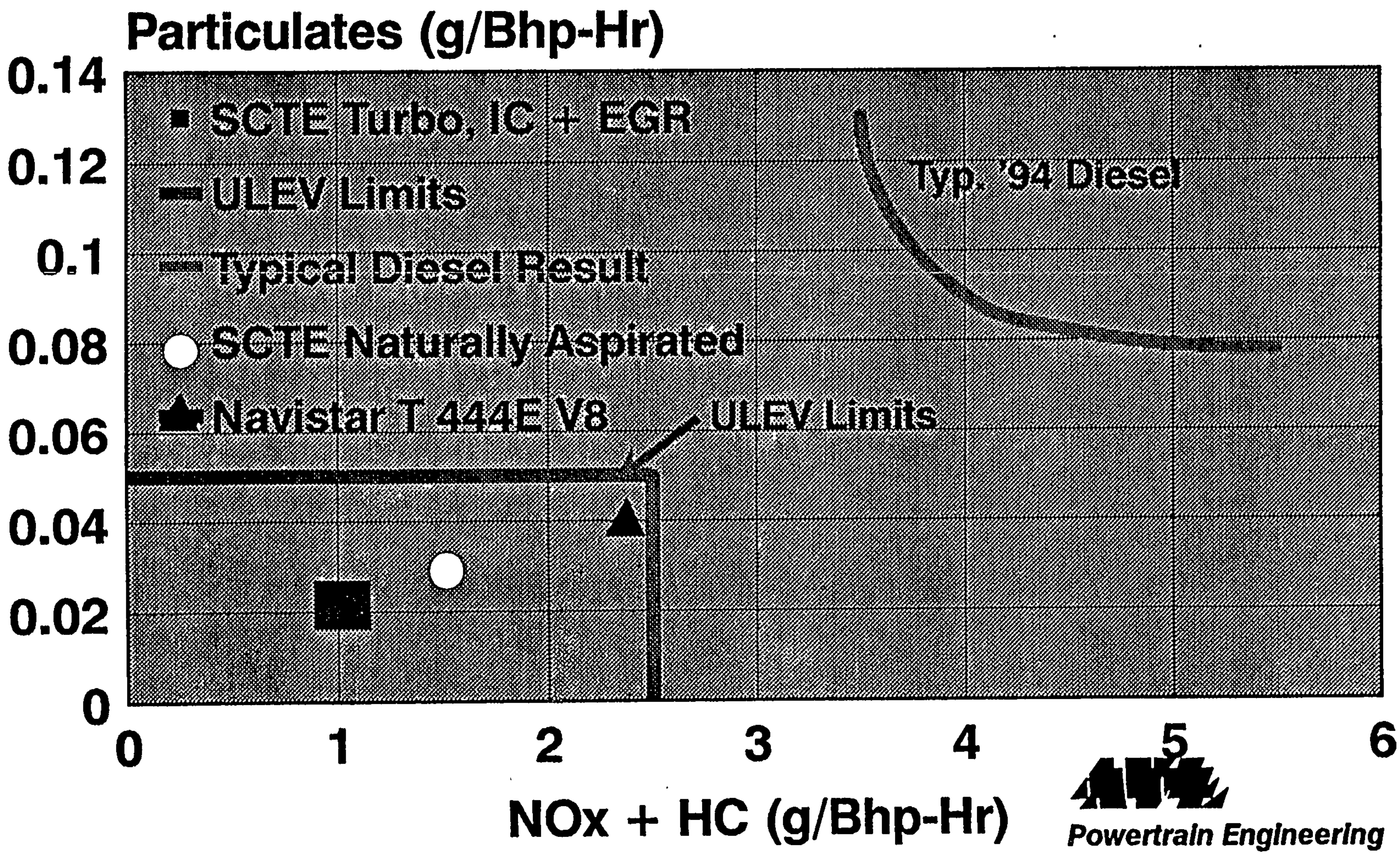
AVL 2.0L Single Cyl. Research Engine

Test Program Summary

- Special Fuel Injection System
  - Highly Rate Shaped
  - Low Peak Pressures(<300 Bar)
- Low Swirl Head
- Emissions Achievements
  - Naturally Aspirated...1.5 g/bhp NOx
  - Turbo/Intercooled... ~ 1.0 g/bhp NOx
  - Totally Smokeless
  - Diesel Efficiency
  - Gasoline Noise Levels

AVL Powertrain Engineering

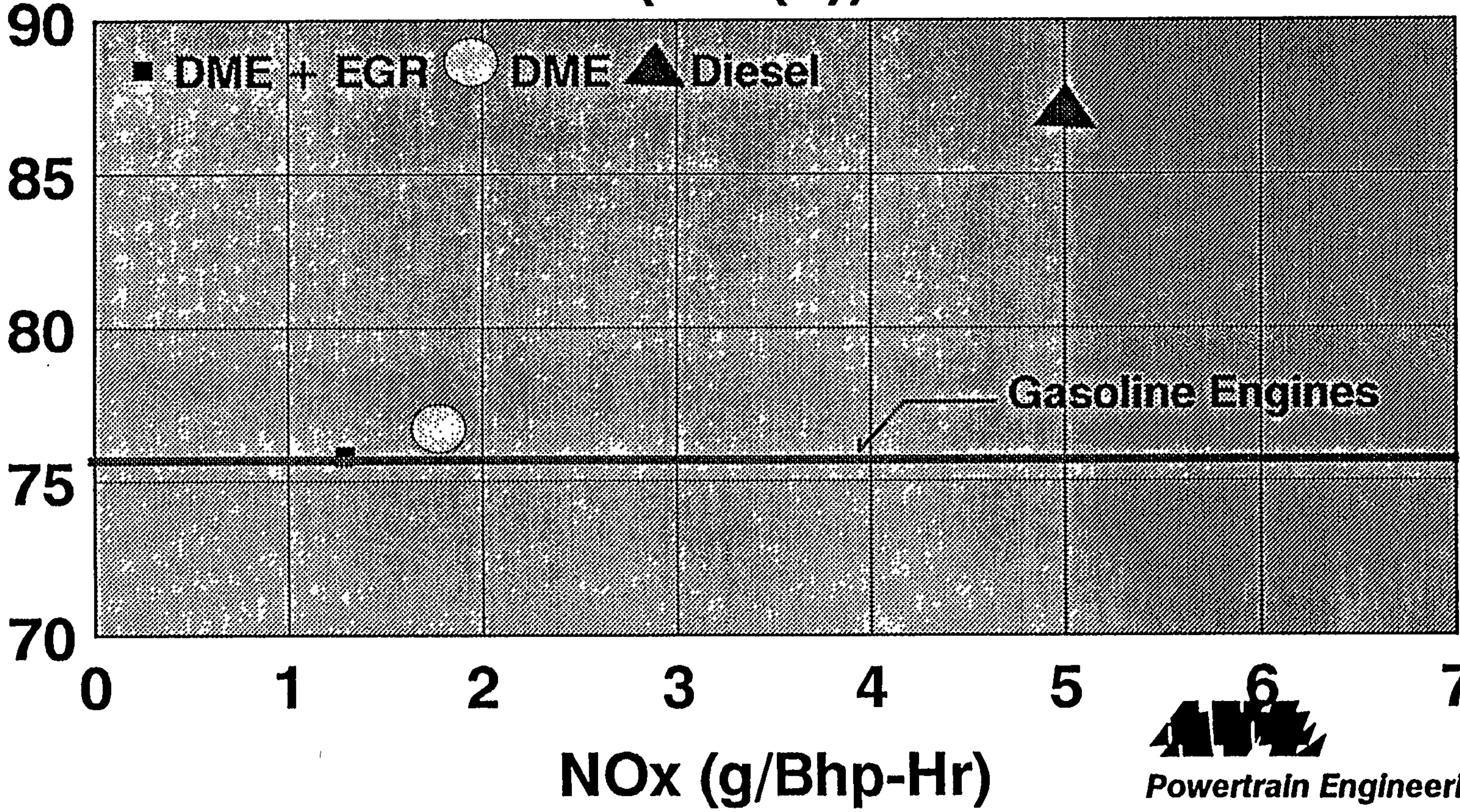
DME Emissions Results



Powertrain Engineering

Combustion Noise Survey

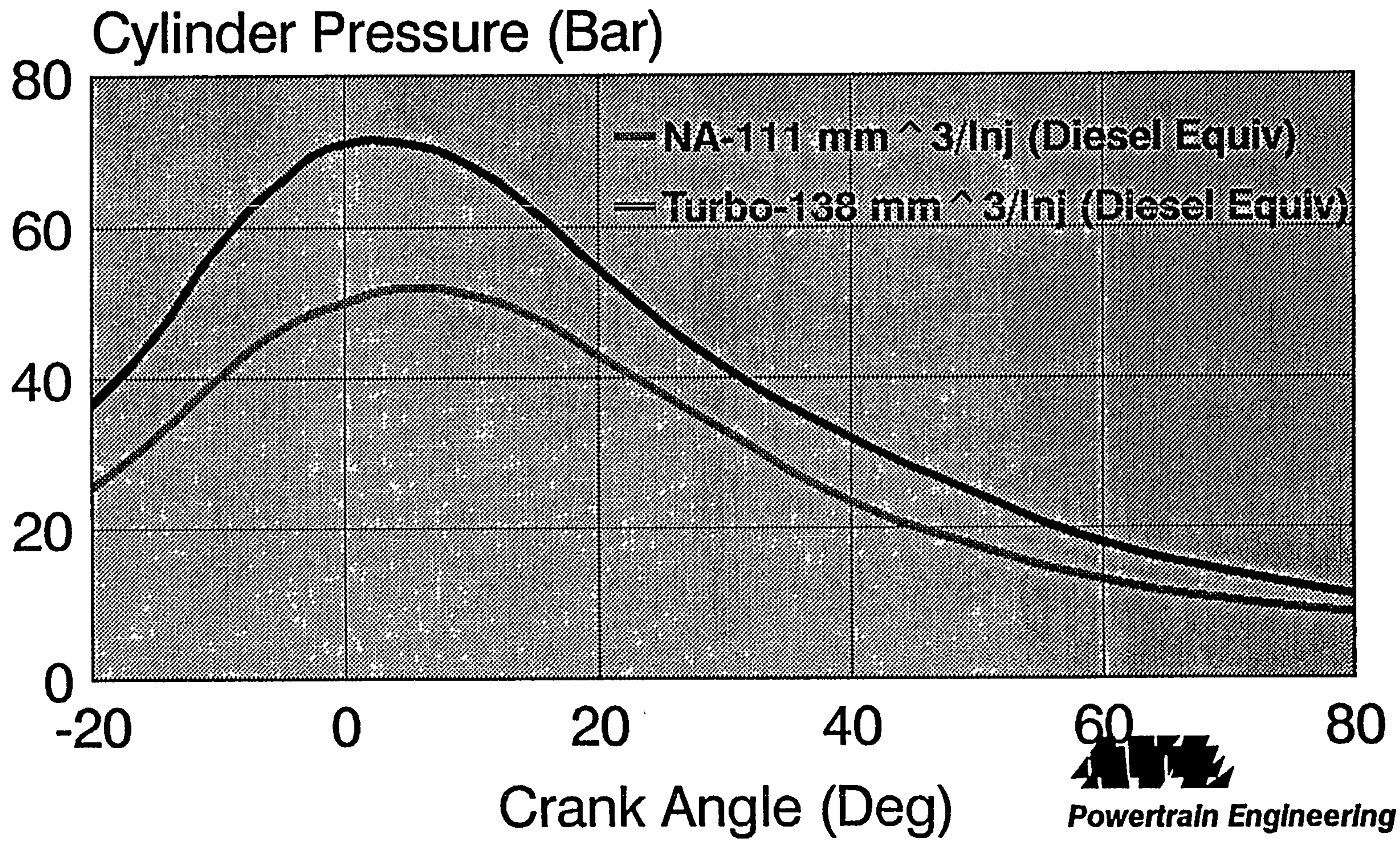
...DME & Diesel Fuel...



Powertrain Engineering

Cylinder Pressure Diagrams

...DME Fuel w/Proprietary EFI System...



Powertrain Engineering

Common Rail Injection System Design Concept

AVL
Powertrain Engineering

Design Objectives

...DME Injection System...

- Low Peak Pressures (< 250 Bar)
- Flexible Injection Rate Shaping
  - Very Low Initial Injection Rate (NOx/Noise)
  - Electronically Variable (W/Speed & Load)
- 300 MM ^ 3/Inj. Delivery in <40 Deg Crank (300 BHP)
- "Bolt On" Existing Engines

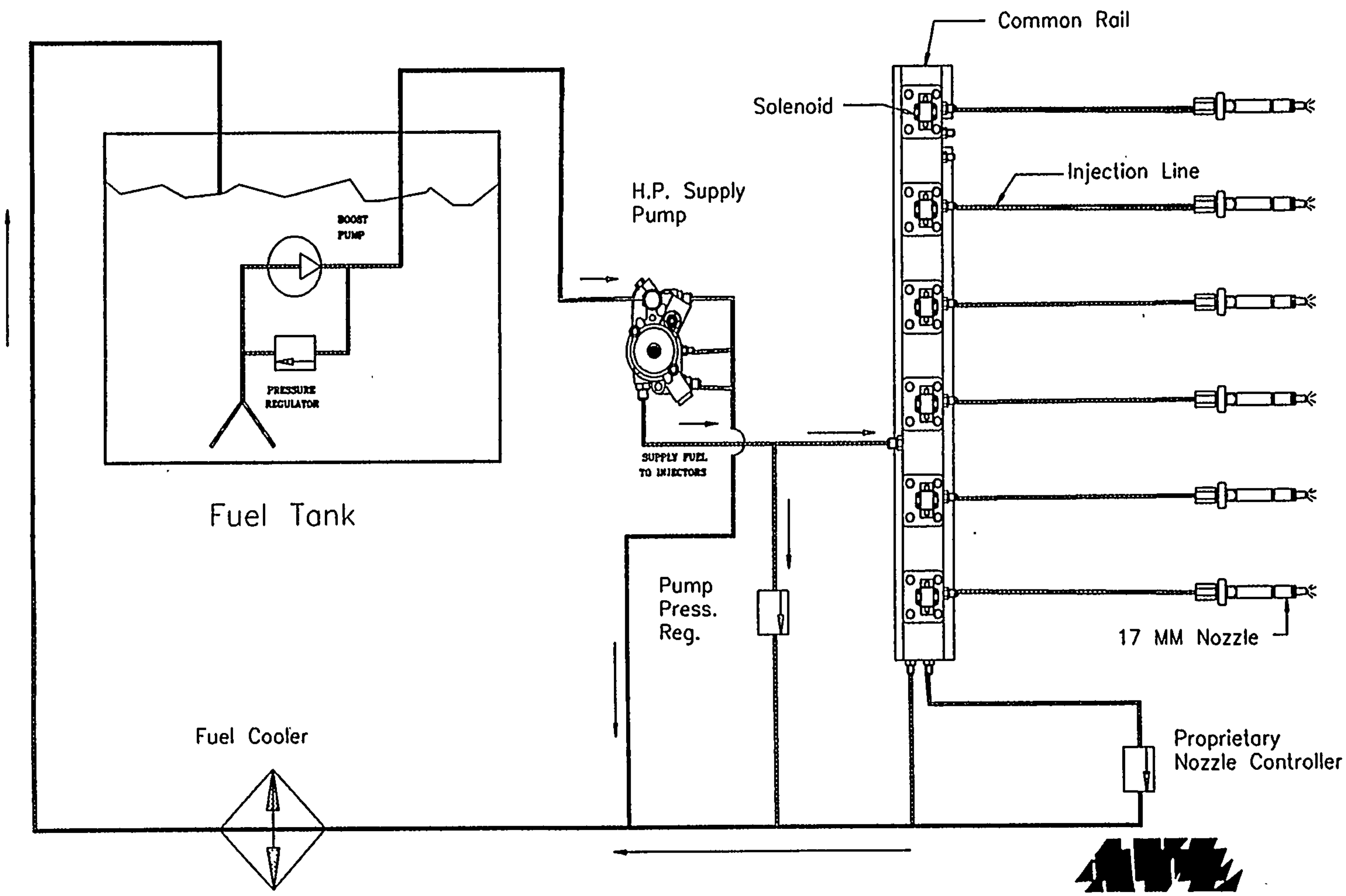
AVL Powertrain Engineering

DME Injection System Design Concept

- Low Pressure (<250 Bar) Common Rail
- Swash Plate Piston Pump-Bellows Sealed
- Solenoid Actuated, Electronically Controlled 17 MM Injectors
- Proprietary "Rate Shaping" Technology
- Propane Type Fuel Handling System

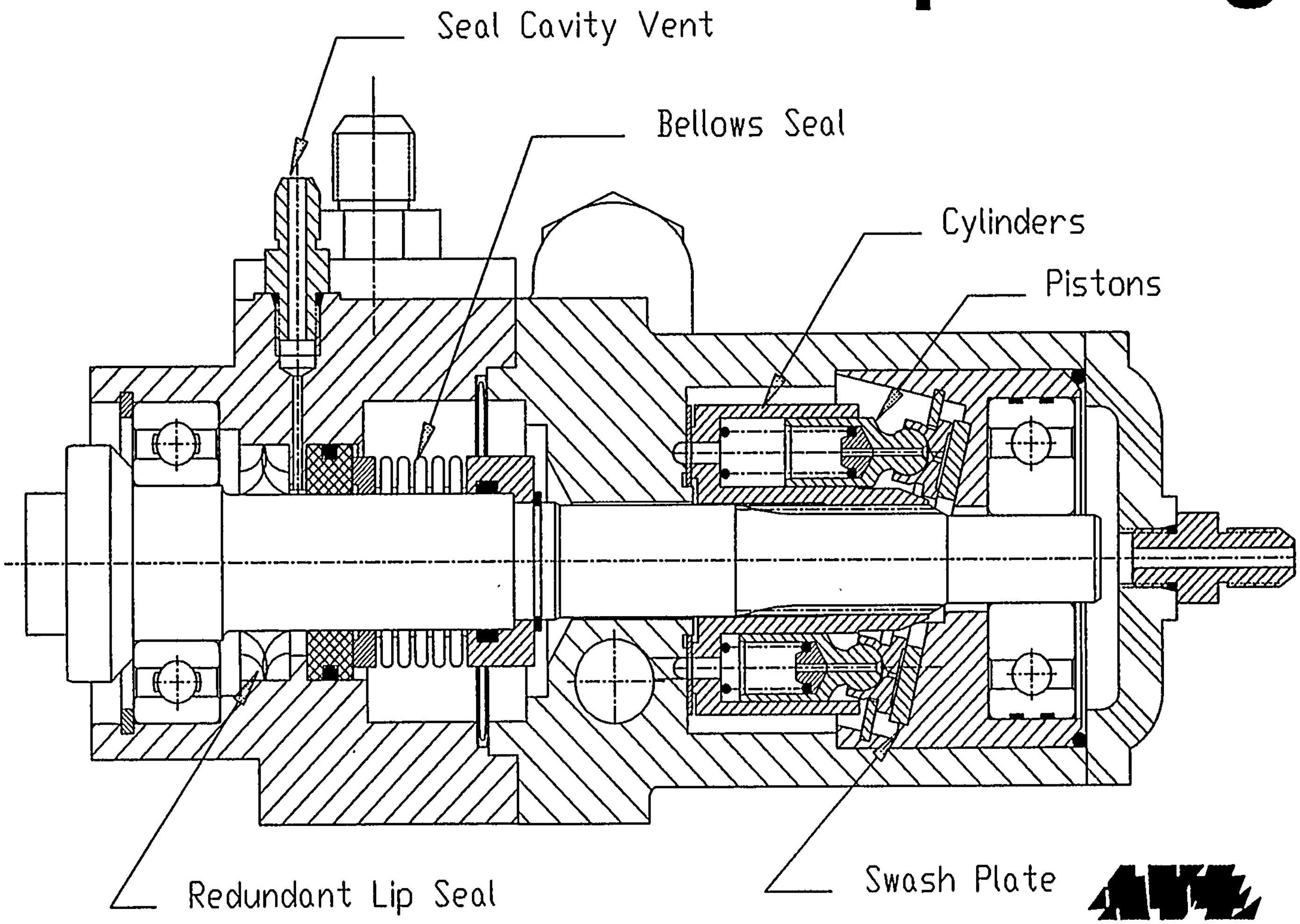
AVL Powertrain Engineering

DME Common Rail Injection System



Powertrain Engineering

Swash Plate Pump Design



Powertrain Engineering

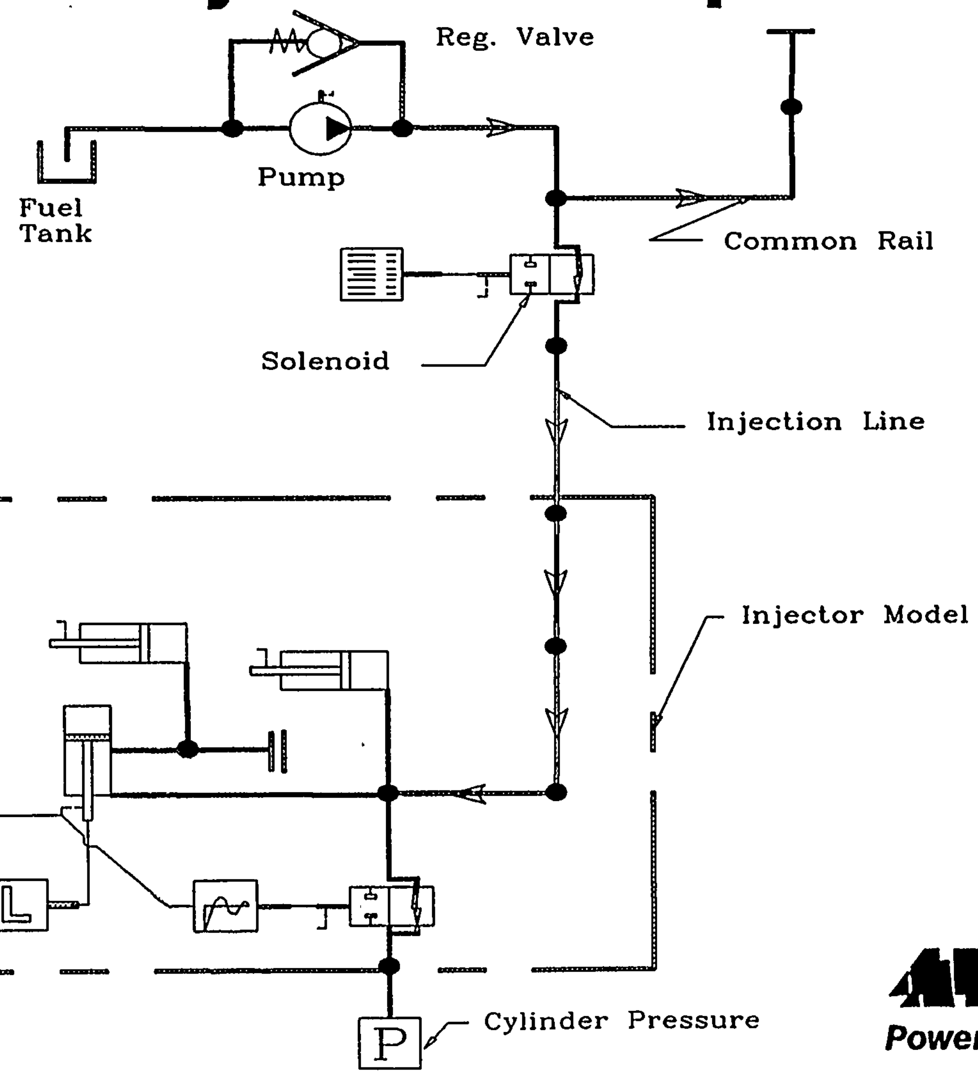
Computer Modeling & Simulation

- 1D Computer Model Constructed
- Fully Describes System & All Components
- DME Physical Characteristics Included
- Sophisticated Electronic **Rate Shaping Feature Developed
- System Fully Optimized & Proven Robust (200 Simulations)

***Rate Shaping Technology Will Not Be Disclosed*

AVL Powertrain Engineering

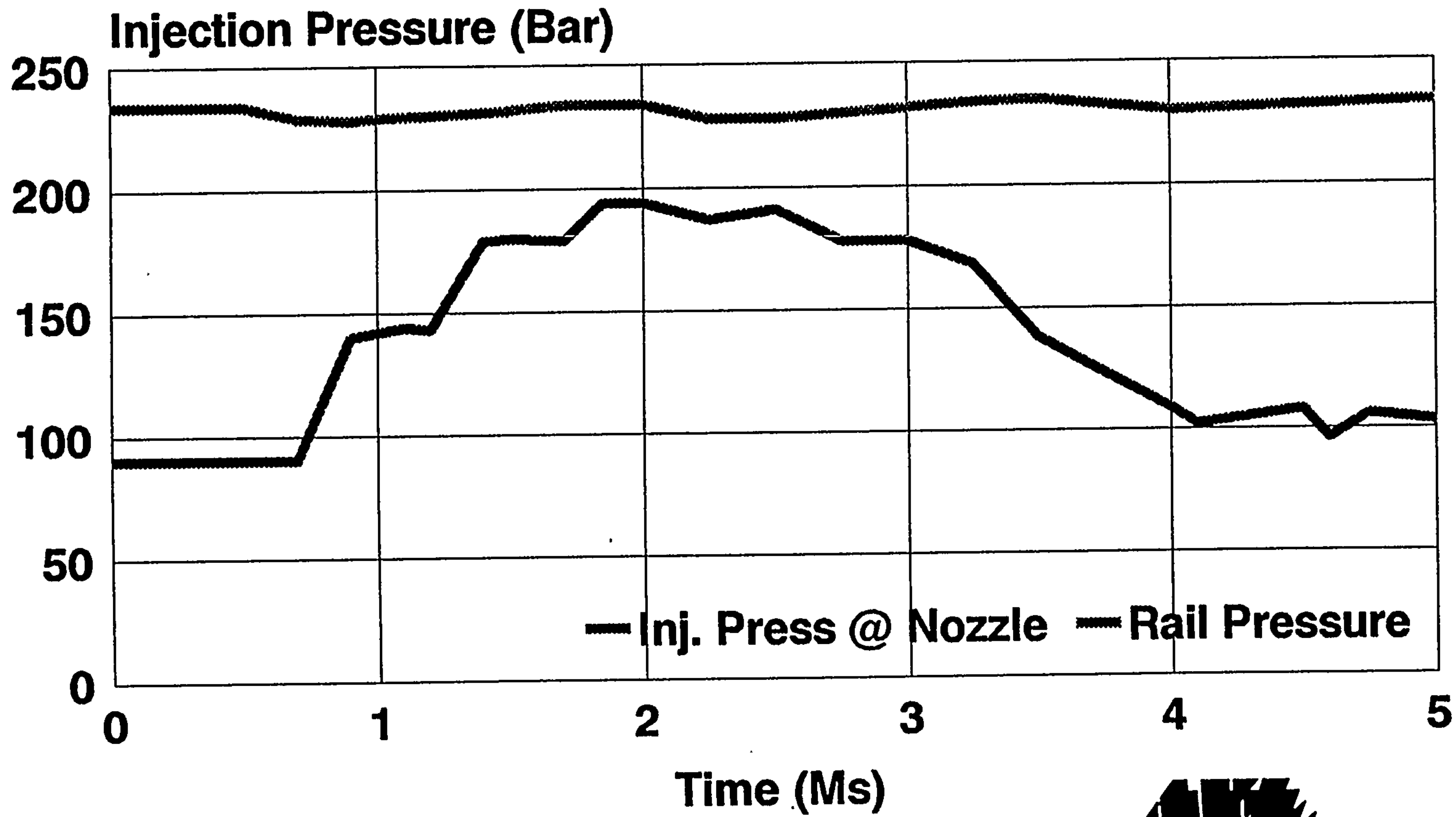
Injection System Computer Model



Powertrain Engineering

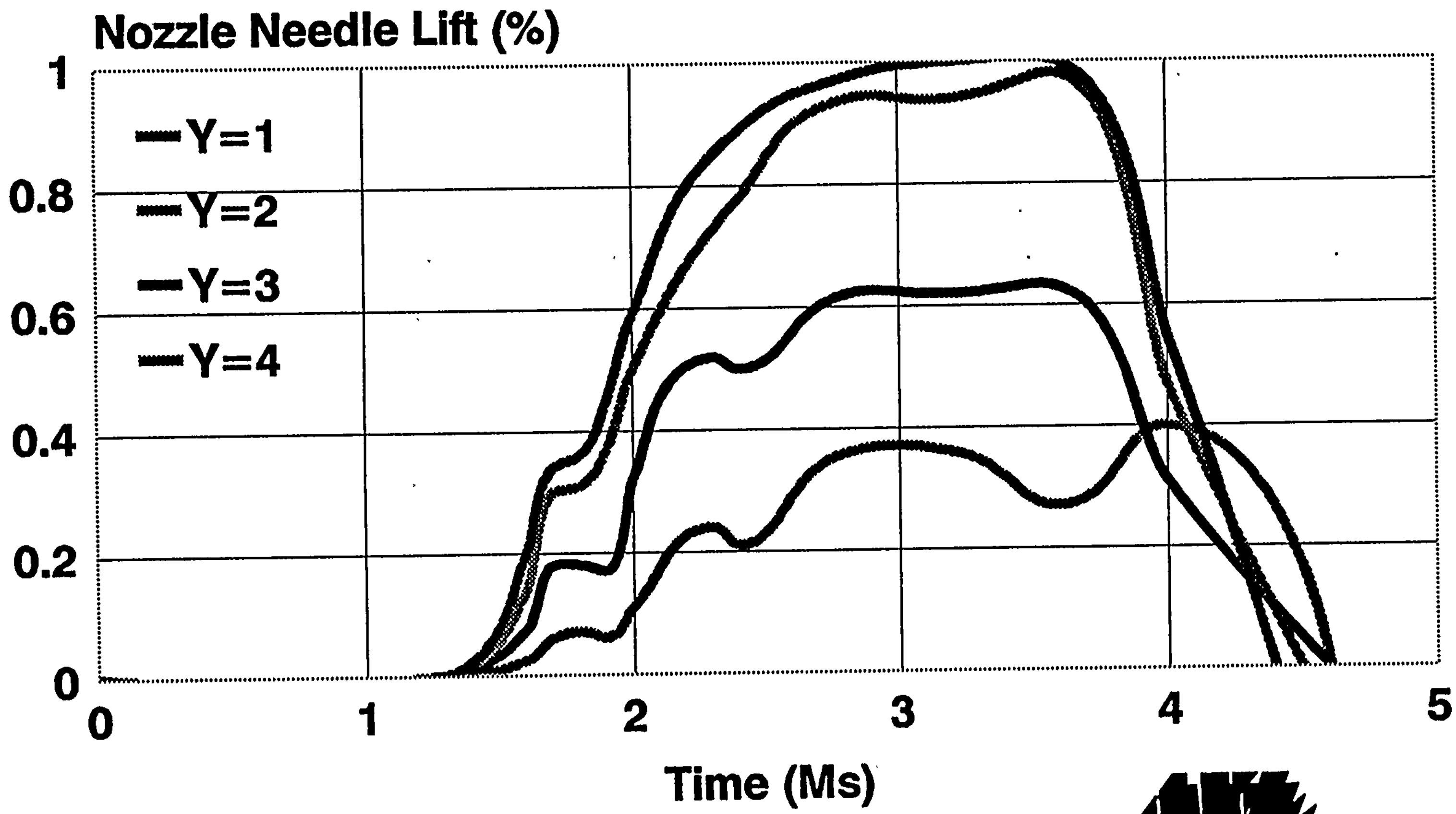
Injection Pressure History

...Simulation, 250 MM ^ 3/Inj...



Powertrain Engineering

Effect of Rate Shaping Parameter "Y"



Powertrain Engineering

Computer Modeling & Simulation

...Conclusions...

- System Performs as Expected
- Three Degrees of Freedom Demonstrated
  - *Duration (Pulse Width)*
  - *Rail Pressure (Press & Rate)*
  - *Initial Rate of Inj. (Rate Shaping)*
- Should Provide Very Low Emissions, Noise & Fuel Consumption

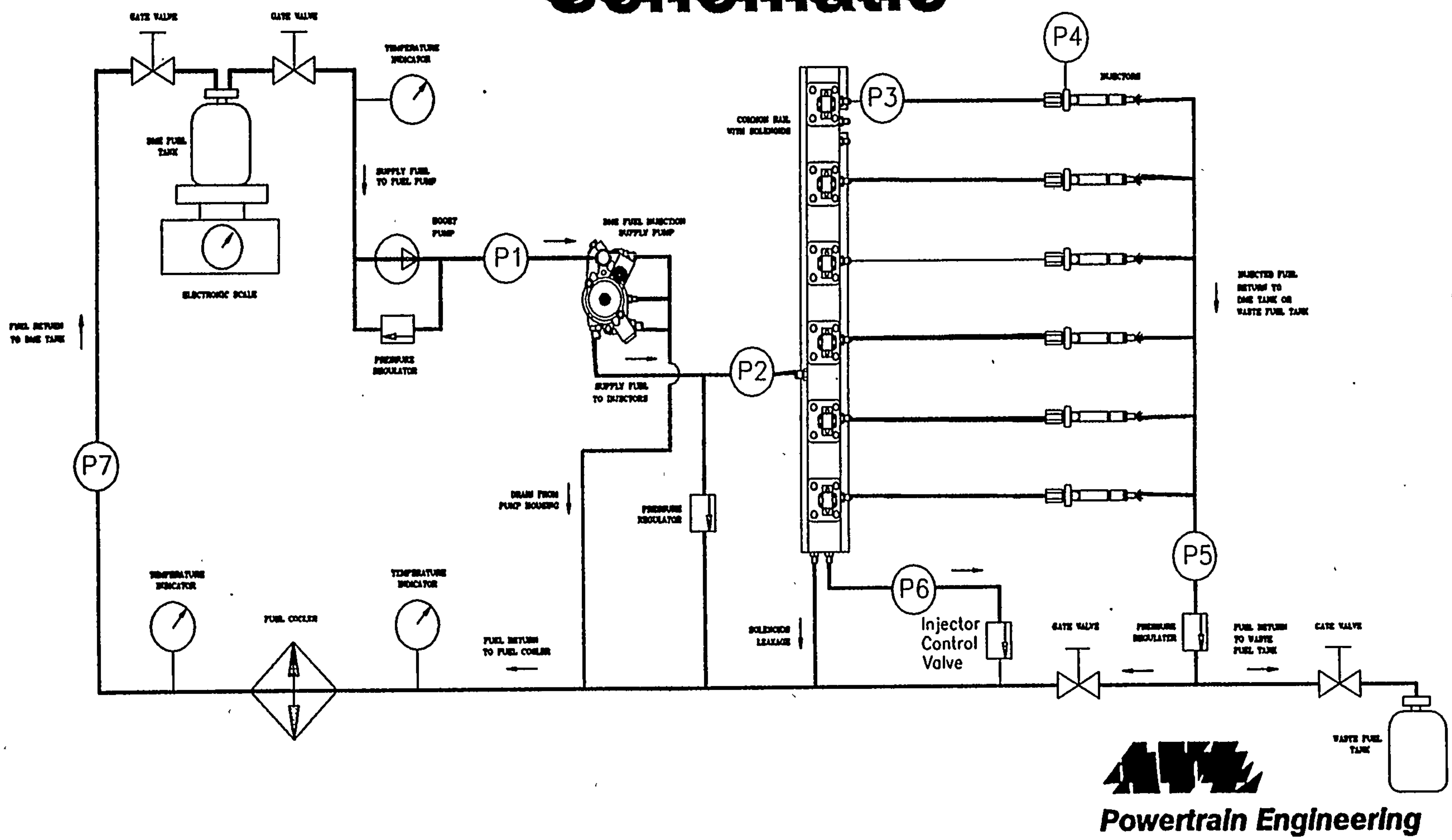
AVL Powertrain Engineering

Program Status

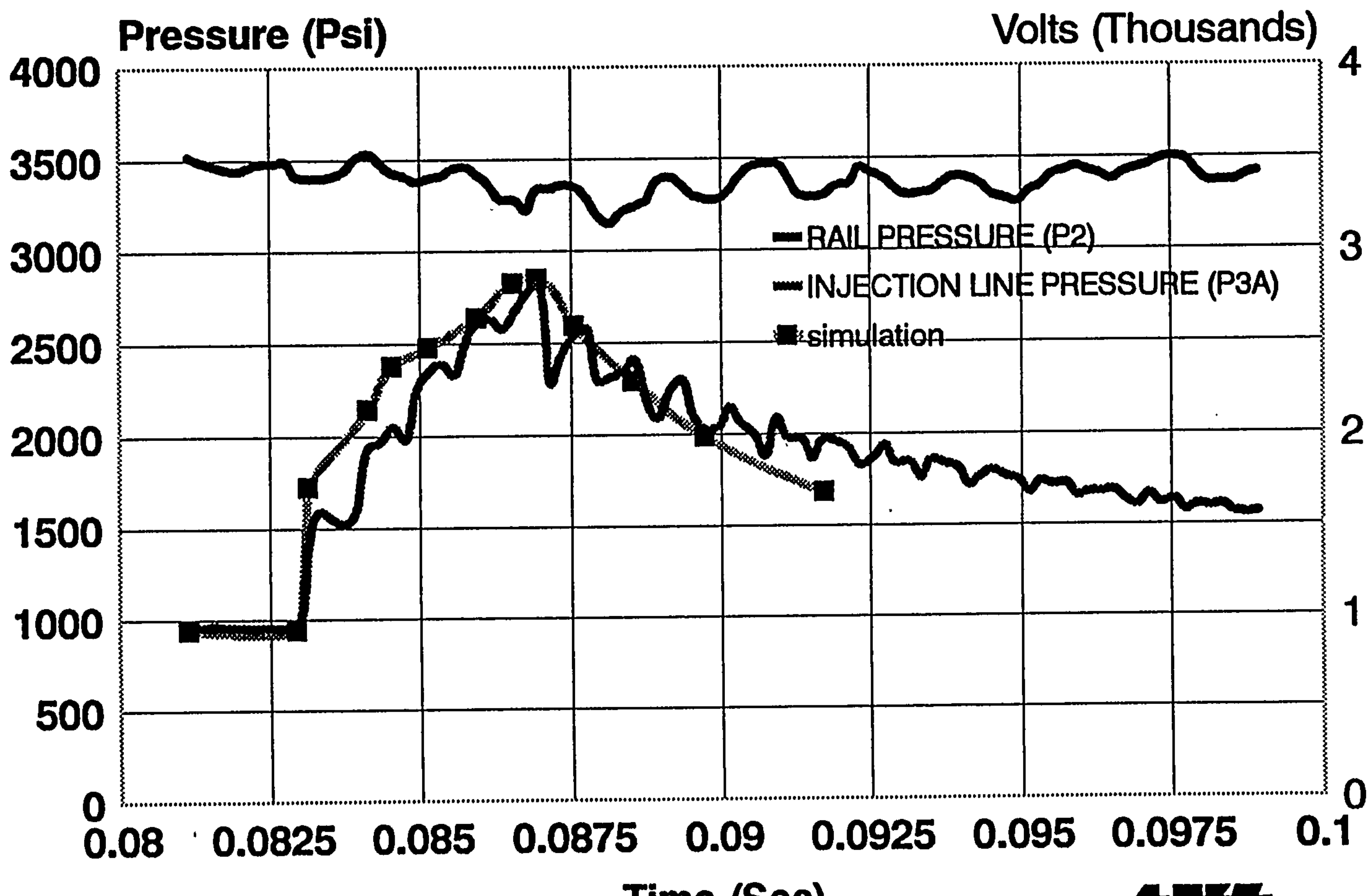
- Detail Design Completed
- Simulations Indicate Robust/Flexible Design
- Parts Procured
- Initial Bench Tests Underway
- Preliminary Results Substantiate Simulations
- Engine Testing to Begin ~ August, 1996

AVL Powertrain Engineering

DME Injection System Bench Test Schematic



Comparison of Simulation to Bench Test Results



Powertrain Engineering

Summary

- DME is a Very Promising Fuel for H.D. Vehicles
  - Very Low Emissions & Noise
  - Economically Viable
- Key to Low Emissions are Injection Characteristics
- The Fuel System Shown Will Provide Req'd. Injection Characteristics
- Forecast: DME Will Become a Popular Truck Fuel in Urban Area's

Powertrain Engineering

Development of Ignition System and Combustion Monitoring Technology for Premixed Charge Alternative Fuelled Engines

D. P. Gardiner, R.W. Mallory, G.R. Pucher, M.K. Todesco
Thermotech Engineering
Kingston, Ontario

M.F. Bardon
Royal Military College of Canada
Kingston, Ontario

Acknowledgments

- Transport Canada
- Natural Resources Canada (CANMET)
- U.S. Department of Energy (NREL)
- General Motors of Canada Ltd. (Oshawa)

Light Duty Vehicle Applications (Stoichiometric Alcohol or Gasoline)

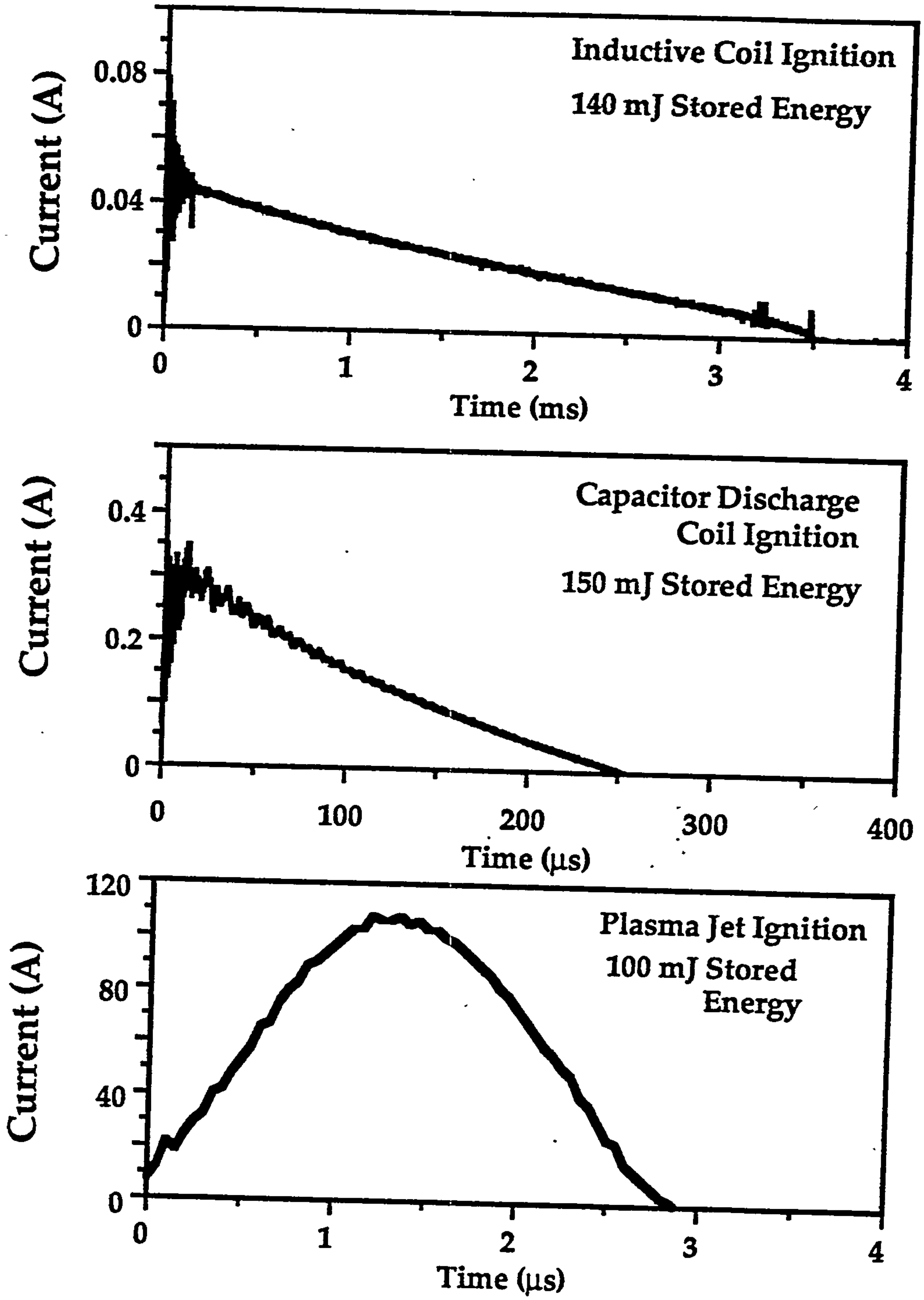
- Enhanced Ignition - intermittent duty high energy "boost" for cold starting
- Combustion Monitoring - on-board diagnostics (OBD II) for misfire detection

Medium/Heavy Duty Vehicle Applications (Lean Burn Natural Gas or Propane)

- Enhanced Ignition - continuous duty, low energy operation for lean burn (extend lean limit)
- Combustion Monitoring - closed loop air/fuel ratio control near the lean limit (detect poor combustion prior to misfiring)

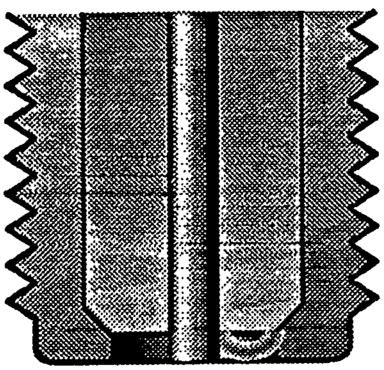
Low Energy Plasma Jet Ignition

- Ignition by plasma jets involves a different mechanism than ignition by conventional sparks
- Ignition by plasma jets does not necessarily involve higher energy levels than ignition by conventional sparks

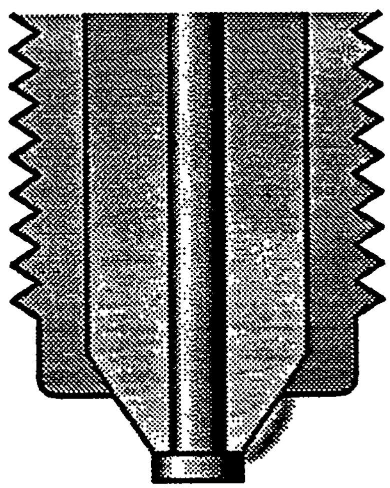


Typical Spark Current Profiles for Different Ignition System Types

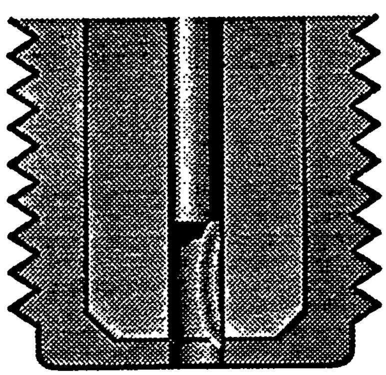
SURFACE DISCHARGE IGNITORS



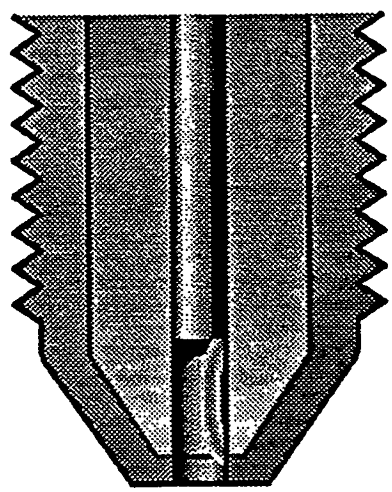
Flush Tip
Surface Gap



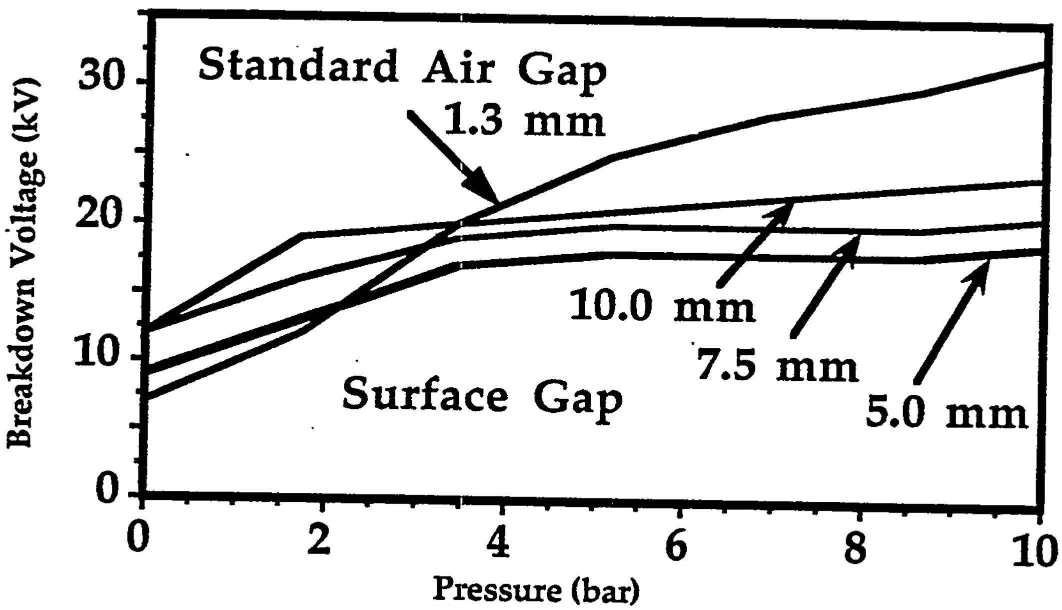
Projected Tip
Surface Gap



Flush Tip
Recessed Gap

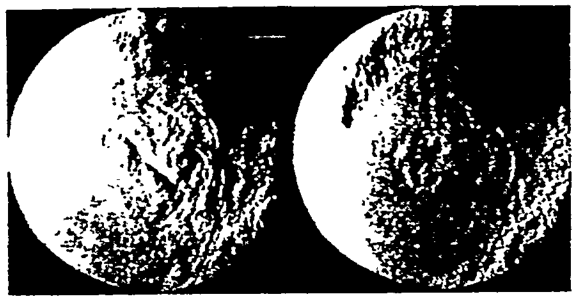


Projected Tip
Recessed Gap



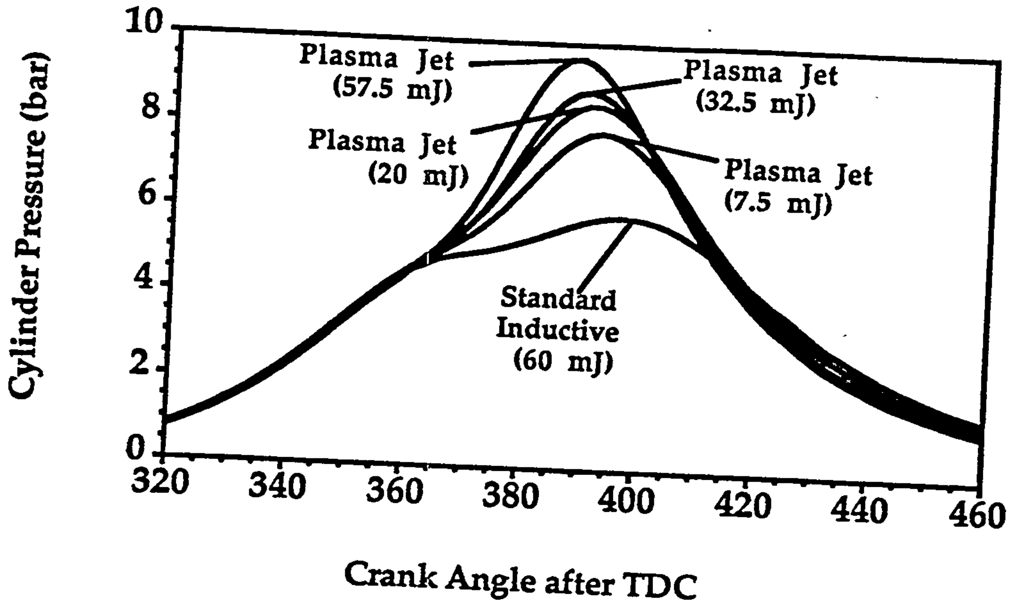
Effect of Pressure on Breakdown Voltage For Air Gap and Surface Gap Ignitors

Inductive Ignition
Standard Spark Plug

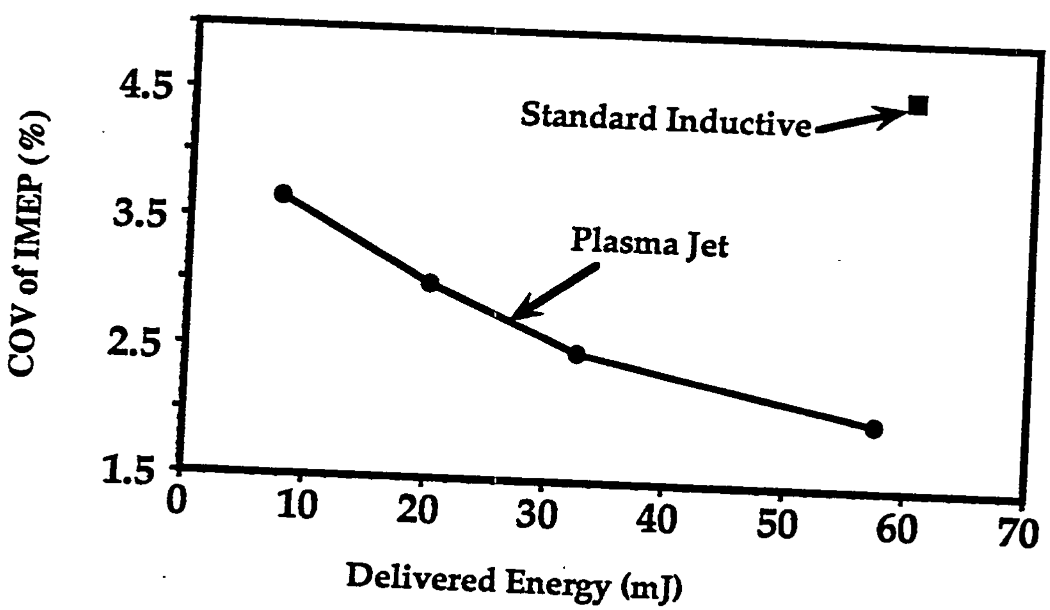


Plasma Jet
Ignition (300 mJ)

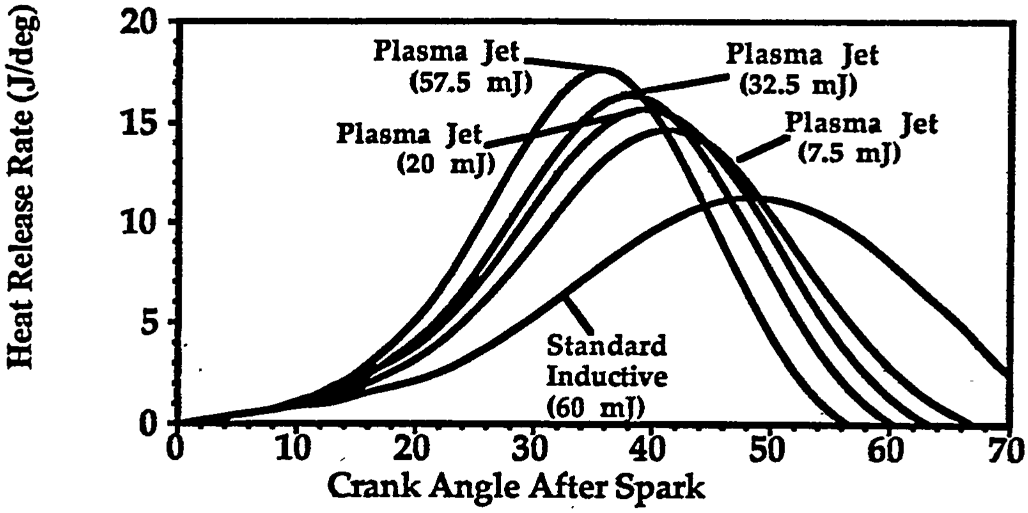
Ignition of Lean Methane-Air Mixtures with 10 m/s Swirl
(Murase *et al*, 1989)



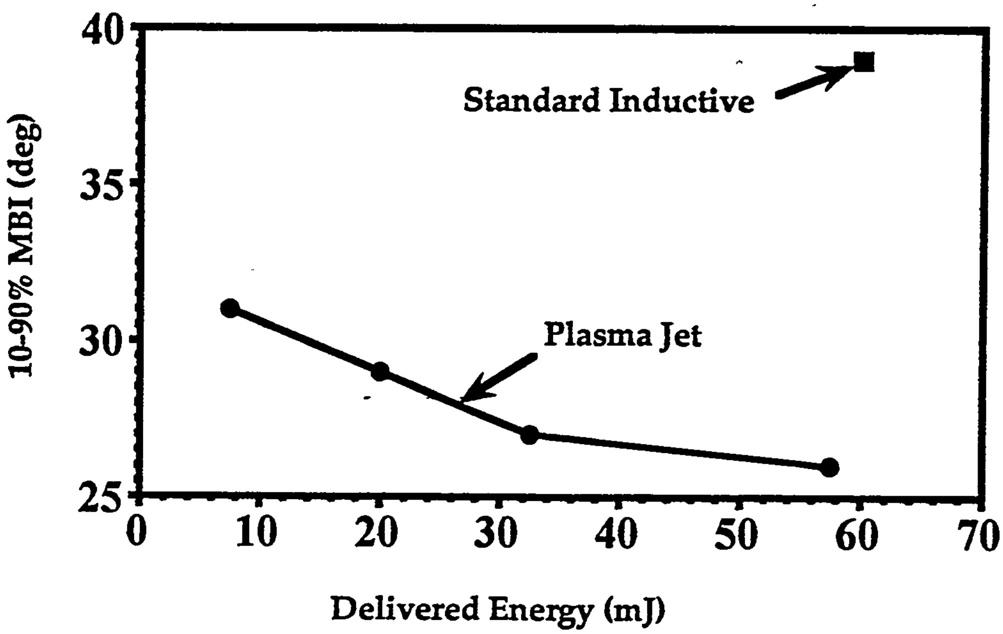
Effect of Delivered Ignition Energy on Cylinder Pressure



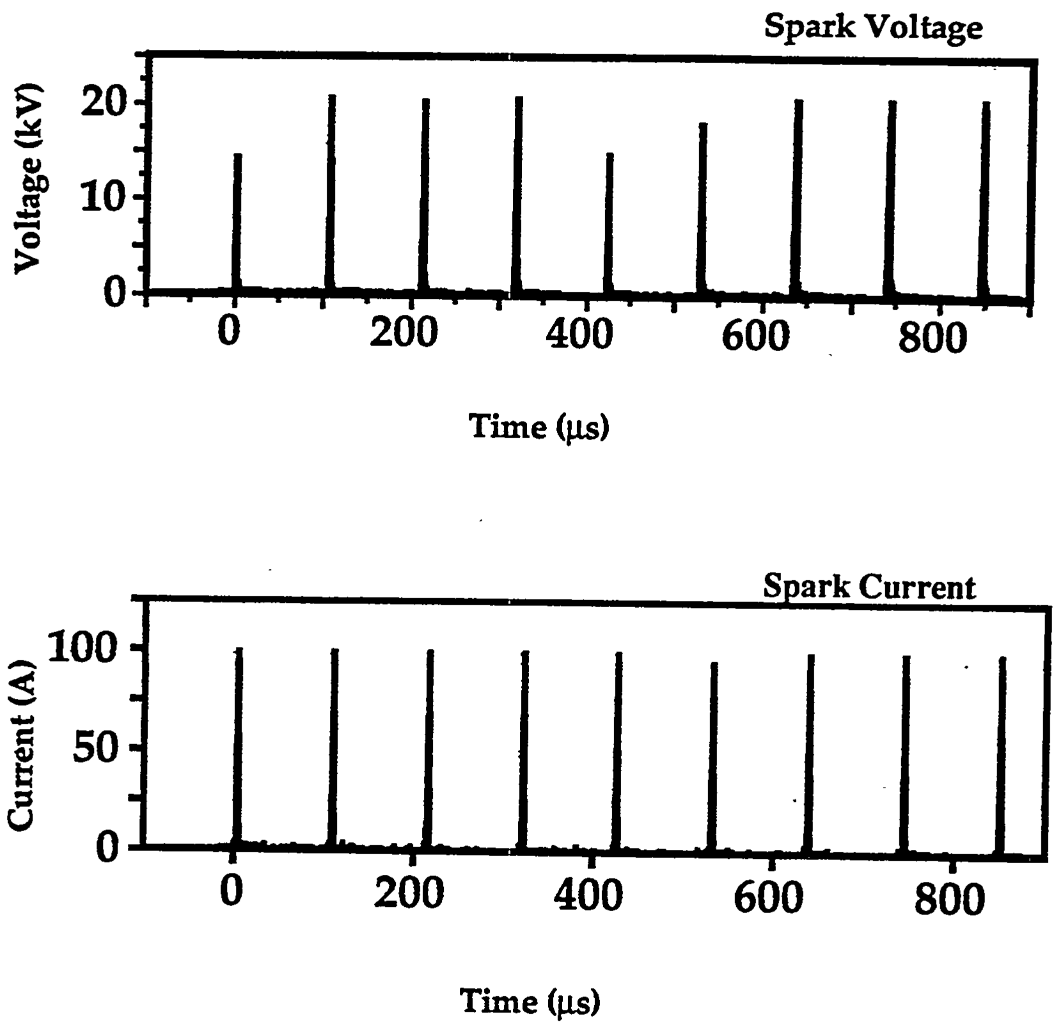
Effect of Delivered Ignition Energy on Coefficient of Variation of Indicated Mean Effective Pressure



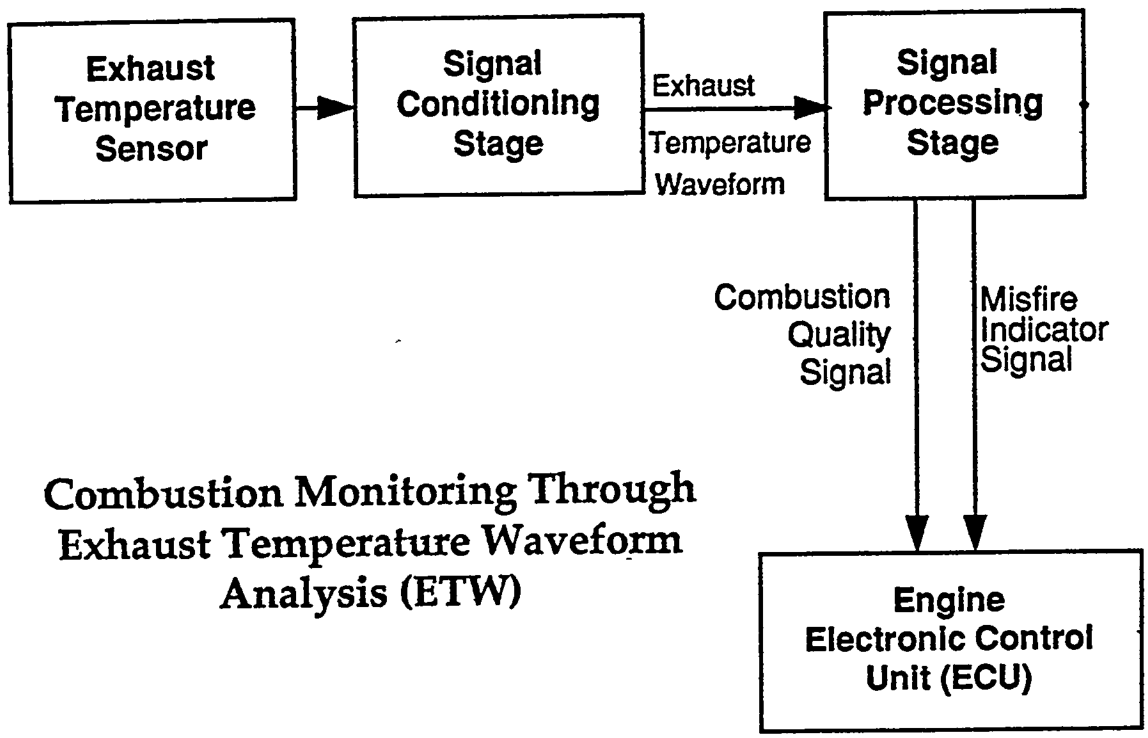
Effect of Delivered Ignition Energy on Heat Release Rate



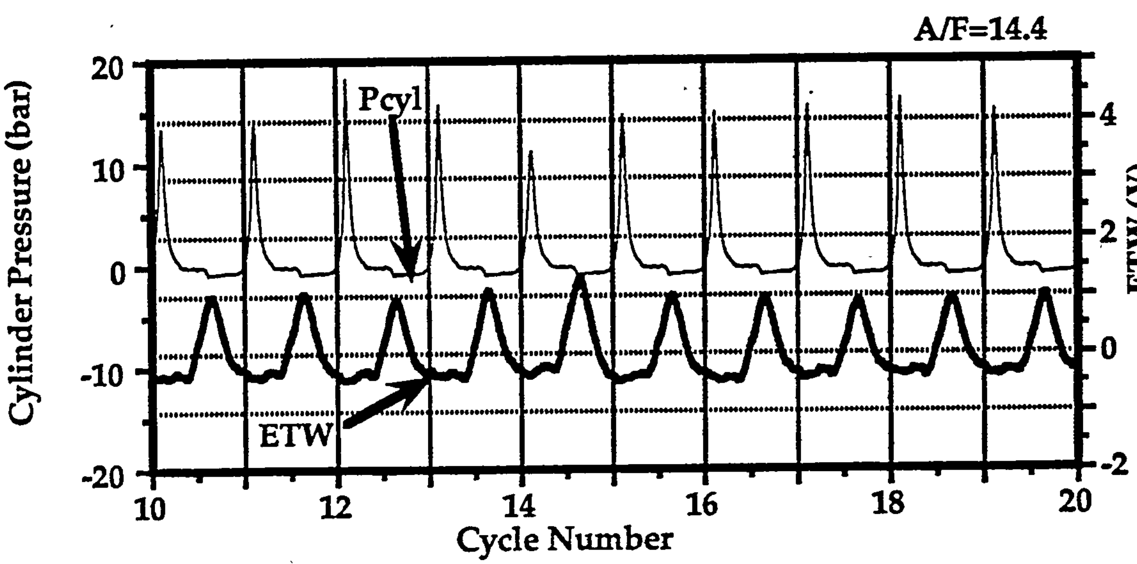
Effect of Delivered Ignition Energy on 10-90% Mass Burn Interval



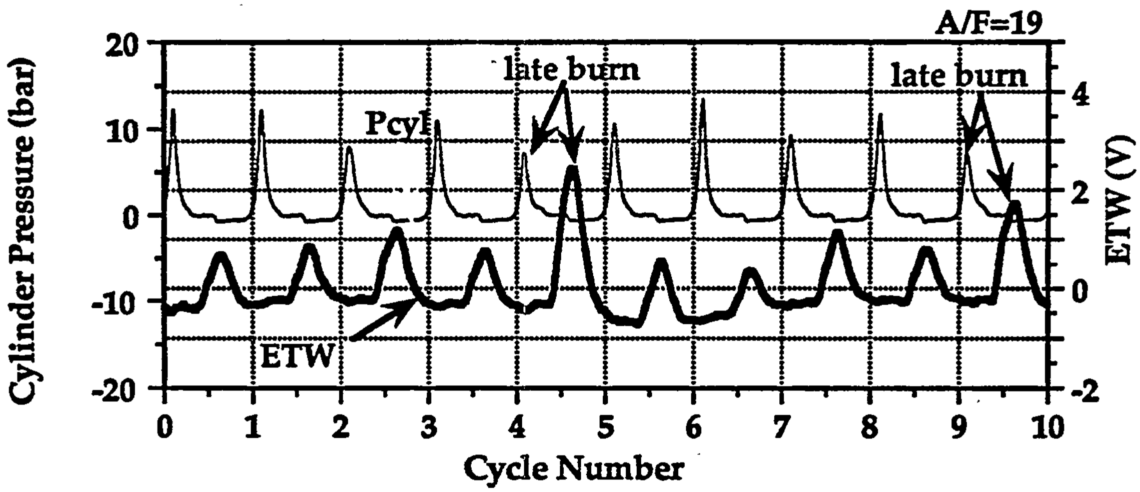
Multistrike Plasma Jet Ignition
(7.5 mm gap, 12.5 bar chamber pressure)



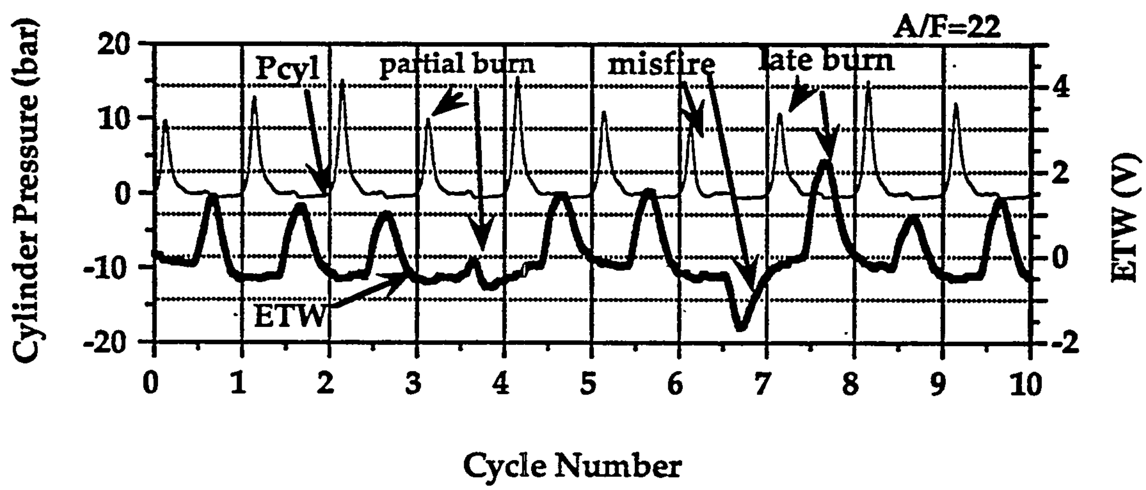
Combustion Monitoring Through Exhaust Temperature Waveform Analysis (ETW)



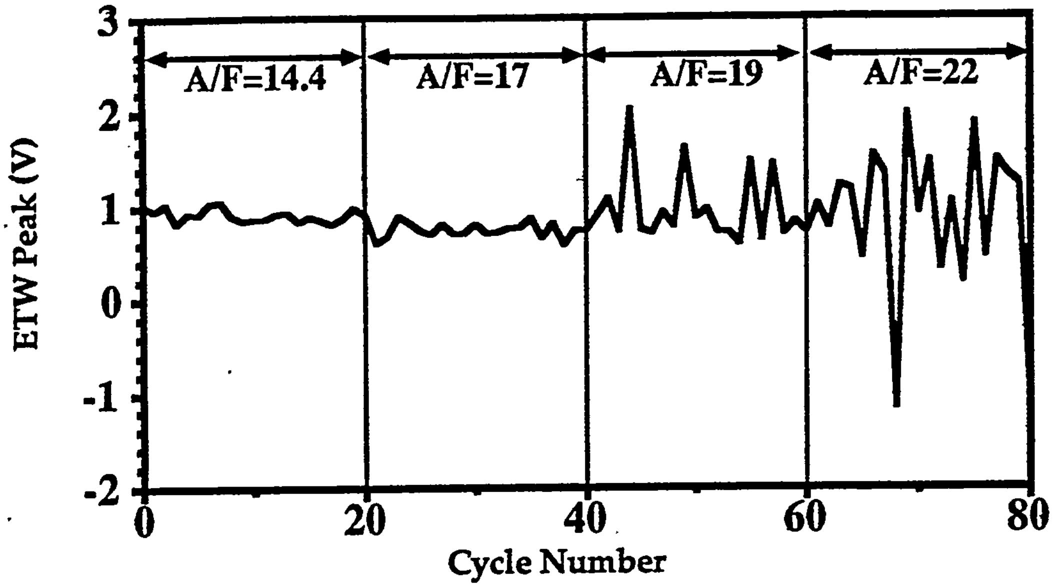
Lean Mixture Comparison of Cylinder Pressure and ETW Signal
(2000 rpm, 2 bar BMEP)



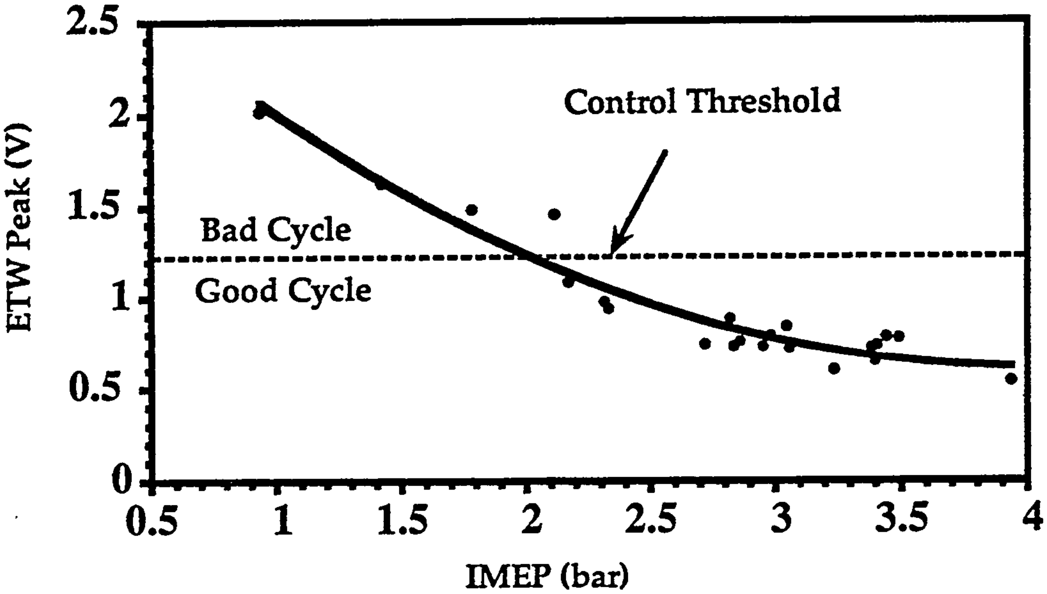
Lean Mixture Comparison of Cylinder Pressure and ETW Signal (2000 rpm, 2 bar BMEP)



Lean Mixture Comparison of Cylinder Pressure and ETW Signal (2000 rpm, 2 bar BMEP)



Effect of Air/Fuel Ratio on Cycle-to-Cycle Fluctuations in Peak ETW Value (2000 rpm, 2 bar BMEP)



Relationship Between Peak ETW Values and Indicated Mean Effective Pressure of Consecutive Cycles (A/F=19)

Synergy Between Ignition System and Combustion Monitoring Technology

- Plasma jet ignition can provide lean limits which are imposed by slow burning rather than ignition failure
- Exhaust Temperature Waveform monitoring is particularly sensitive to slow burning cycles

BIODIESEL - AN UPDATE

Steve Howell, National Biodiesel Board
Leon Schumacher, University of Missouri/Columbia
Wendel Goetz, ORTECH Corporation

(Presentation unavailable at time of publication)

SESSION 6

HOW CLEAN ARE ALTERNATIVE FUELS?

Chair: **Greg Rideout, Environment Canada**

Comparison of Off-Cycle and Cold Start Emissions from Dedicated NGVs and Gasoline Vehicles

Louis Lautman

Gas Research Institute
8600 West Bryn Mawr Avenue
Chicago, IL 60631

OUTLINE OF PRESENTATION

- OVERVIEW
- OBJECTIVES
- TEST VEHICLES & FUELS
- TEST CYCLES
- TEST MATRIX
- RESULTS
- OBSERVATIONS
- REMAINING WORK

OVERVIEW

- Compare exhaust emissions from OEM-built, dedicated NGVs with gasoline vehicles of same make and model
- Funded by Gas Research Institute (GRI)
- Managed by Engine, Fuel, and Emissions Engineering, Inc. (EF&EE)
- Emission testing by Automotive Testing Laboratories
- Testing to be completed in June 1996

OBJECTIVES

- Assess emission benefits of NGVs compared to gasoline vehicles
  - Federal Test Procedure
  - Realistic Driving Conditions
    - Aggressive driving (SFTP)
    - Air conditioning on (SFTP)
    - Low temperature (Cold FTP)
    - Wide open throttle (WOT)

TEST VEHICLES

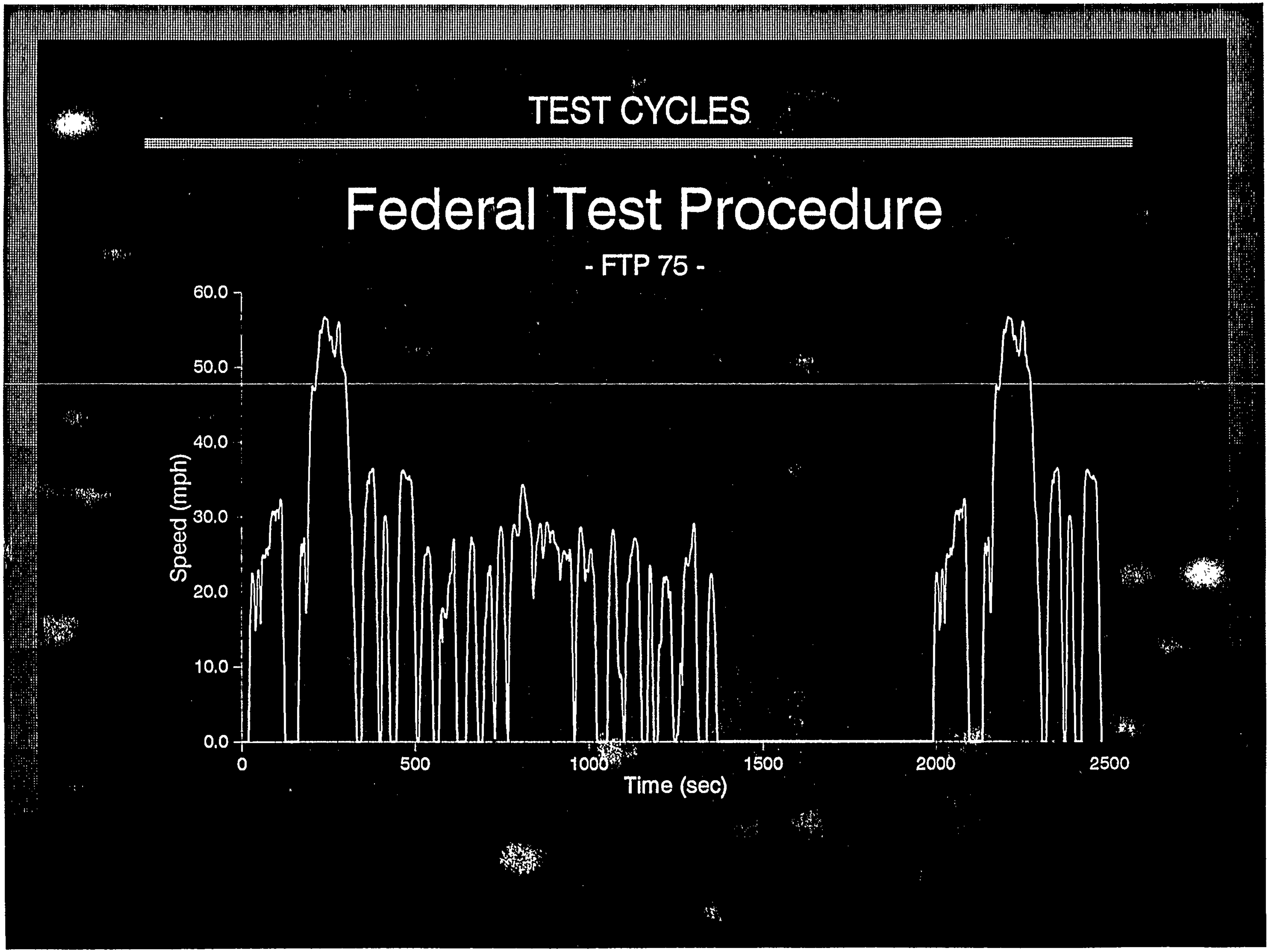
Vehicle #	Fuel	Model	Mileage
A	Gasoline	1995 Ram Van	in progress
B	Gasoline	1995 Ram Van	in progress
C	CNG	1994 Ram Van	24,570
D	CNG	1994 Ram Van	in progress
E	Gasoline	1996 Crown Vic	7,600
F	Gasoline	1996 Grand Mar	8,200
G	CNG	1996 Crown Vic	4,100
H	CNG	1996 Crown Vic	6,000
I	Gasoline	1995 Caravan	14,992
J	Gasoline	1995 Caravan	10,982
K	CNG	1995 Caravan	5,586
L	CNG	1995 Caravan	4,146

TEST FUELS

- RFA Fuel
  - Non-oxygenated "Industry Average" Gasoline
- RFG Fuel
  - Federal Phase 2 RFG with 2% MTBE
- CNG Fuel
  - CARB Certification Fuel
- Gasoline RVP adjusted with butane for Cold FTP testing

TEST CYCLES

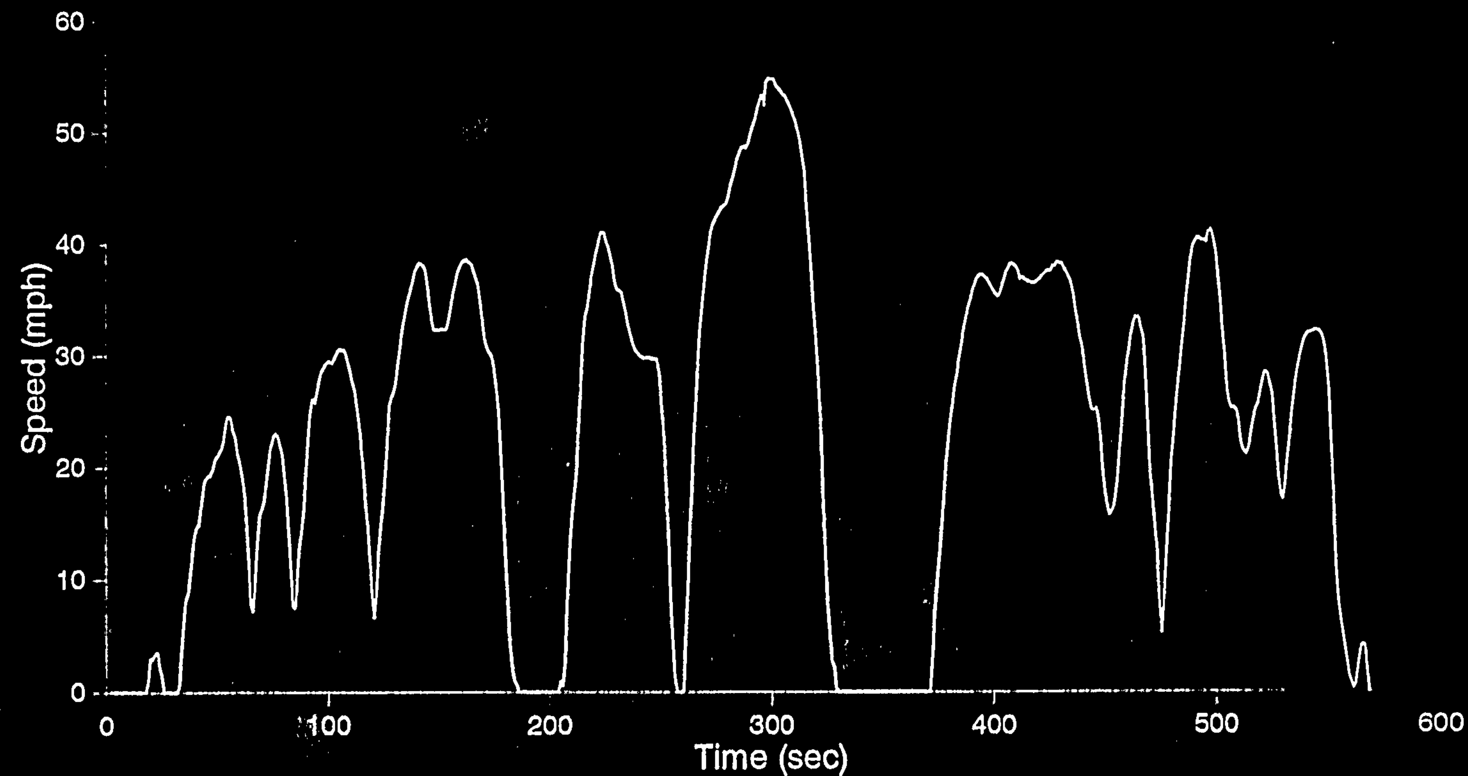
- Federal Test Procedure (FTP)
- Supplemental Federal Test Procedure (SFTP)
  - 866 Cycle, FTP Bag 2 with air conditioning (SFTP Bag 4)
  - Start Control Cycle, SC01 (SFTP Bag 5)
  - Aggressive Driving Cycle, US06 (SFTP Bag 6)
- Cold FTP
  - Similar to FTP except testing is conducted at 20 degree F instead of 75 degree F

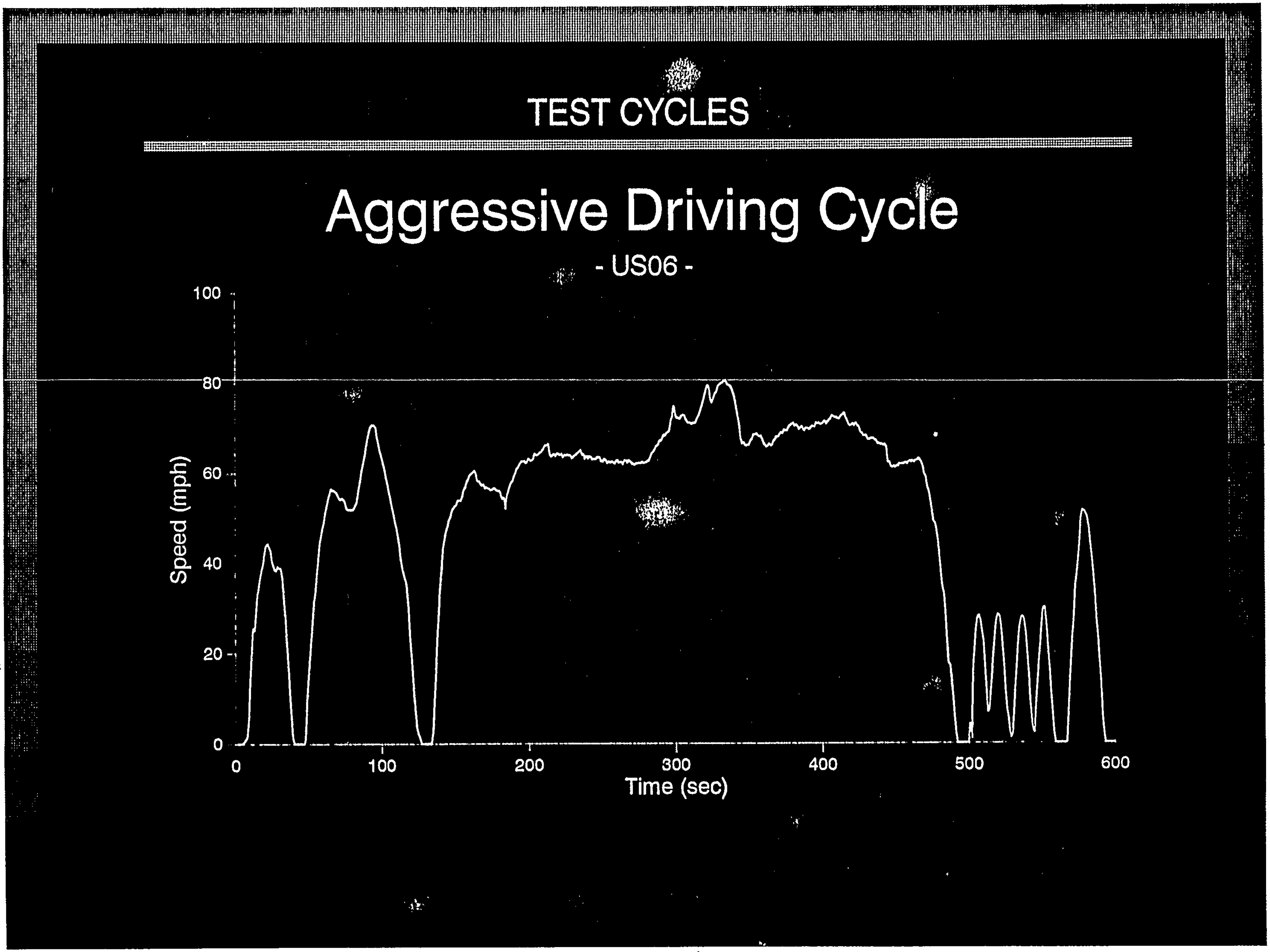

TEST CYCLES
Federal Test Procedure
- FTP 75 -
Speed (mph)
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0
500
1000
1500
2000
2500
Time (sec)

TEST CYCLES

Start Control Driving Cycle

- SC01 -




TEST CYCLES
Aggressive Driving Cycle
- US06 -
Speed (mph)
100
80
60
40
20
0
0
100
200
300
400
500
600
Time (sec)

SUPPLEMENTAL FEDERAL TEST PROCEDURE

EPA Proposed Weighting Scheme for
Pollutants in Composite Calculation

Test Cycle	(Bag #)	THC/NMHC	CO & NOx
FTP 505	(Bag 1)	0.21	0.15
866 with a/c	(Bag 4)	0.24	0.37
SC01	(Bag 5)	0.27	0.20
US06	(Bag 6)	0.28	0.28

TEST MATRIX

Vehicle #	Fuel	FTP	SFTP	Cold FTP	WOT	Speciation
RamVan A	RFA	1	1	1	1	1
	RFG	2	2	2	1	1
RamVan B	RFA	2	2	2	1	1
	RFG	1	1	1	1	1
RamVan C	CNG	1	1	1	1	1
RamVan D	CNG	2	2	2	1	1
CrownVic E	RFA	1	1	1	1	1
	RFG	2	2	2	1	1
GrandMar F	RFA	2	2	2	1	1
	RFG	1	1	1	1	1
CrownVic G	CNG	2	2	2	1	1
CrownVic H	CNG	1	1	1	1	1
Caravan I	RFA	1	1	1	1	1
	RFG	2	2	2	1	1
Caravan J	RFA	2	2	2	1	1
	RFG	1	1	1	1	1
Caravan K	CNG	2	2	2	1	1
Caravan L	CNG	1	1	1	1	1

DATA COLLECTION

- THC, NMHC, CO, NOx, CO_2, and CH_4 Emissions
- Fuel Economy
- Speciation Data
  - NMOG Emissions
  - Benzene, 1,3-Butadiene, Formaldehyde, and Acetaldehyde Emissions
- Other HC species
- Real Time Data (for WOT only)
  - THC, CO, NOx and CO_2 Emissions
  - Catalyst Temperature and Efficiency

REACTIVITY-ADJUSTED NMOG EMISSIONS CALCULATION

- The reactivity-adjusted NMOG was calculated based on the measured NMOG emissions, the specific reactivity (MIR) of the exhaust emissions, and the specific reactivity for RFG assigned by CARB

REACTIVITY-ADJUSTED NMOG EMISSIONS CALCULATION

EXAMPLE: CARAVAN FTP

	RFA	RFG	CNG
NMOG (g/mile)	0.179	0.153	0.009
Specific Reactivity (gO_3/gNMOG)	3.963	3.827	0.022

CARB's Specific Reactivity for RFG is 3.13 gO_3/gNMOG[1]

Therefore:

The Reactivity-Adjusted NMOG is

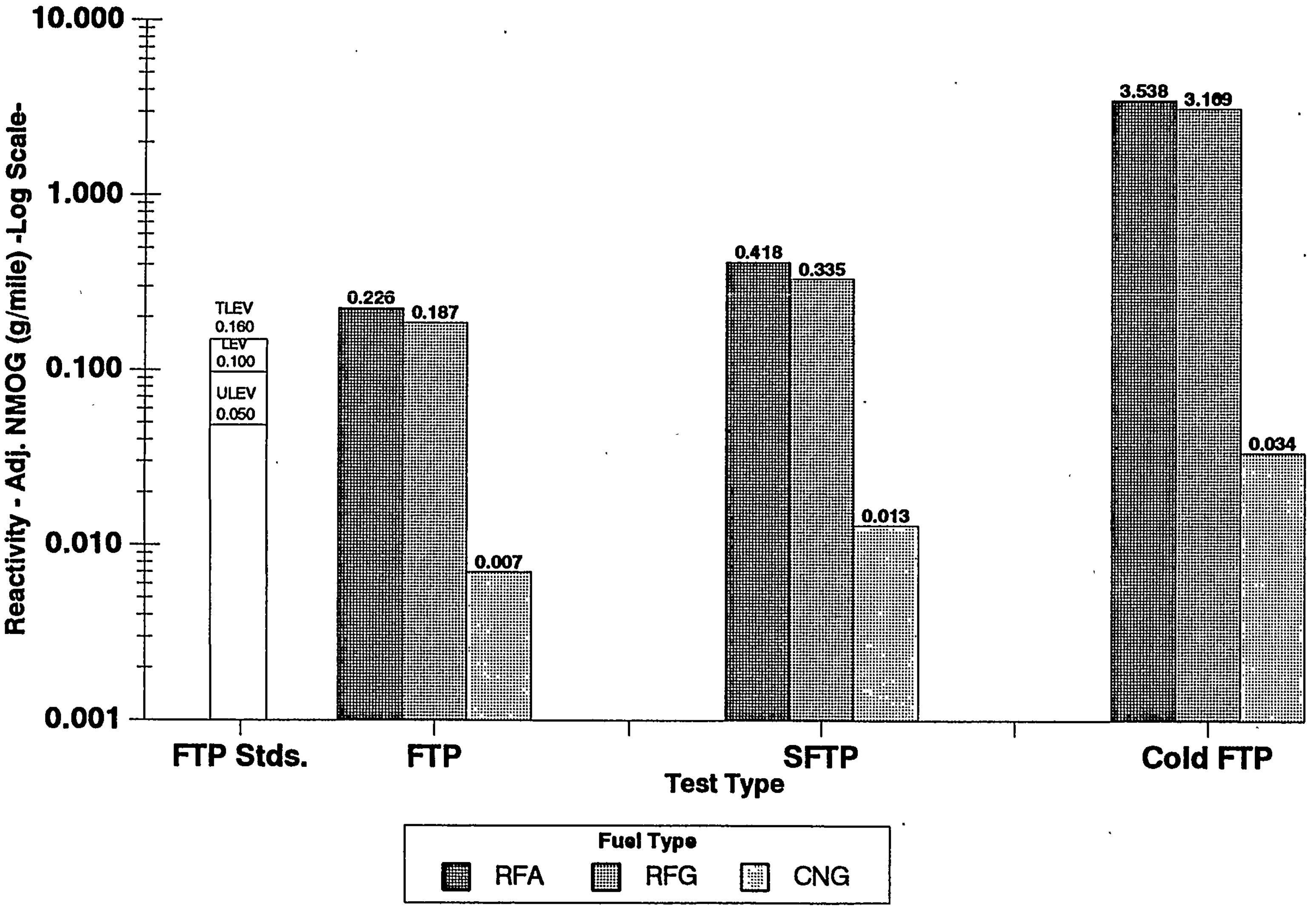
RFA: 0.179*3.963/3.13 = 0.226

RFG: 0.153*3.827/3.13 = 0.187

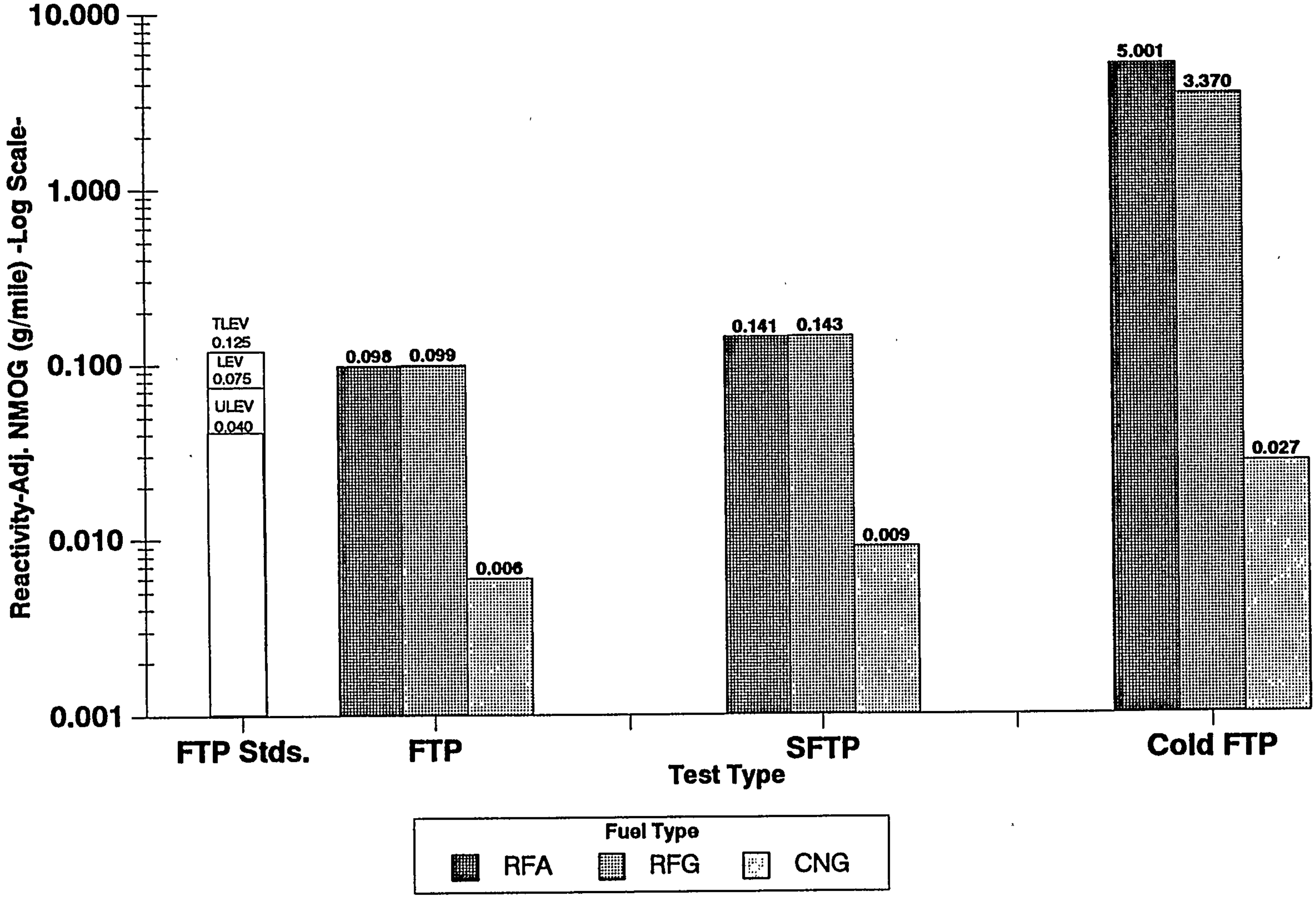
CNG: 0.009*2.417/3.13 = 0.007

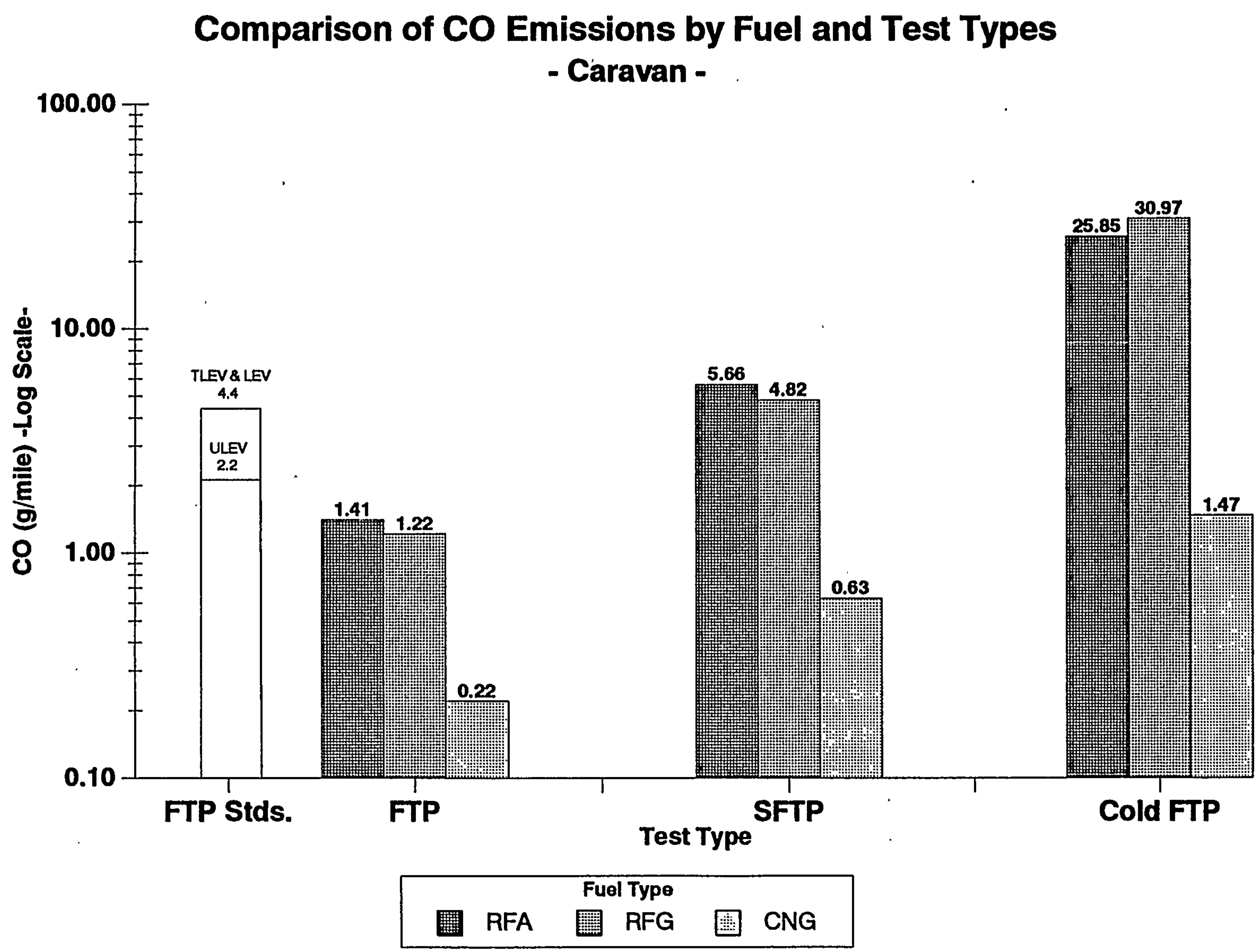
[1] Reactivity Adjustment Factors, CARB 1993

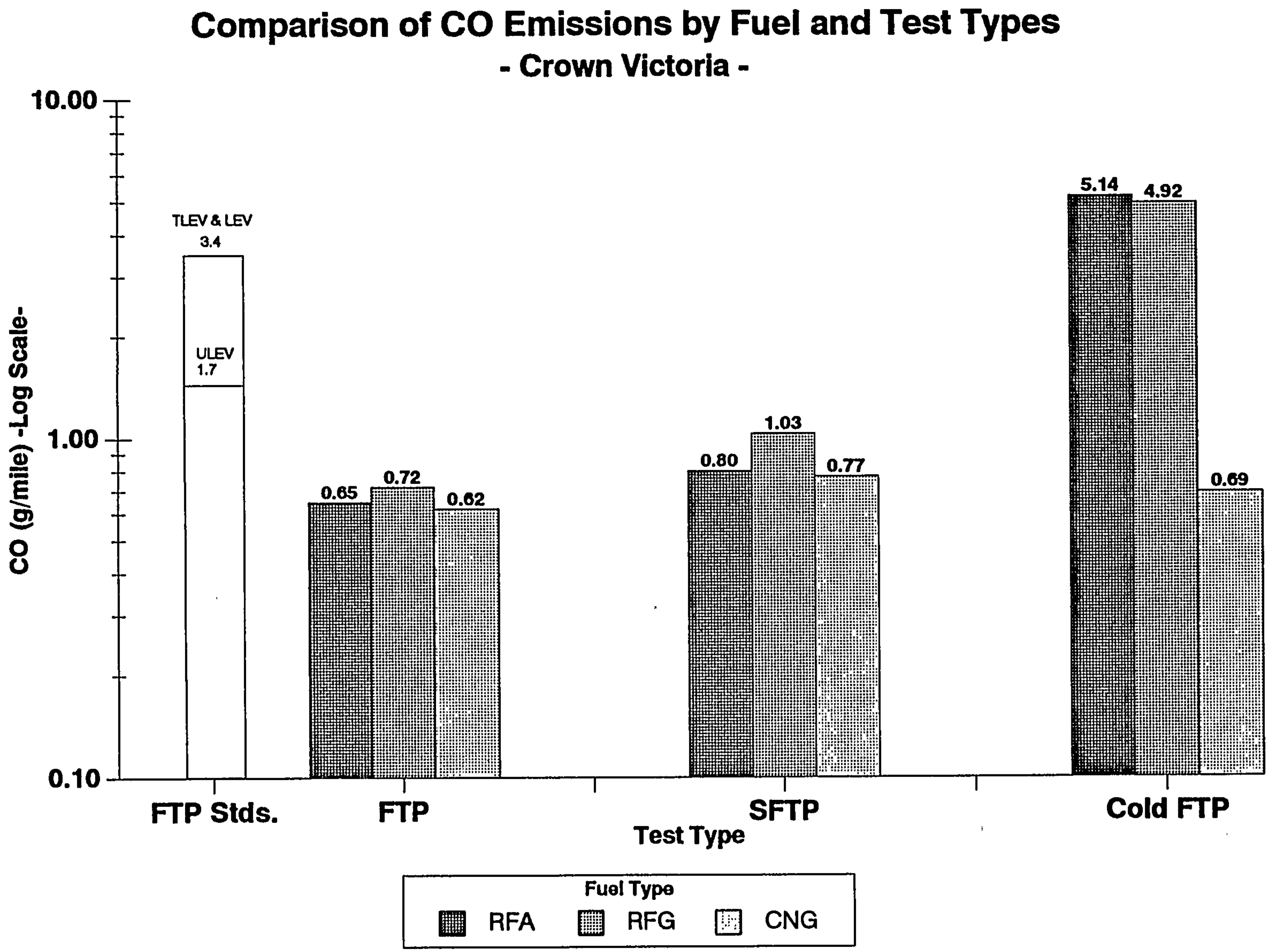
Comparison of Reactivity - Adj. NMOG Emissions by Fuel and Test Types
- Caravan -

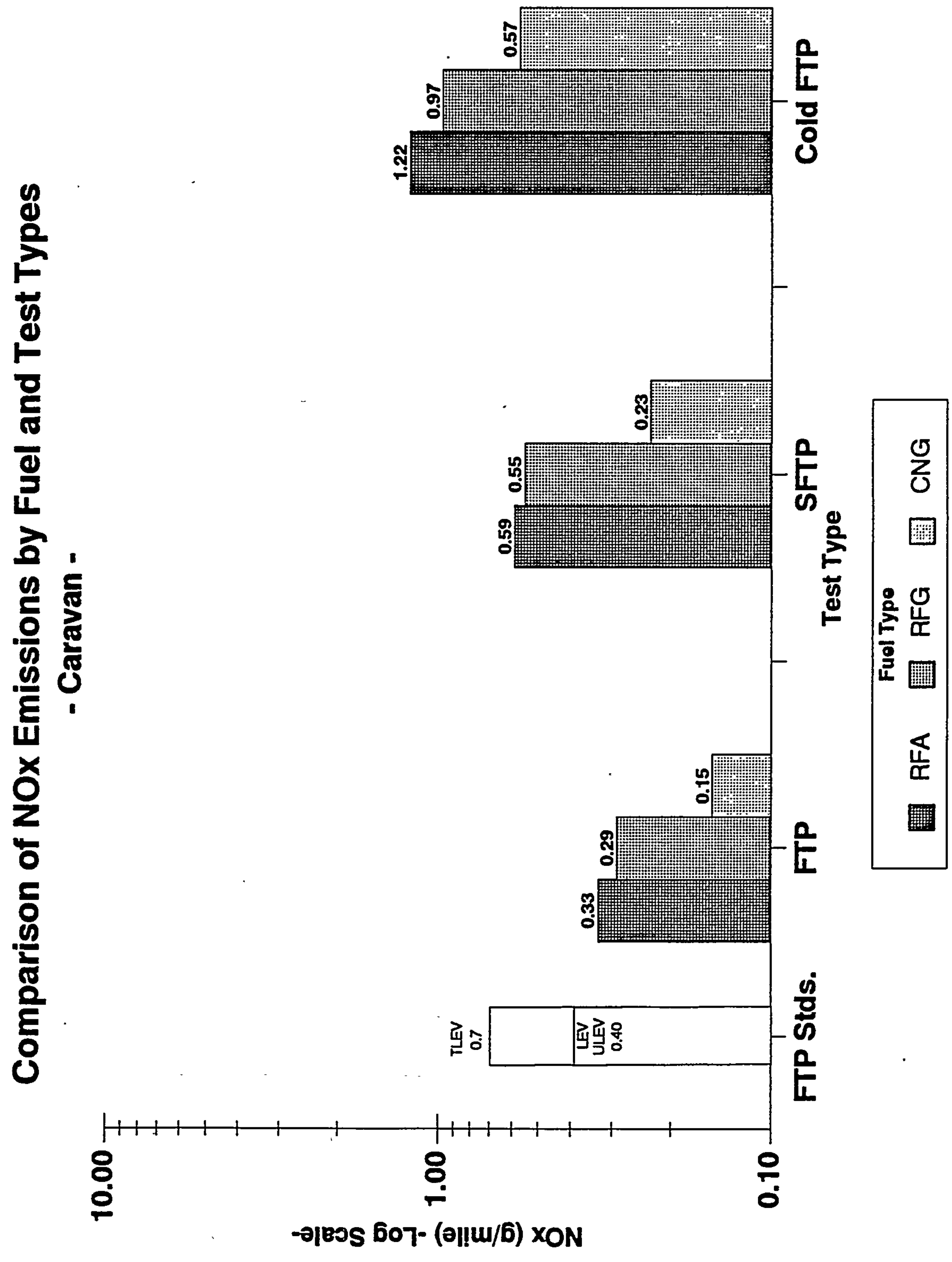


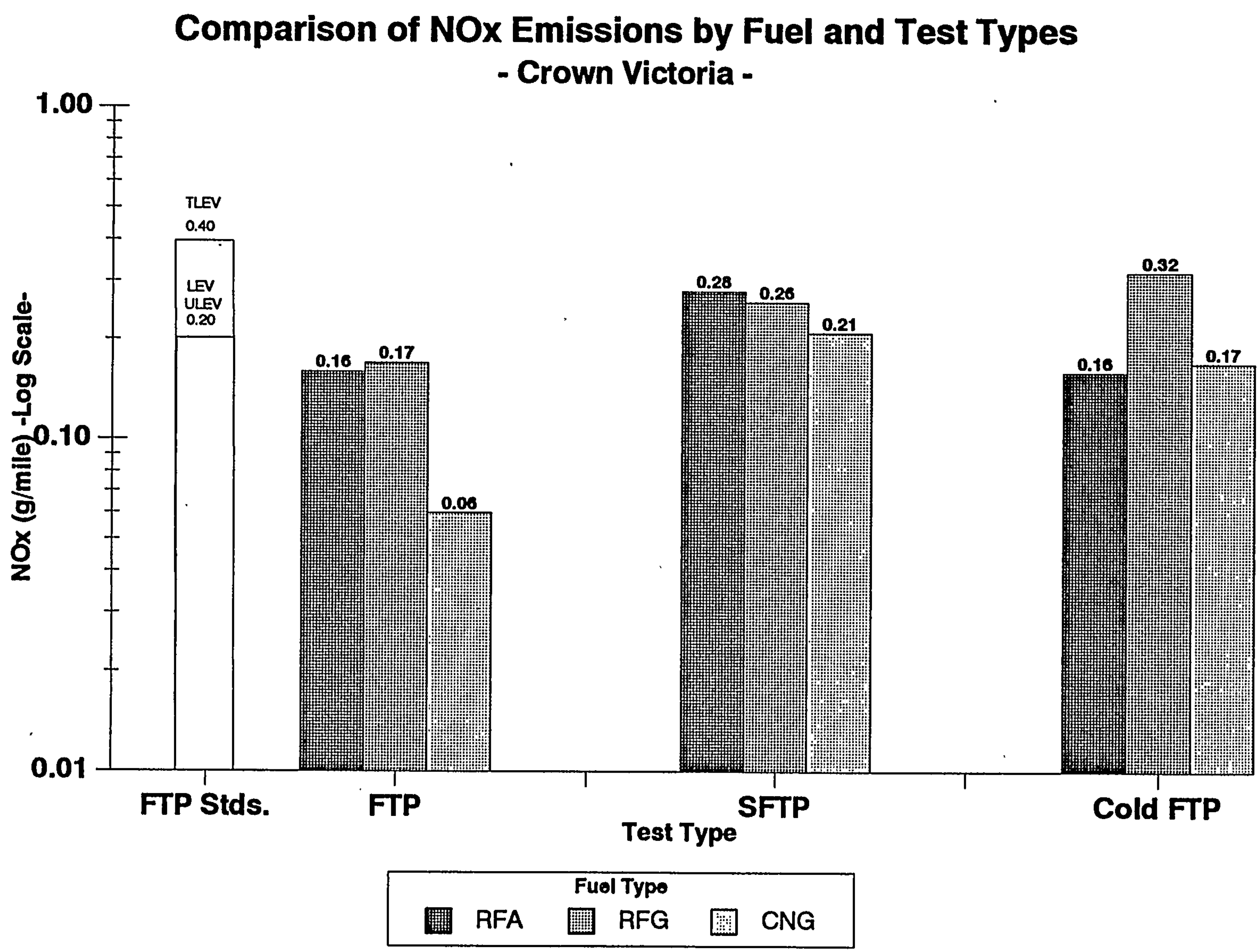
Comparison of Reactivity - Adj. NMOG Emissions by Fuel and Test Types
- Crown Victoria -




Comparison of CO Emissions by Fuel and Test Types
- Caravan -
CO (g/mile) -Log Scale-
100.00
10.00
1.00
0.10
TLEV & LEV
4.4
ULEV
2.2
1.41
1.22
0.22
5.66
4.82
0.63
25.85
30.97
1.47
FTP Stds.
FTP
SFTP
Cold FTP
Test Type
Fuel Type
RFA
RFG
CNG


Comparison of CO Emissions by Fuel and Test Types
- Crown Victoria -
CO (g/mile) -Log Scale-
10.00
1.00
0.10
TLEV & LEV
3.4
ULEV
1.7
0.65
0.72
0.62
0.80
1.03
0.77
5.14
4.92
0.69
FTP Stds.
FTP
SFTP
Cold FTP
Test Type
Fuel Type
RFA
RFG
CNG


Comparison of NOx Emissions by Fuel and Test Types
- Caravan -
NOx (g/mile) -Log Scale-
10.00
1.00
0.10
TLEV
0.7
LEV
ULEV
0.40
0.33
0.29
0.15
0.59
0.55
0.23
1.22
0.97
0.57
FTP Stds.
FTP
SFTP
Cold FTP
Test Type
Fuel Type
RFA
RFG
CNG


Comparison of NOx Emissions by Fuel and Test Types
- Crown Victoria -
NOx (g/mile) -Log Scale-
1.00
0.10
0.01
TLEV
0.40
LEV
ULEV
0.20
0.16
0.17
0.06
0.28
0.26
0.21
0.16
0.32
0.17
FTP Stds.
FTP
SFTP
Cold FTP
Test Type
Fuel Type
RFA
RFG
CNG

TOXICITY-WEIGHTED TOTAL TOXIC EMISSION CALCULATION

- The toxicity-weighted (benzene eqv.) total toxic emissions were calculated from the measured toxic emissions and relative toxicity factors taken from an EPA study[1]
- Toxicity factor was normalized to that of benzene

[1] Motor Vehicle-Related Air Toxic Study, EPA 1993

TOXICITY-WEIGHTED TOTAL TOXIC EMISSIONS CALCULATION

EXAMPLE: CARAVAN FTP

Toxic (mg/mi)	RFA	RFG	CNG	Risk Factor	Weight Factor
Benzene	6.980	4.610	0.070	30.000	1.000
1,3-butadiene	1.070	0.900	0.000	1013.000	34.200
Formaldehyde	3.375	3.790	1.170	46.000	1.600
Acetaldehyde	0.815	0.720	0.080	8.000	0.300

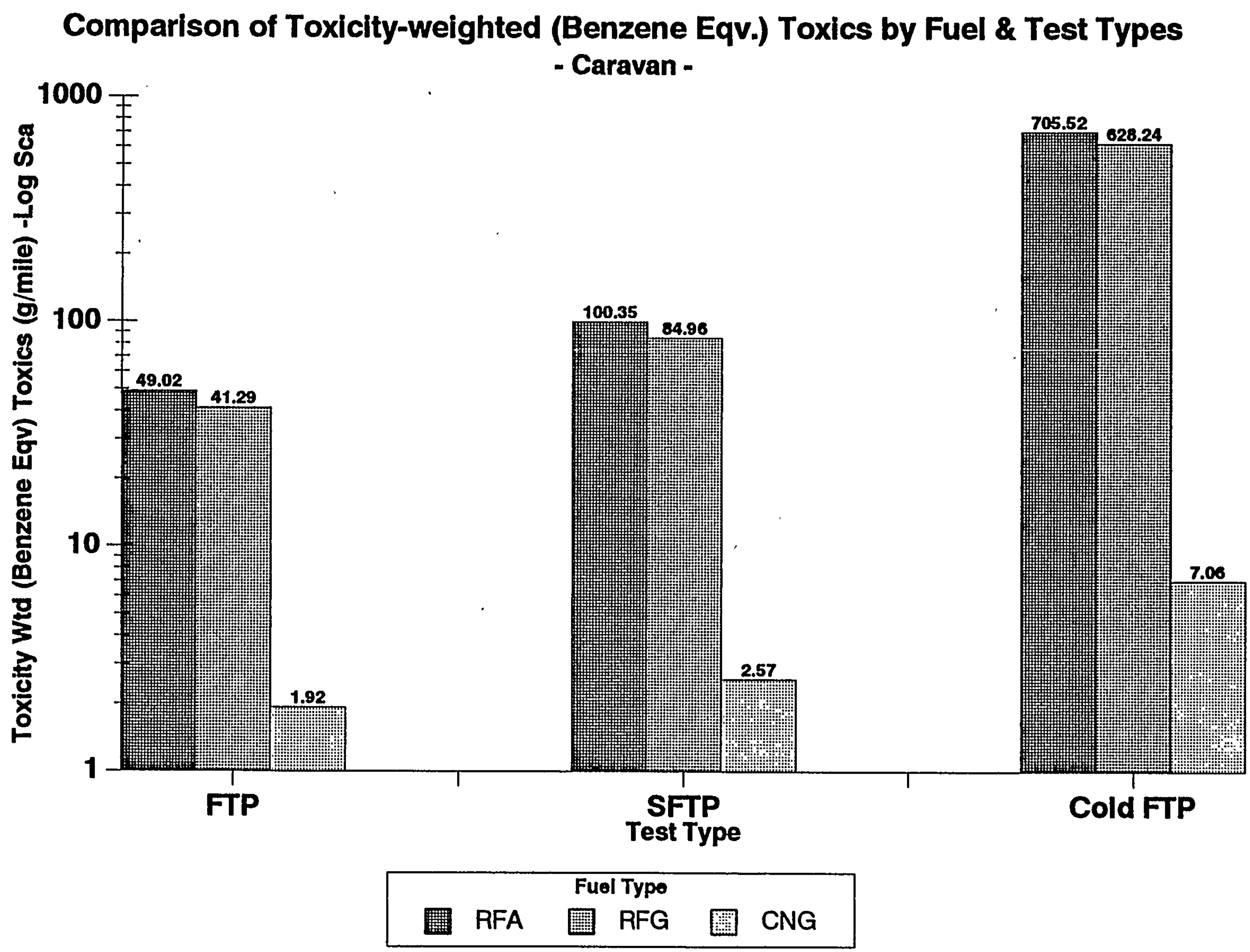
Therefore:

The Toxicity-Weighted (Bezene Eqv.) Total Toxic Emissions is:

RFA: 6.980*1.0 + 1.070*34.2 + 3.375*1.6 + 0.815*0.3 = 49.02 mg/mi

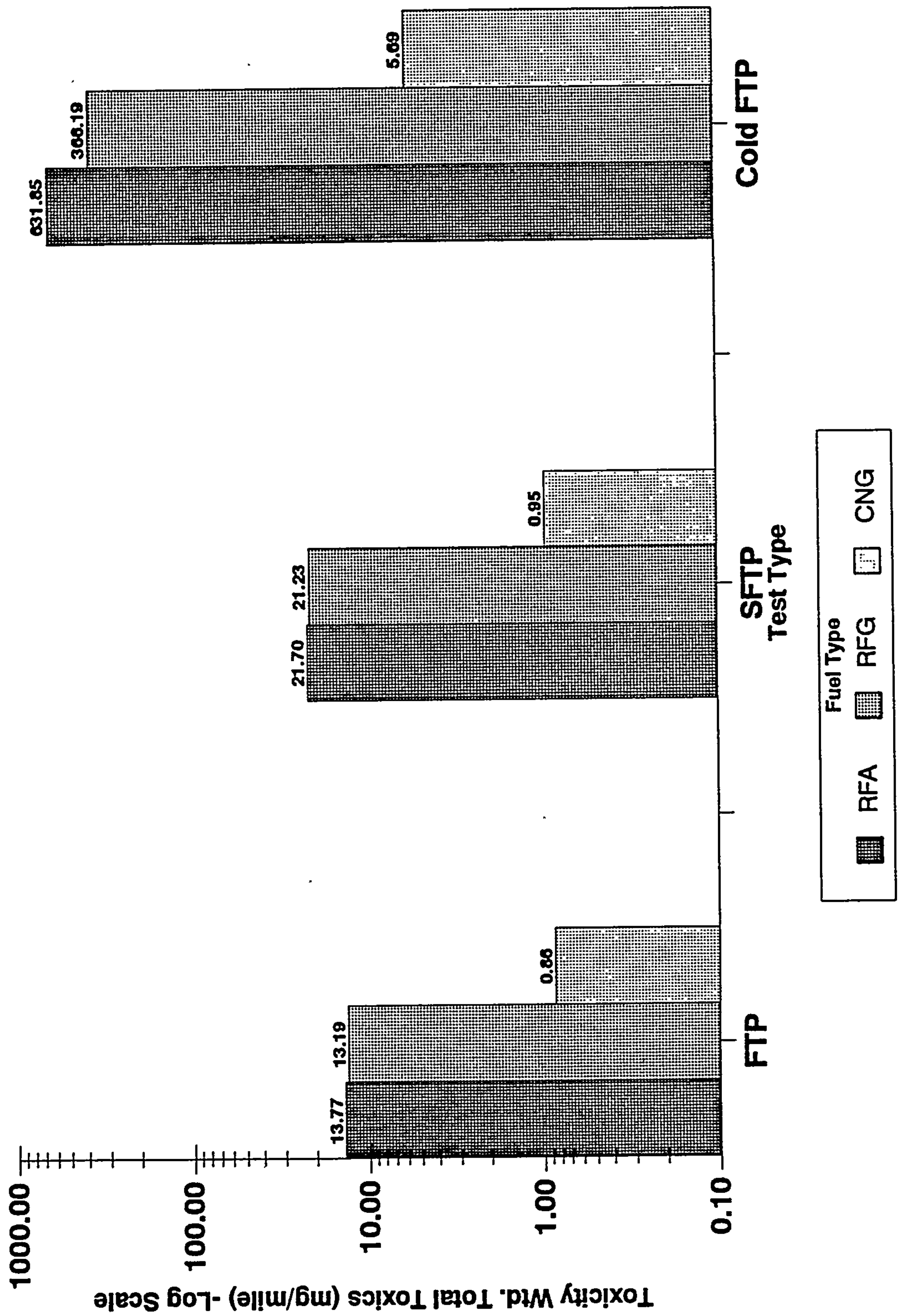
RFG: 4.610*1.0 + 0.900*34.2 + 3.790*1.6 + 0.720*0.3 = 41.29 mg/mi

CNG: 0.070*1.0 + 0.000*34.2 + 1.170*1.6 + 0.080*0.3 = 1.92 mg/mi


Comparison of Toxicity-weighted (Benzene Eqv.) Toxics by Fuel & Test Types
- Caravan -
Toxicity Wtd (Benzene Eqv) Toxics (g/mile) -Log Sca
1000
100
10
1
49.02
41.29
1.92
100.35
84.96
2.57
705.52
628.24
7.06
FTP
SFTP
Cold FTP
Test Type
Fuel Type
RFA
RFG
CNG

Comparison of Toxicity-weighted (Benzene Eqv.) Toxics by Fuel and Test Ty

- Crown Victoria -



OBSERVATIONS

- Significant emission benefits for NGVs on FTP and real driving conditions
- Emission benefits from RFG fuel compared to RFA fuel were modest compared to CNG
- OEM gasoline vehicles are getting cleaner as a result of tightening emission standards

REMAINING WORK

- Complete testing on the last test vehicle (CNG Ram Van) and present the results on this vehicle group
- Analyze and compare unregulated pollutants from speciated data
- Analyze and compare composite and real time data for WOT condition
- Issue final report in August 1996 (Report #: GRI-96/0217)

Direct Comparison of CNG, Methanol, and Gasoline Ford Tauruses in Fleet Operation in New York

Richard Bechtold, P.E., Arthur Vatsky, P.E.
Christopher Moog, P.E., Ajay Yelne
EA Engineering, Science and Technology, Inc.

ABSTRACT

This alternative fuel vehicle (AFV) demonstration project is characterized by its unique approach of comparing CNG, methanol and gasoline fueled vehicles of the same model in operation in a single fleet in Monroe County, (Rochester) New York. Parameters compared include emissions, fuel economy, maintenance and vehicle driveability. The 13 fleet vehicles, including methanol (flexible fuel), CNG (bi-fuel) and gasoline control Ford Tauruses, met requisite safety standards and operated without any safety problems for the test period of three years, accumulating over 240,000 miles. During the data collection period, no fuel system safety problems occurred and no significant fuel system failures occurred. Laboratory testing using the City, Highway and NYCC driving cycles revealed that the flexible fuel vehicles (FFVs) using M85 had the highest energy economy, followed by the gasoline control vehicles and the bi-fuel vehicles using CNG. The bi-fuel vehicles operating on CNG averaged higher CO and NO_x emissions but lower NMHC emissions compared to the FFVs operating on M85 and the gasoline control vehicles. During performance testing the gasoline control vehicles accelerated faster than the FFVs which in turn were significantly faster than the CNG bi-fuel vehicles. The FFVs had fuel system related maintenance whereas the CNG bi-fuel and the gasoline control vehicles had none. Both M85 and CNG fuel vehicles experienced some cold starting problems.

PROJECT DESCRIPTION

The objective of this project was to evaluate methanol (M85)[1] and compressed natural gas (CNG)[2] as alternative vehicle fuels in the same model vehicle as part of the New York State Energy Research and Development Authority's (NYSERDA) Alternative Fuels for Vehicles Fleet Demonstration Program (AFV-FDP). The goals of the AFV-FDP are to develop timely data regarding AFV emissions, so the State can make informed decisions about strategies for meeting federally mandated air quality standards, and to develop an AFV knowledge base enabling fleet operators to act upon mandates requiring adoption of AFVs to improve air quality and reduce dependence on petroleum.

This fleet demonstration is characterized by its unique approach of comparing two alternative

[1]M85 is a mix of 85 volume percent methanol and 15 volume percent gasoline.

[2]CNG is natural gas compressed to decrease its storage volume, allowing the fuel to be carried in compact form suitable for motor vehicles. Typical storage pressures are 2400 psi, 3000 psi, and 3600 psi.

fuels, M85 and CNG, by using them in the same fleet, in similar vehicles, supported by the same maintenance staff, and in the same climatic conditions. Monroe County (the city of Rochester is in Monroe County) co-funded the purchase and conversion of the alternative fuel vehicles with NYSERDA. Additional funding was also provided by the local utility company, Rochester Gas and Electric. The Monroe County test fleet obtained important operational and maintenance information from the M85 flexible fuel, CNG bi-fuel and gasoline control Ford Tauruses. The operation of the fleet began in September 1992 for the M85 vehicles and in May 1994 for the CNG vehicles. A total of 63 emission tests were performed using the City and Highway Cycles of the Federal Test Procedure, and the New York City Cycle. Over 170 vehicle-months of alternative fuel vehicle operating data were obtained.

VEHICLES

The Monroe County alternative fuel demonstration fleet consisted of both M85 and CNG fueled vehicles, listed in Table 1. In addition to these vehicles, this paper also includes the emissions and fuel economy of more recent technology FFVs for comparative purposes. The FFVs used port fuel injection systems with closed-loop control. The bi-fuel vehicles used a port fuel injection system for gasoline and an IMPCO mechanical fuel mixer (carburetor) with electronic feedback control fuel system for CNG. The vehicles operated in suburban/metropolitan traffic conditions. All fleet vehicles operated without any major problems in an extreme temperature environment spanning 115 degrees Fahrenheit.

Table 1. Project Vehicles

No. of Vehicles	Vehicle Type	Fuel System Configuration	Engine Configuration
5	1991 Ford Taurus	Flexible Fuel M85/gasoline (operates on M85 and gasoline)	3.0 liter V-6, 144 hp
3	1994 Ford Taurus	Bi-Fuel CNG/gasoline (manual fuel selection)	3.0 liter V-6, 140 hp
5	1992/94 Ford Taurus	Gasoline Only (Control Vehicles)	3.0 liter V-6, 135 hp (1992) 3.0 liter V-6, 140 hp (1994)

Methanol Flexible Fuel Vehicles

The M85 vehicles consisted of five FFVs capable of operation on both M85 and gasoline. The FFVs started operation in the fall of 1992 and continued through October 1994, when at Ford's request, the five FFVs were converted to dedicated gasoline operation because Ford was no longer going to support these vehicles with FFV replacement parts. Figure 1 shows a schematic detailing the fuel system related components of the FFV Taurus that are modified from those for gasoline only operation. Of these, the methanol fuel sensor and the cold-start injector mounted on the throttle body are the only added components.

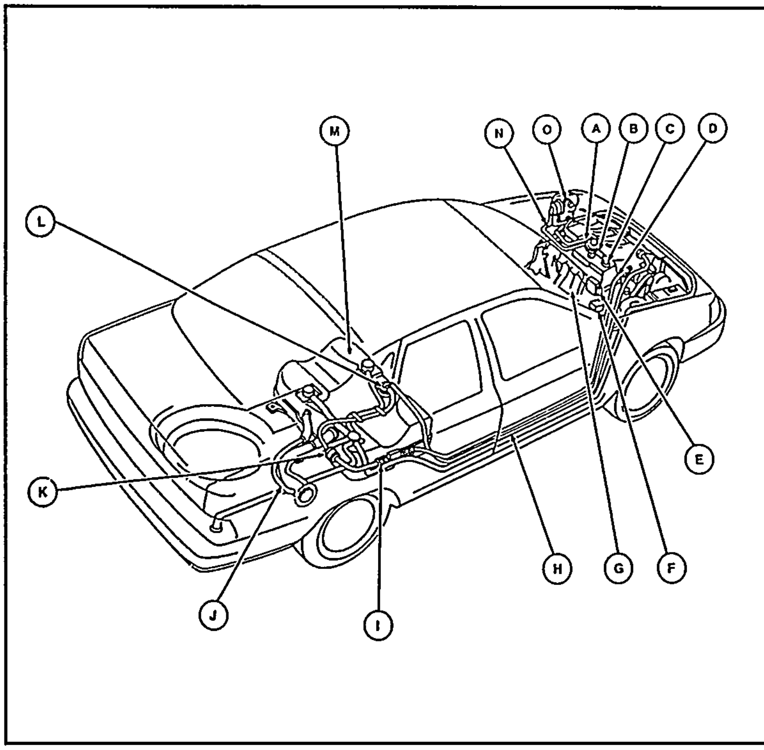


Figure 1. M85 Flexible Fuel Taurus Schematic
Courtesy: Ford Motor Company

COMPONENT SUMMARY	
A	Spark Plugs
B	Fuel Injectors
C	Fuel Rail
D	Fuel Pressure Regulator
E	EEC-IV Microprocessor
F	Wiring Harness
G	Engine Oil
H	Fuel Supply/return/vapor Lines
I	Fuel Sensor
J	Filler Pipe
K	Fuel Filter
L	Fuel Pump Assembly/ Fuel Sending Unit
M	Fuel Tank
N	Cold Start System
O	Evaporative Emissions System

CNG Bi-fuel Vehicles

In the spring of 1994 CNG fuel systems were added to three new 1994 Ford Tauruses making them bi-fuel gasoline and natural gas vehicles. One Brunswick CNG tank per vehicle was used for fuel storage and was placed in the trunk compartment. The fuel tank is made from composite materials for weight savings and has a storage capacity equivalent to 9 gallons of gasoline. When operating on CNG alone, the vehicle should be able to go 200 miles plus an additional 350 miles on gasoline for a total of 550 miles.

The total conversion cost per vehicle was approximately $4,200. The CNG system uses the existing O_2 sensors to provide a signal to adjust the mixture strength of natural gas and air. The vehicles began operation in May 1994. Figure 2 illustrates one of the CNG bi-fuel vehicles.

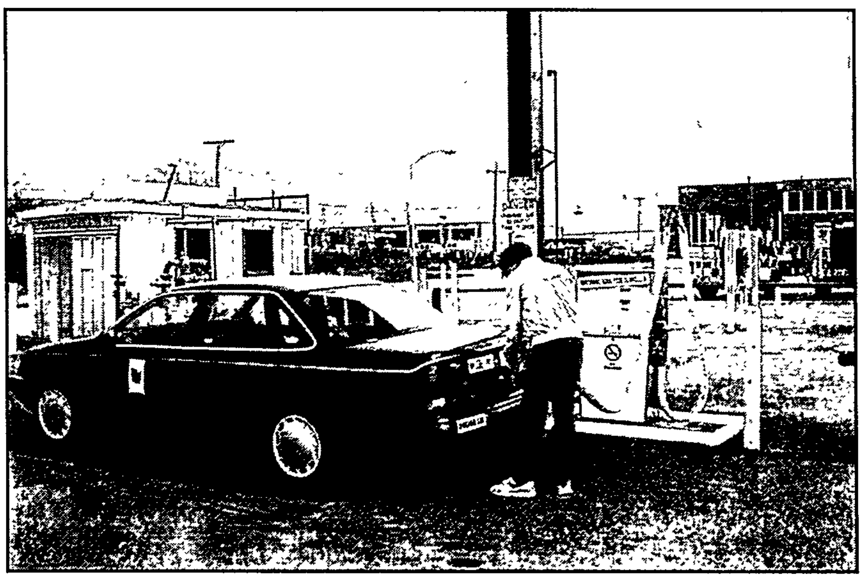


Figure 2. CNG Bi-fuel Vehicle Being Refueled

FACILITIES

Refueling Facilities

The M85 refueling facility, shown in Figure 3, consisted of a 1,000 gallon aboveground storage tank and dispenser. The storage tank, its accessories, and the dispenser were designed and specified for use with both neat methanol and its blends such as M85. Both the storage tank and the M85 dispenser were configured for Stage II vapor recovery. The system functioned in the same manner as a conventional gasoline dispensing system. The fire suppression system for the refueling facility provided both overhead and curb level fire protection.

Figure 3. M85 Refueling Facility

Figure 4 illustrates the CNG refueling facility that was installed by Rochester Gas and Electric (RG&E) and is located on their own property, approximately 2.5 miles from the Monroe County maintenance facility. While not open to the general public, the CNG station is available for fueling private vehicles by prior arrangement. Vehicles need a RG&E-issued refueling card in order to use the facility.

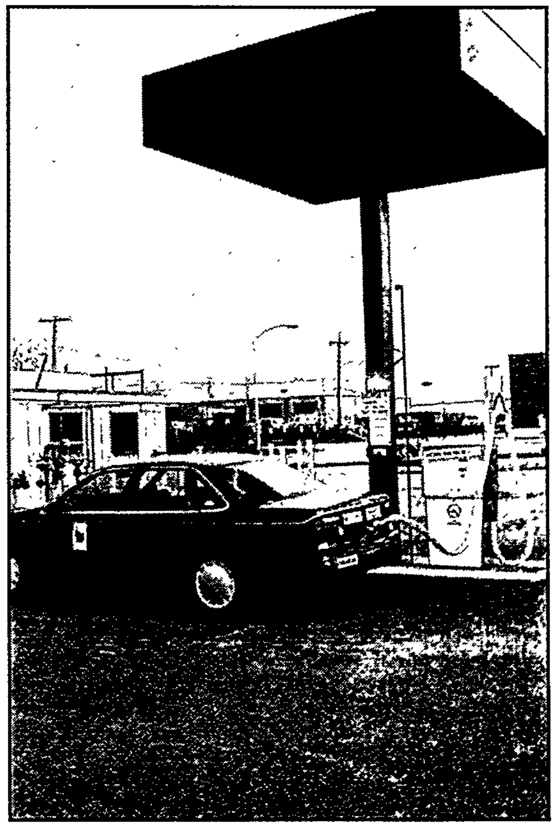


Figure 4. CNG Refueling Facility

Maintenance Facilities

Before the FFVs were implemented, Monroe County personnel were given safety training about handling methanol fuel. In that training personnel were taught how to properly store and dispose of waste M85 during vehicle maintenance activities. No modifications of the maintenance facility were deemed necessary at that time to accommodate the FFVs.

A site safety assessment of the vehicle storage and maintenance facilities was performed in April 1994 in anticipation of maintaining and storing the CNG bi-fuel vehicles. In compliance with the recommendations of this site assessment, Monroe County upgraded their hoist, lift, and garage door opener for the CNG bay. These upgrades were electrical modifications intended to minimize the risk of overhead ignition sources. New procedures for risk minimization were adopted, including keeping CNG vehicles outdoors overnight and servicing them when CNG tank pressure is low. Future upgrades, currently awaiting funding, include purchasing of a methane detection system, higher speed ventilation fan, and installation of a heating system that does not present ignition sources.

FUEL USAGE AND MILEAGE ACCUMULATION

Table 2 gives the details of fuel usage and mileage accumulation for all the demonstration vehicles. The FFVs accumulated over 120,000 miles over 26 months of operation and the CNG bi-fuel vehicles accumulated approximately 29,000 miles over 15 months of operation. M85 and CNG usage remained high throughout the duration of the project and M85 accounted for 66% of the total fuel consumption (volume based) for FFVs and CNG accounted for 78% of the total fuel consumption (energy based) for the CNG bi-fuel vehicles. Figure 5 illustrates the cumulative distance traveled and the fuel consumed by the M85 vehicles. Figure 6 illustrates the cumulative distance traveled and total fuel usage by CNG vehicles.

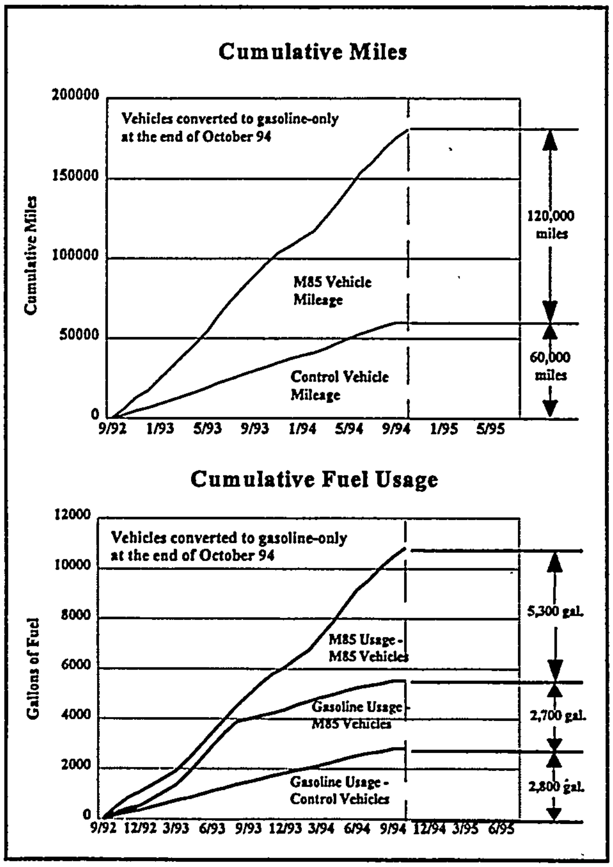


Figure 5. Cumulative Miles and Fuel Usage - M85 Vehicles

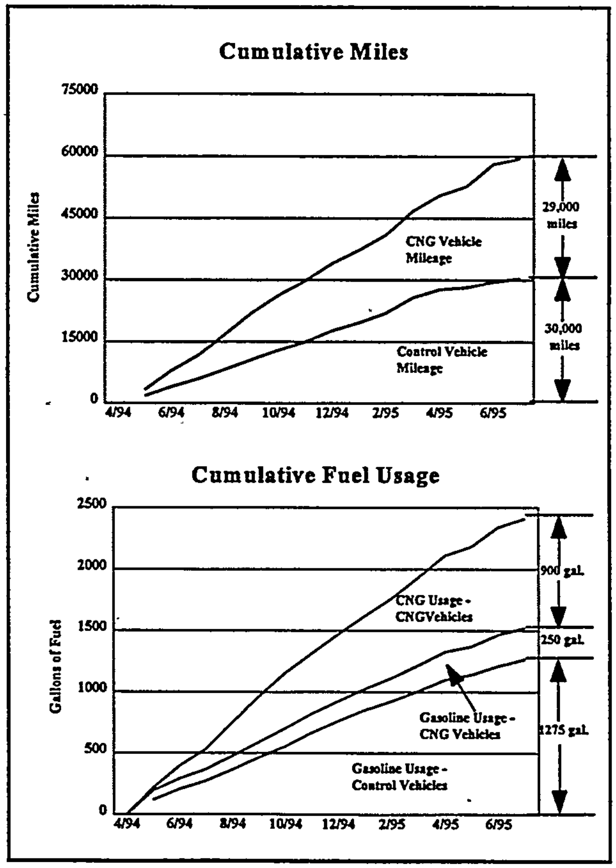


Figure 6. Cumulative Miles and Fuel Usage - CNG Vehicles

Table 2. Fleet Fuel Consumption and Mileage Accumulation

Vehicle Information		Miles/ Vehicle	Months of Service	Miles/ month/ vehicle	Alternative Fuel Usage (Gals.)	Gasoline Usage (Gals.)	Alternative Fuel Usage (% of total fuel used)
Type	#						
1991 M85 - FFVs	5	24,103	25	964	5,285	2,737	66%
1992 Gasoline Control	3	20,029	25	801	NA	2,423	NA
1994 CNG - Bi-fuel	3	9,662	16	604	886	256	78%
1994 Gasoline Control	2	15212	16	951	NA	1268	NA

The cost of fuel varied during the course of the project. Gasoline prices ranged from $0.50/gal in the beginning of the data collection period in 1993 to $0.70/gal after the summer of 1995. Similarly, CNG prices[3] varied from $0.50/gal in early 1994 to $0.67/gal in the summer of 1995. M85 prices were steady and averaged $1.32/gal. This is equivalent to $2.30 per gasoline equivalent gallon. (All reported prices do not include taxes.) Gasoline was typically 3-4 cents more expensive than CNG per equivalent gallon.

DRIVEABILITY

Starting problems during the cold winter months were initially present with the FFVs caused primarily by M85 with insufficient vapor pressure. (The M85 was splash-blended using summer grade gasoline.) This resulted in some of the drivers refueling their cars using gasoline instead of M85. A fresh batch of M85 using winter grade gasoline was procured and the starting problems were cured.

In the winter of 1994, cold weather also caused the CNG vehicles to have longer starting times. During acceptance testing after installation of the CNG fuel systems, a hesitation problem was found. This problem was fixed by resetting a dip switch in the ignition electronics box of the CNG fuel system. Since that time, the problem has not recurred. The fleet manager at Monroe County reported that the overall driveability of these vehicles was acceptable. There was a reduction in acceleration time, which is discussed in the next section.

ACCELERATION TESTING

Acceleration performance was recorded by conducting quarter-mile, wide-open-throttle acceleration runs from a standing start. Figure 7 presents the speed vs. time relationships for the

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[3] CNG prices are reported per gasoline equivalent gallon.

CNG bi-fuel, the 1993 M85 flexible fuel, and gasoline control vehicles. Table 3 gives the 0-60 mph acceleration times. The FFVs operating on M85 averaged 11.6 seconds to accelerate from 0-60 mph and were 0.9 seconds slower than the gasoline control vehicles which averaged 10.7 seconds. On gasoline the FFVs averaged 0.2 seconds slower than on M85 for the same test. The 0-60 mph times for the CNG bi-fuel vehicles operating on CNG averaged 14.4 seconds, 3.7 seconds slower than the gasoline control vehicles. The loss of power when using CNG is due primarily to fuel system calibration and not vehicle weight increase (about 140 lbs.), because when running the CNG bi-fuel vehicles on gasoline, the acceleration time was just slightly slower than the gasoline control vehicles.

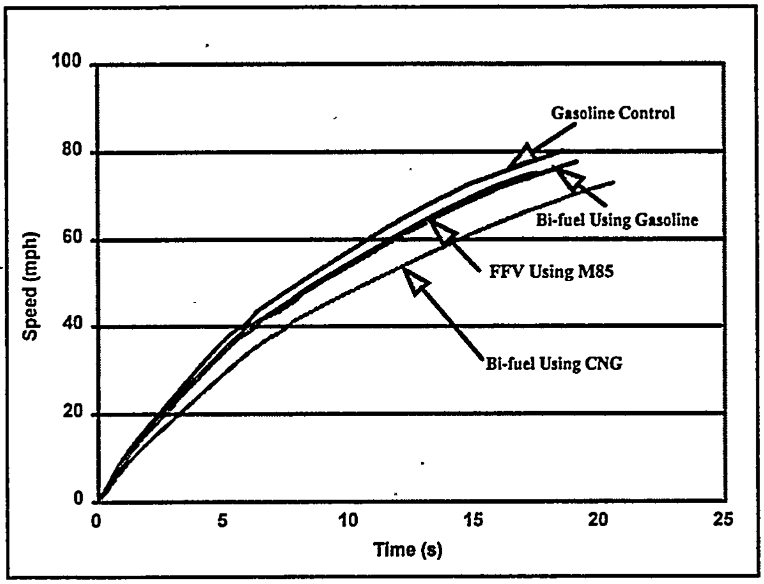

Figure 7. Acceleration Performance

Table 3. Acceleration Performance

Vehicle	Fuel	Time (s) 0-60 mph
FFV	M85	11.6
FFV	Gasoline	11.8
Bi-fuel	CNG	14.4
Bi-fuel	Gasoline	11.8
Control	Gasoline	10.7

MAINTENANCE

Analyses of fuel system related repairs were conducted to look for trends between vehicle types, with respect to weather and with accumulated mileage. It was expected that maintenance actions regarding the fuel and cranking system would be more frequent in winter periods. Figure 8 shows the vehicle starting problems with time through the project duration and the average daily temperature. As expected, in periods of cold ambient temperatures the frequency of starting problems increased.

Further analysis of the differences between the M85, CNG, and gasoline control vehicles reveal that while CNG system starting problems were present in the winter of 1994-1995, they remained well under the level of the FFVs using M85. Most of the initial FFV starting problems were caused by M85 with insufficient vapor pressure, which was subsequently corrected. However, the most cold start problems with these FFVs occurred when the temperature was the coldest in the winter of 1993-94. FFVs using M85 appear to be inherently more difficult to start in cold weather than gasoline or CNG vehicles. This is likely due predominantly to the fact that

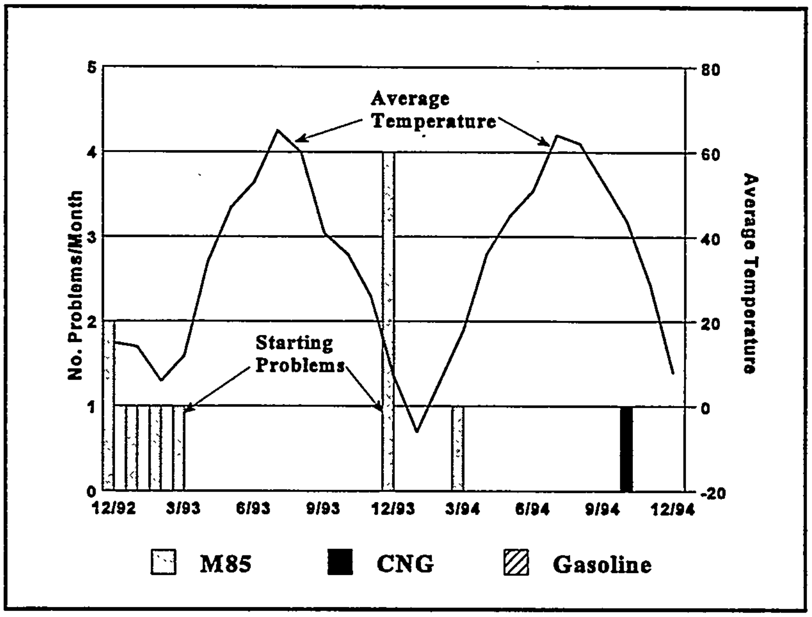

Figure 8. Vehicle Starting Problem Frequencies by Date

methanol does not vaporize as rapidly as gasoline does, and that methanol is conductive, and will short circuit spark plugs wet with liquid methanol. As the outside air temperature drops, a methanol fueled vehicle adds more fuel to assure that sufficient vapor is produced for cold-start. This increases the probability of the spark plug wetting and fouling. M85 fleets have sometimes chosen to add more gasoline to the methanol/gasoline blend during cold weather, which makes more gasoline available to vaporize so that the engine is able to start more reliably. Once started and warmed up, the methanol and gasoline are ignited with no further problems. The gasoline control vehicles had no starting problems during the period of data collection.

Over the course of the project there were four failures of the Ford M85 fuel pump module and two failures of the fuel sensors. Replacement components were installed for each of these failures. This was a common problem in 1991 Ford Taurus FFVs and also occurred in earlier model FFVs such as the Ford Crown Victoria. Figure 9 presents the fuel system repairs. The figure shows that all repairs were for the flexible fuel systems. The CNG and gasoline systems had no fuel system maintenance.

Oil changes for all the vehicles averaged between 3,000 and 4,000 miles. No attempt was made to optimize oil change frequencies based on the fuel used. All vehicles had similar, acceptable oil consumption rates.

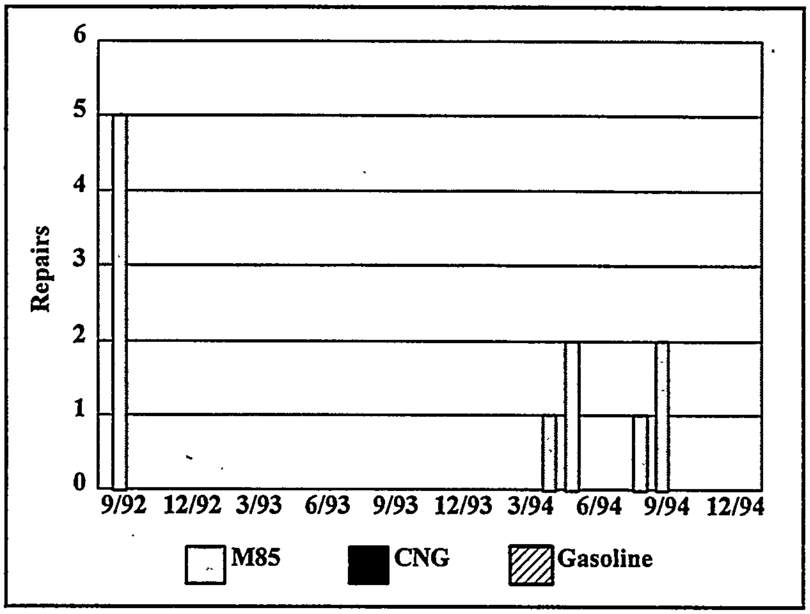

Figure 9. Fuel System Repair Frequencies

FUEL ECONOMY

Energy economy[4] was measured and compared both in the laboratory under highly controlled conditions and on-road in actual use. Table 3 compares average values for both the laboratory and on-road fuel/energy economy results.

Table 3. Comparison of Average Laboratory and On-Road Fuel Energy Economies

			Highway	City	NYCC	On-road
M85 FFV	1991	M85 (Volumetric) M85 (Energy Eq.)* Gasoline	20.3 35.8 33.0	12.4 21.9 19.5	6.3 11.2 10.0	13.4 23.7 22.5
	1993	M85 (Volumetric) M85 (Energy Eq.)* Gasoline	20.2 35.7 35.3	12.6 22.2 21.6	6.6 11.6 11.1	N/A
Control		Gasoline	34.4	21.0	10.9	22.2
CNG Bi-fuel		CNG*	33.7	19.4	9.6	24.0
		Gasoline	36.1	21.5	11.1	23.6

* M85 and CNG fuel economy reported in miles/gasoline equivalent gallons
N/A- The 1993 M85 FFVs were operated by the New York State Thruway Authority. Since they operate mostly on the Thruway (similar to most interstates) at relatively high and constant speeds, their on-road mileage is not comparable.

[4] Energy economy is the distance in miles traveled by the vehicle on fuel which contains the same amount of energy as a gallon of gasoline i.e. 115,400 Btu.

Laboratory Fuel Economy

Laboratory fuel economies were obtained as an integral part of the emissions testing conducted on the demonstration vehicles. For these tests three 1991 model year M85 flexible fuel, four 1993 model year M85 flexible fuel, three 1994 model year CNG bi-fuel, and three gasoline control Ford Taurus vehicles were tested from 1993 through 1995. The fuel economy results from these tests are presented in Figures 10 and 11. These figures present the laboratory fuel economy results for the Highway and Urban (City) Cycles of the Federal Test Procedure and the New York City Cycle (NYCC) driving cycles in the form of floating bars. The top of the bar represents the maximum, the bottom represents the minimum and the line inside represents the average fuel economy sampled. The on-road fuel economies are represented similarly.

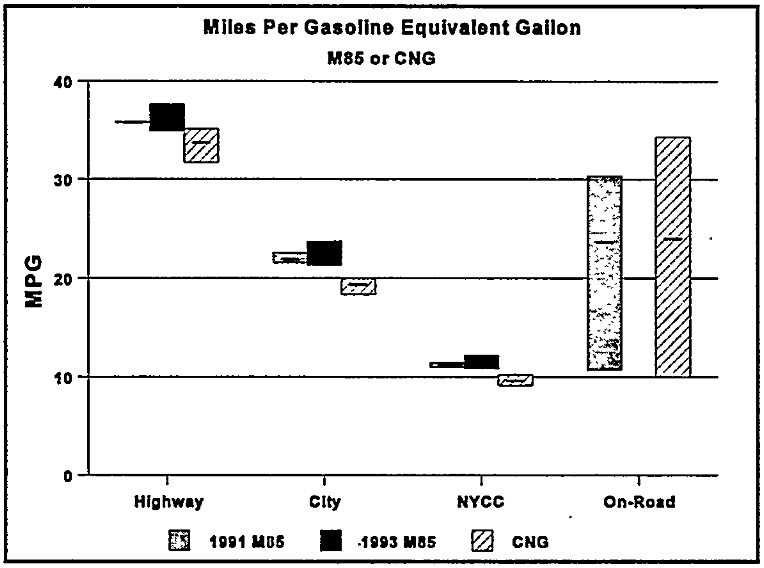

Figure 10. M85/CNG Energy Economy

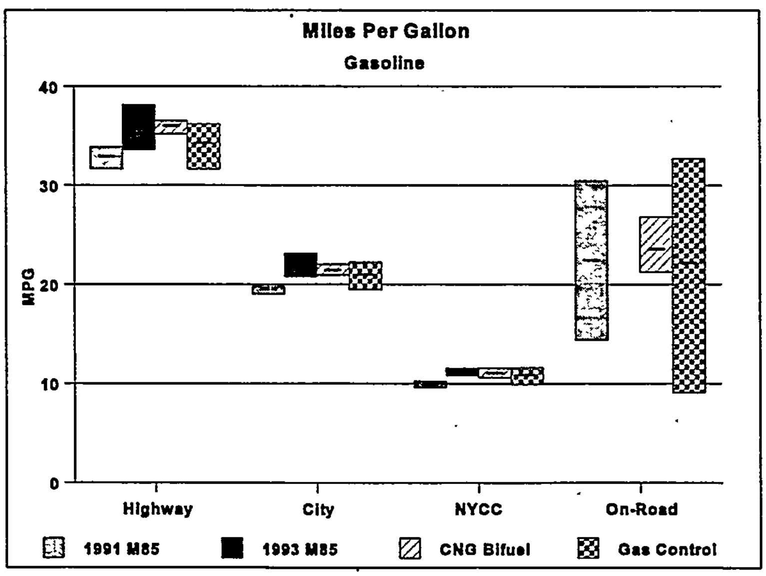

Figure 11. Gasoline Fuel Economy

On Road Fuel Economy

The on-road fuel economies for the 1991 model year FFVs and the gasoline control vehicles were calculated by measuring the amount of miles traveled by each vehicle and dividing it by the number of gallons of fuel consumed in that period. For the CNG bi-fuel vehicles, on-road energy economies were calculated by dividing the miles traveled in a given time interval by the gasoline energy equivalent gallons of CNG consumed in that same interval.

Discussion of Fuel Economy Results

Comparison between on-road and laboratory fuel economies indicate that the laboratory FTP City Cycle fuel economies most closely resemble the on-road fuel economies. This is not surprising due to the fact that the vehicles operated primarily in city/suburban driving conditions.

Direct comparison between M85 and CNG energy economies obtained from laboratory tests indicates that for all of the three test cycles, both 1991 and 1993 model year M85 FFVs averaged higher in energy economy relative to CNG vehicles. A possible explanation for this could be that the M85 vehicles were OEM vehicles and hence better optimized for operation on M85, whereas the calibration of the CNG bi-fuel vehicles is always a compromise. The CNG bi-fuel vehicles also were heavier by the weight of the CNG fuel system and cylinders, estimated to be about 140 pounds.

The energy economies for the 1991 and 1993 FFVs on M85 are very similar and higher than those on gasoline for both dedicated gasoline vehicles and the FFVs. However, the energy economy for operation on CNG is lower than that for operation on gasoline. Average on-road energy economies were similar for the FFVs operating on M85 and for bi-fuel vehicles operating on CNG and gasoline. Gasoline control vehicles and FFVs operating on gasoline had slightly lower energy economies.

EMISSIONS

Collection of emissions data was a very important part of the Monroe County M85/CNG demonstration project. Since 1993 emission tests were performed on three 1991 M85 flexible fuel Ford Tauruses, three 1994 CNG bi-fuel Ford Tauruses, and three gasoline control Ford Tauruses.

In accordance with the Federal Test Procedure, the exhaust of each test vehicle was sampled and analyzed for major emission constituents: carbon monoxide (CO), oxides of nitrogen (NO_x), methane (CH_4), non-methane hydrocarbons (NMHC), and aldehydes (ALD). Figure 12 illustrates the City Cycle emissions for the tested vehicles in the form of floating bars. The top of the bar represents the maximum, the bottom represents the minimum and the line inside represents the average value of the emissions.

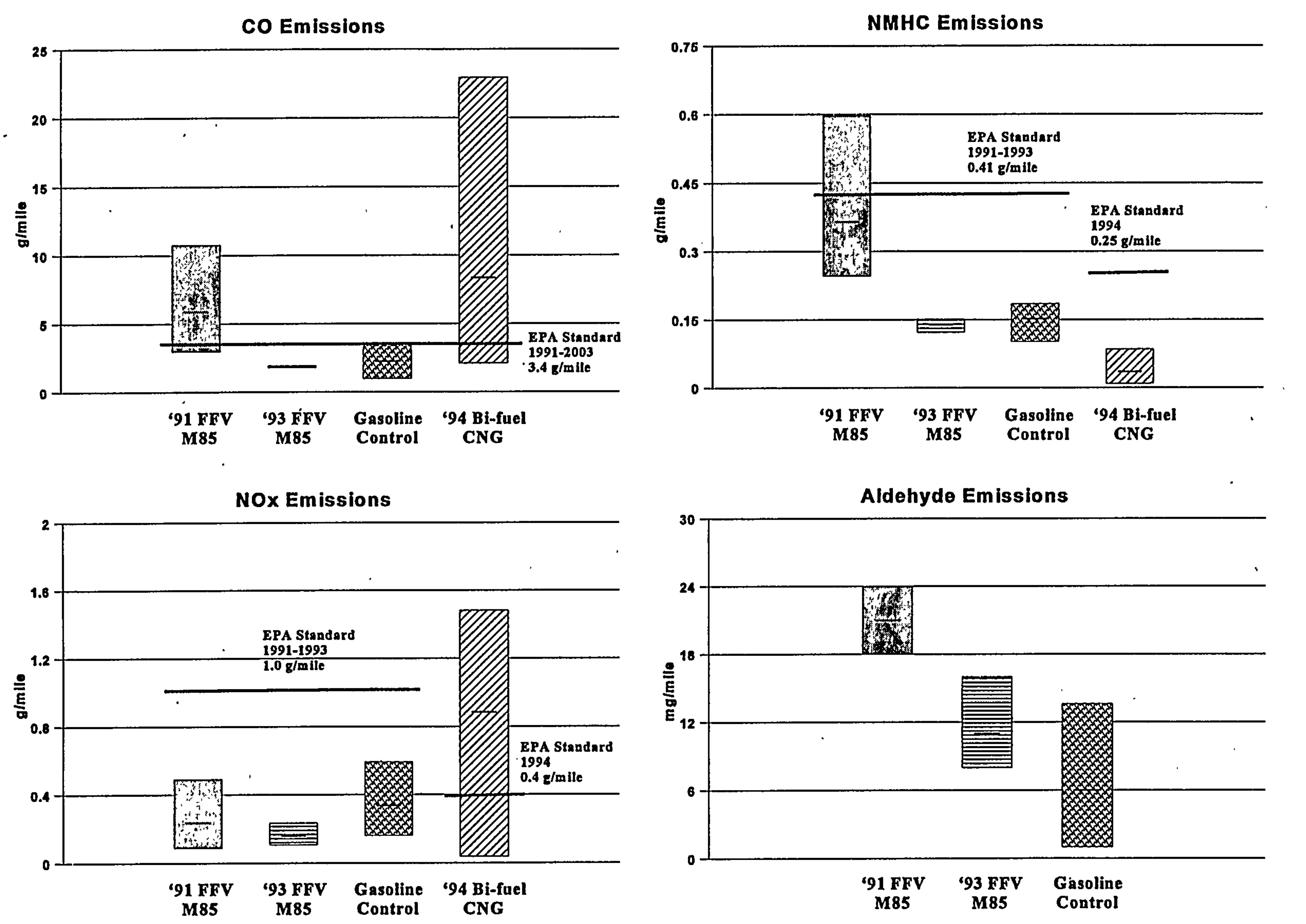

Figure 12. City Cycle Laboratory Emissions

Discussion of Emissions Results

Flexible Fuel Vehicles:

Both the 1991 and 1993 FFVs were evaluated on the EPA City Cycle for emissions. The 1991 Ford Taurus FFV was built and sold by Ford as an experimental vehicle and was not required to meet EPA standards for its model year. The 1993 Ford Taurus FFV was sold as a production vehicle in full compliance with EPA requirements. Results of emissions tests on these two vehicle types indicate that 1991 vehicles did, in fact, exceed EPA emissions limits for CO and HC emissions while the 1993 FFVs were able to satisfy EPA emissions about as well as the gasoline baseline vehicles.

The 1993 Ford Taurus is an upgraded version of its earlier M85 flexible fuel design. This model benefitted from the experience gained on the earlier model Ford FFVs such as the ones used by Monroe County. Results of the emissions tests on these vehicles indicate a significant reduction in the CO and HC emissions when tested on the City Cycle. Some improvements are also seen in NO_x and aldehyde emissions.

The 1993 Ford Taurus FFVs had aldehyde emissions of 11 mg/mile with M85 fuel and 13 mg/mile when using gasoline. Recent data on 1996 Ford Taurus FFVs[1] report lower values of aldehyde emissions: 3.9 gm/mile on M85 and 0.8 gm/mile on gasoline. Use of close-coupled light-off catalysts in the 1996 Ford Taurus FFVs is a primary reason for this reduction. Significant emissions reductions were also reported for CO, NO_x and HC emissions with the 1996 Ford FFV relative to the 1993 Ford FFV (both using M85).

CNG Vehicles:

The converted 1994 Ford Taurus CNG bi-fuel vehicles were also emissions tested. Data varied significantly from vehicle to vehicle and were in excess of EPA emissions requirements for CO and NOx. This result is not uncommon for CNG conversion systems using first generation closed-loop fuel system technology.

To reduce the variability and average level of emissions from these vehicles, it may be necessary to calibrate the fuel system with the vehicle installed on a chassis dynamometer - a procedure that is not feasible for typical fleets. When properly adjusted the converted CNG bi-fuel vehicles can be as clean as the same model gasoline vehicle. However, emissions testing of OEM dedicated CNG vehicles (such as the Dodge CNG minivans) demonstrate that such vehicles can have lower emissions than their gasoline counterparts.[2]

SUMMARY

This project demonstrated successful operation of CNG bi-fuel, M85 flexible fuel and gasoline control vehicles in fleet use in Monroe County, New York. Extensive data on fuel consumption, mileage accumulation, laboratory emissions testing and maintenance were collected. Refueling and maintenance facilities were modified or constructed and then operated based on specific requirements for either M85 or CNG fuel. Each vehicle type was evaluated on a variety of criteria, such as fuel economy, emissions, acceleration and maintenance. Important conclusions based upon the experience gained during this fleet operation are summarized below.

- Both FFV and CNG bi-fuel vehicles were adequate to meet the operating needs of Monroe County.
- The FFVs required the most maintenance among these Tauruses (FFV, CNG bi-fuel, and gasoline) due to cold-start problems and fuel system component failures.
- The FFVs experienced cold-start problems in very cold weather relative to the gasoline and CNG bi-fuel Tauruses.
- All the vehicles had acceptable driveability.
- The CNG bi-fuel Tauruses had significantly slower acceleration compared to the gasoline and FFV Tauruses.
- The energy economies for the FFVs on M85 were higher than those on gasoline for both, dedicated gasoline vehicles and the FFVs. Also, the energy economy for operation on gasoline is higher than for operation on CNG.
- Early 1990's models of CNG bi-fuel vehicles and FFVs were not effective at reducing emissions levels relative to conventional gasoline fueled vehicles. More recent FFVs and CNG vehicles have lower emissions.
- Facility changes for M85 are normally not required because the fuel is a liquid and contains gasoline. Training must be given to mechanics so that safe and proper procedures are used. Depending on the age and condition of the garage facility some facility changes may be needed for CNG service operation. Changes were needed for existing Monroe County garage facilities and more training was required for mechanics to safely service CNG vehicles.

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2. Richard L. Bechtold, P.E., and Arthur Vatsky, P.E. 'South Beach Psychiatric Center Natural Gas Vehicle Demonstration'. Final Report Task 16 - 1996. Prepared for the New York State Energy Research and Development Authority.

THERMAL MANAGEMENT OF AN ETHANOL FUELED FORD TAURUS CATALYTIC CONVERTER

Matt Keyser, National Renewable Energy Laboratory

(Presentation unavailable at time of publication)

SESSION 7

HEAVY DUTY ALTERNATIVE FUEL ENGINES PRESENT AND FUTURE

Chair: **Vinod Duggal, Cummins Engine Company, Inc.**

Cummins Heavy Duty Natural Gas Engine Products

Don R. Welliver
Cummins Engine Company

1996 Windsor Workshop on Alternative Fuels
June 4, 1996
Toronto, Canada

Cummins Natural Gas Engines

- History
  - Gas engine development since mid 1980s
    - » Driven by 1991 transit bus particulate standard
  - Early work performed under contract to Ortech
  - Mechanical fuel management system chosen
    - » No existing technology for electronic controls
    - » Limited development time window
  - Other "off the shelf" components

Cummins Natural Gas Engines

- History
  - Significant field experience gained in late 1980s and early 1990s in fleets such at TTC and HSR
  - Natural Gas Bus Working Committee led by MTO provided industry focus
  - L10-240G CARB certified in August 1992
    - » Included complete deterioration factor testing

Cummins Natural Gas Engines

- Electronic Controls Development
  - Mechanical fuel control system delivered good air fuel ratio response
    - » Sensitive to fuel composition due to volumetric characteristics
    - » Difficult to shape torque curve
  - 1994 L10G improved with electronic waste gate control giving altitude compensation
    - » Allowed uprating to 260 hp

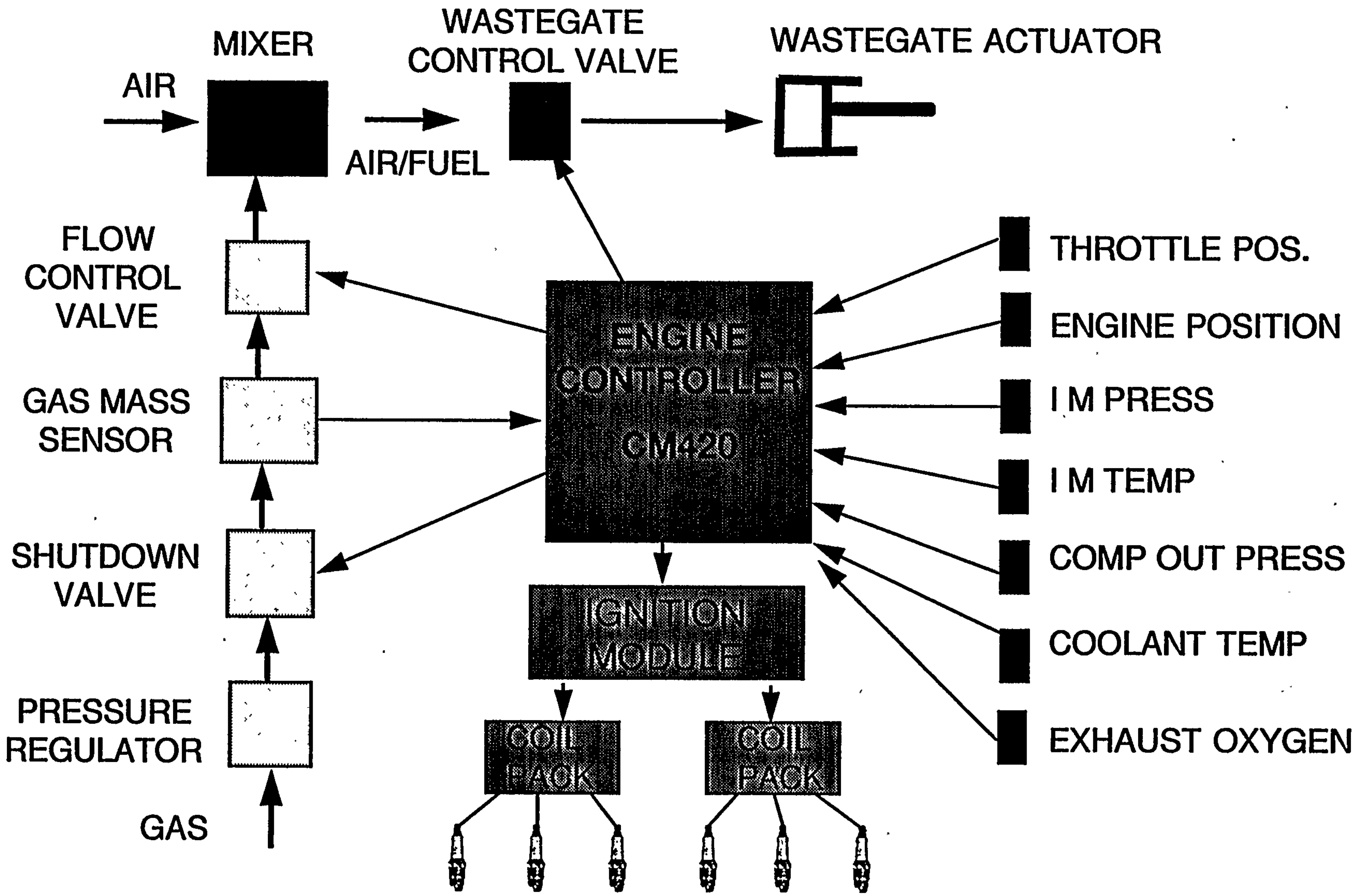
Cummins Natural Gas Engines

- B6G Engine Development
  - B6G platform developed next with specific development goals
    - » Electronic fuel delivery usable on all platforms
    - » In house design and development for all major subsystems
  - Required new skills
    - » Spark ignited engine controls
    - » Ignition systems

Cummins Natural Gas Engines

- ◆ B6G Engine Development
  - – Several new subsystems developed
    - » Lean EGO sensor
    - » Gas mass sensor
    - » Engine controls
    - » Ignition control module
    - » Sensors and actuators

B6G Controls



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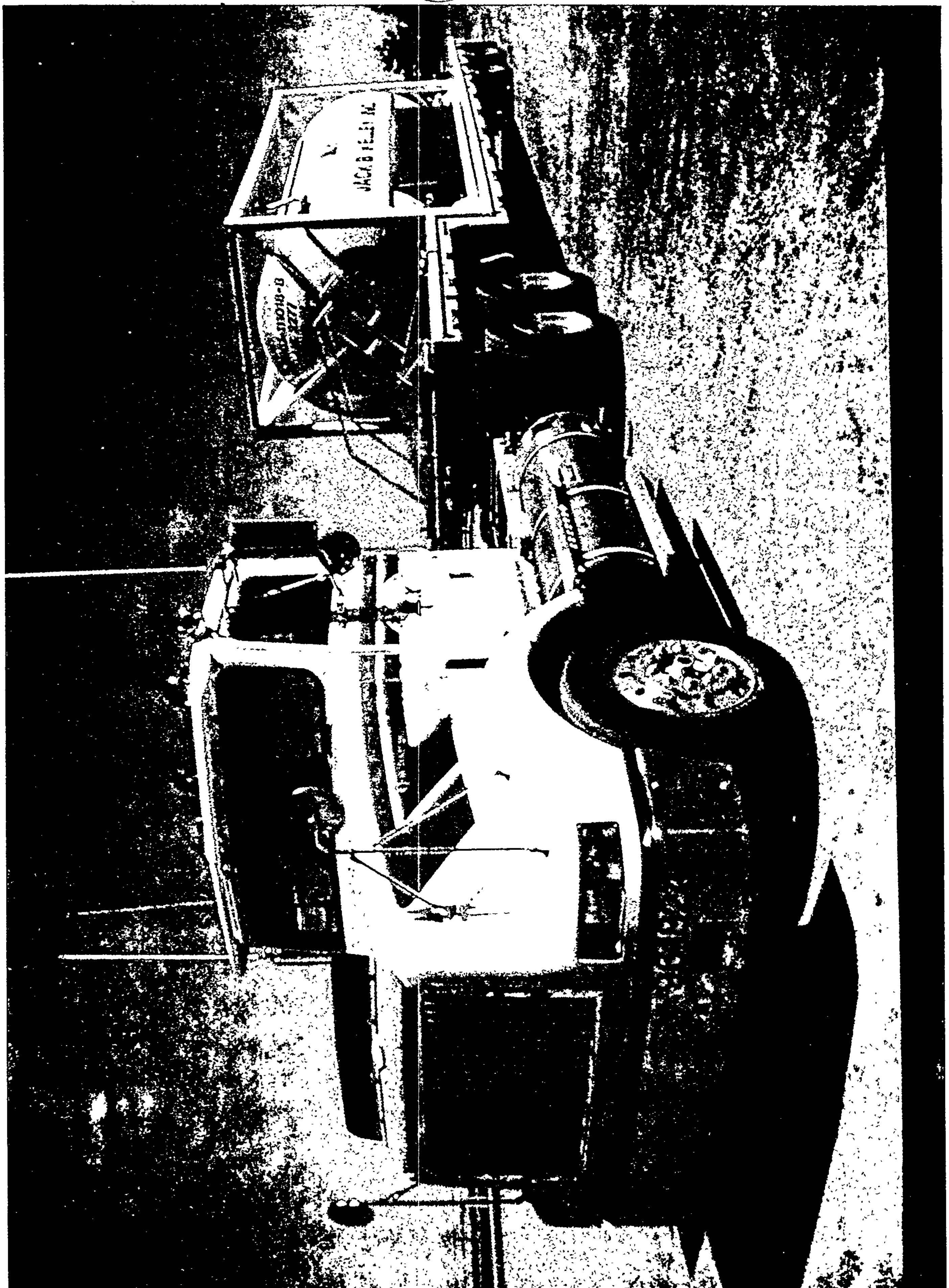
Cummins Natural Gas Engines

- B6G Engine Development
  - Released in December 1994
  - 195hp and 150 hp ratings with 420 lb-ft peak torque
  - 300+ engines built to date
    - School and shuttle bus
    - Package delivery vehicles
    - Yard spotter
    - Street sweeper

Cummins Natural Gas Engines

- 1996 L10G Engine Development
  - Applied B6G component and control technology to the L10G
  - Retained the existing governor
    - » Capacity of current ECM not enough to provide speed control
      - Single service tool downloads both modules as a single calibration and reads both module's diagnostics
  - Uprated to 300 hp, 900 lb-ft peak torque



Cummins Natural Gas Engines

- 1996 L10G Engine Development
  - Available as of January 1996
  - Engineered in several trucks and buses
  - About 60 units operating to date

Cummins Natural Gas Engines

- C8.3G Engine Development
  - Recently released for limited production
  - Advances state of the art in several areas
    - » New gas mass sensor design allows same sensor to be used across multiple platforms
    - » Coil on plug technology
    - » Multiple spark discharge

Cummins Natural Gas Engines

- C8.3G Engine Development
  - 250 hp with 750 lb-ft peak torque
  - 275 hp uprate available in January 1997
  - Eleven vehicles in operation
    - » School bus
    - » Transit bus
    - » Delivery truck

Cummins Natural Gas Engines

- M11G Engine Development
  - Uses M11 diesel carcass as platform
  - Lead platform for several new technologies
    - » Full authority engine control module
    - » Coil on plug (under valve cover)
    - » Ignition control module with diagnostic and prognostic capabilities
    - » Wide band EGO sensor
    - » New fuel metering concept

Cummins Natural Gas Engines

- ◆ M11G Engine Development
  - – 340 hp with 1050 lb-ft peak torque
  - – Available in early 1998

Cummins Natural Gas Engines

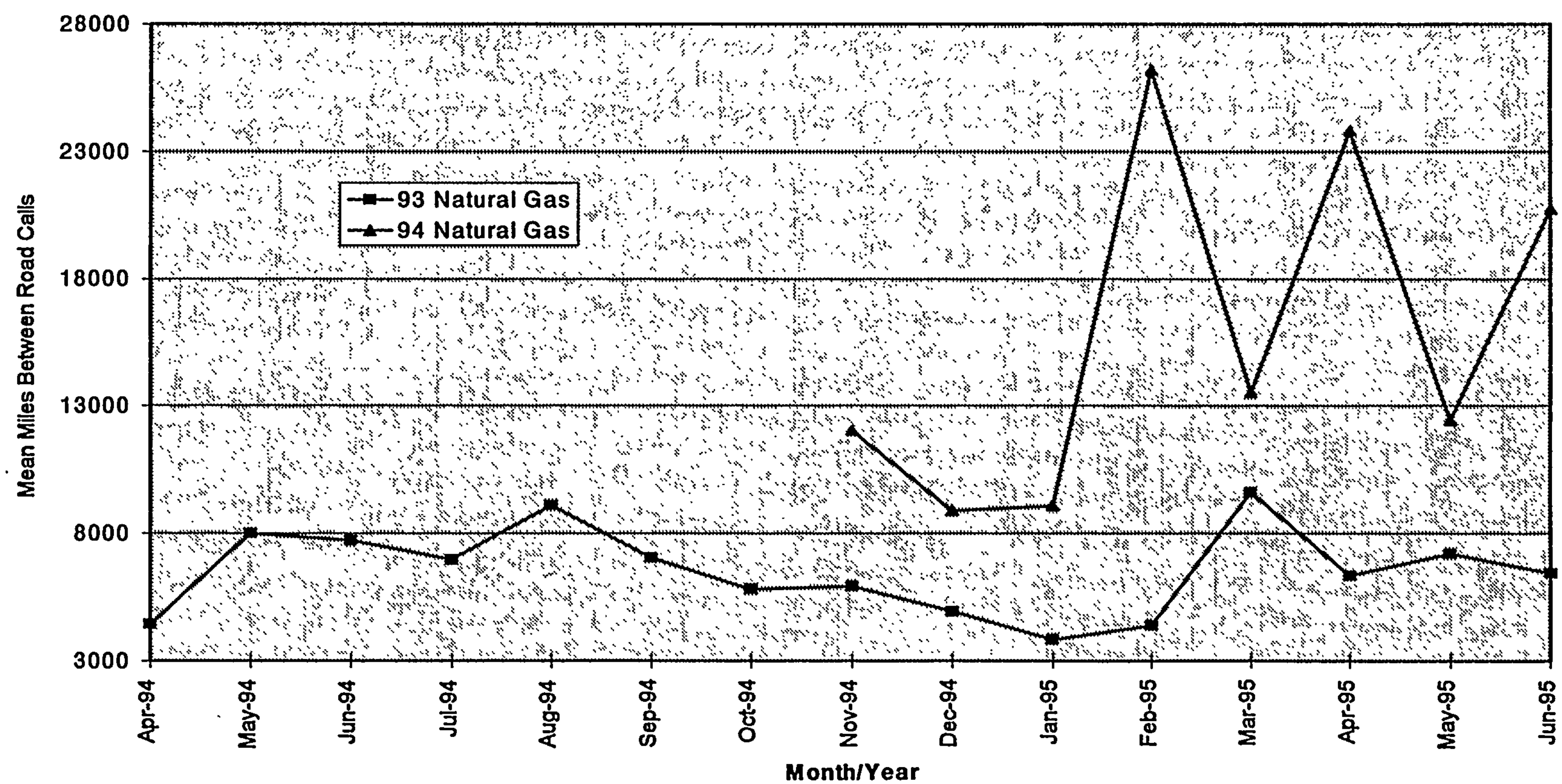
- Summary
  - Cummins has more than 1200 vehicles in operation with over 100 million miles
  - Twenty OEMs offer our engines, over 60 fleets are operating them
  - Market philosophy has been initial conservative ratings, increasing BMEP levels as field experience is gained
  - All major subsystem design performed in house

Cummins Natural Gas Engines

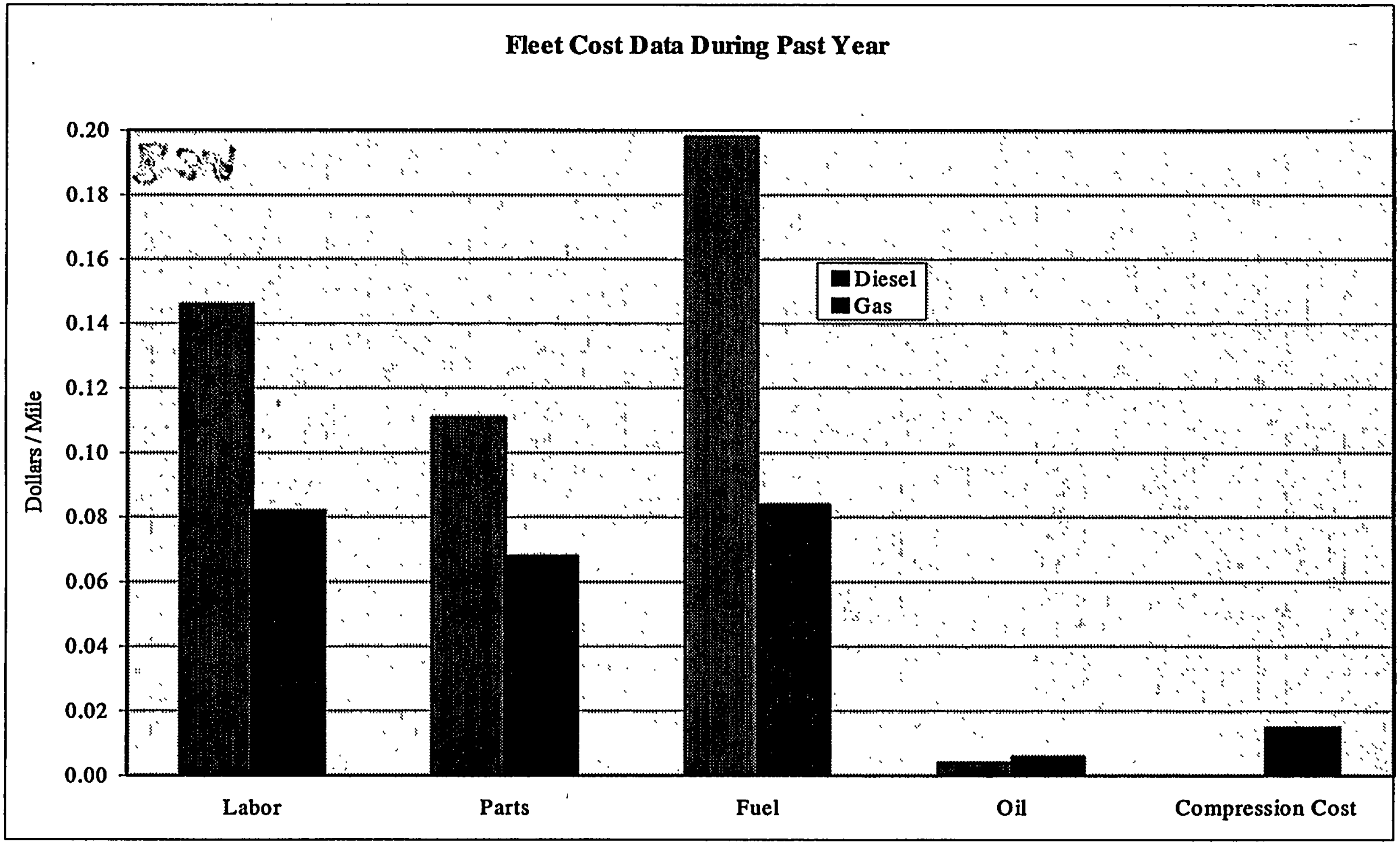
- Summary
  - Each new platform builds on learning from previous designs, thereby advancing the state of the art
  - As new technologies introduced, BMEP has risen from 185 psi in early 1990 to 225 psi today moving to 240 psi in 1998
  - This philosophy has provided advantages for our customers

Cummins Natural Gas Engines

MEAN MILES BETWEEN ROAD CALLS

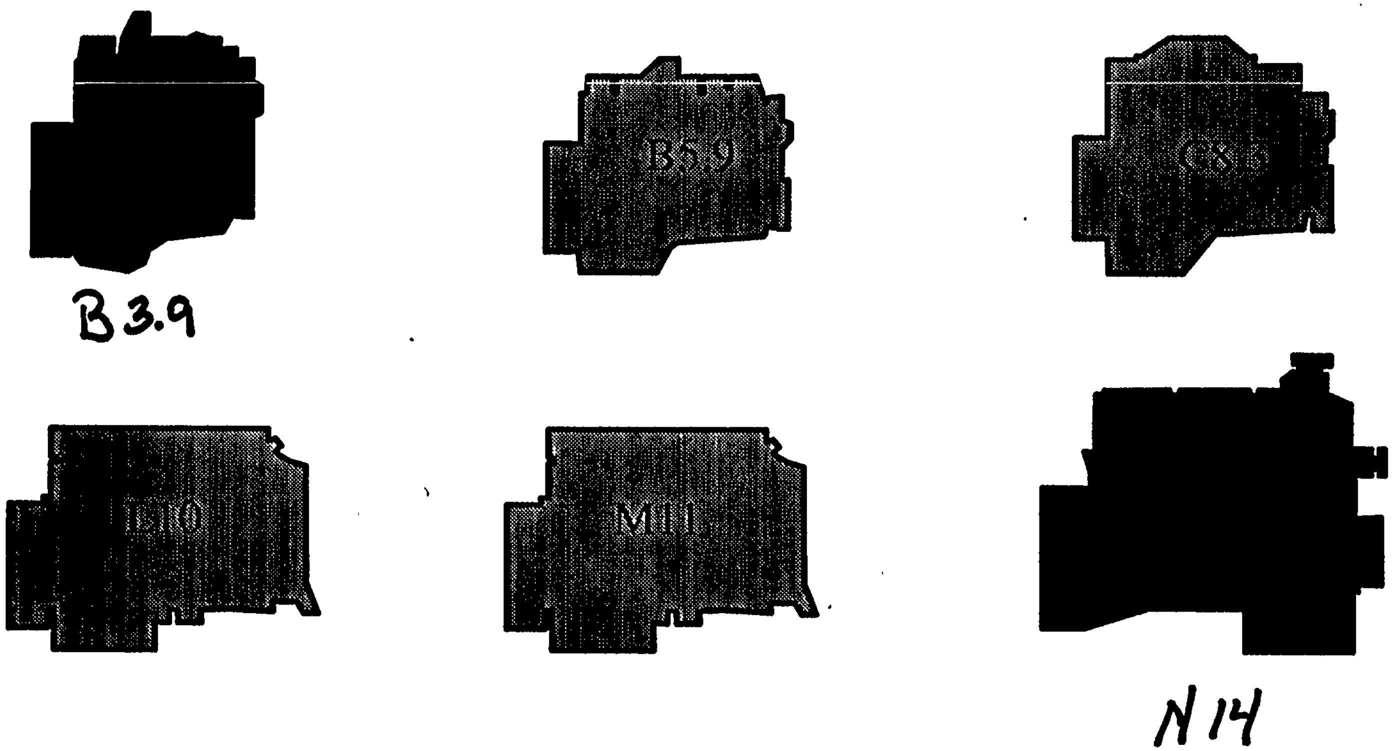


Cummins Natural Gas Engines



Cummins Natural Gas Engines

- Automotive Platforms



Cummins Natural Gas Engines

- Acknowledgments
  - Gas Research Institute
  - Columbia Gas
  - Consolidated Gas
  - SoCal Gas
  - New York Gas Group
  - Gas Technology Canada
  - NYSERDA


MACK'S LNG PROGRAM

CNG MR600 REFUSE TRUCK FOR BFI

- SwRI Performed All Engine & Vehicle Changes
- GRI Funded Program
- Purpose was to Demonstrate Feasibility of Natural Gas
- Operated for One Year in Boston During 1993/94

CNG PROGRAM CONCLUSIONS

- CNG Added 2000 lb. to the Vehicle
- Vehicle Range Needed to be Increased
- Part Load Fuel Consumption was Poor
- Engine Driveability Needed Improvement
- Natural Gas was Viable for Refuse Service

LNG MR600 REFUSE TRUCK

- The Truck was Moved From Boston to Atlanta in 1994
- BFI Replaced CNG with a LNG Fuel System by MVE
- Mack Replaced Original Engine with New Design in Late 1995

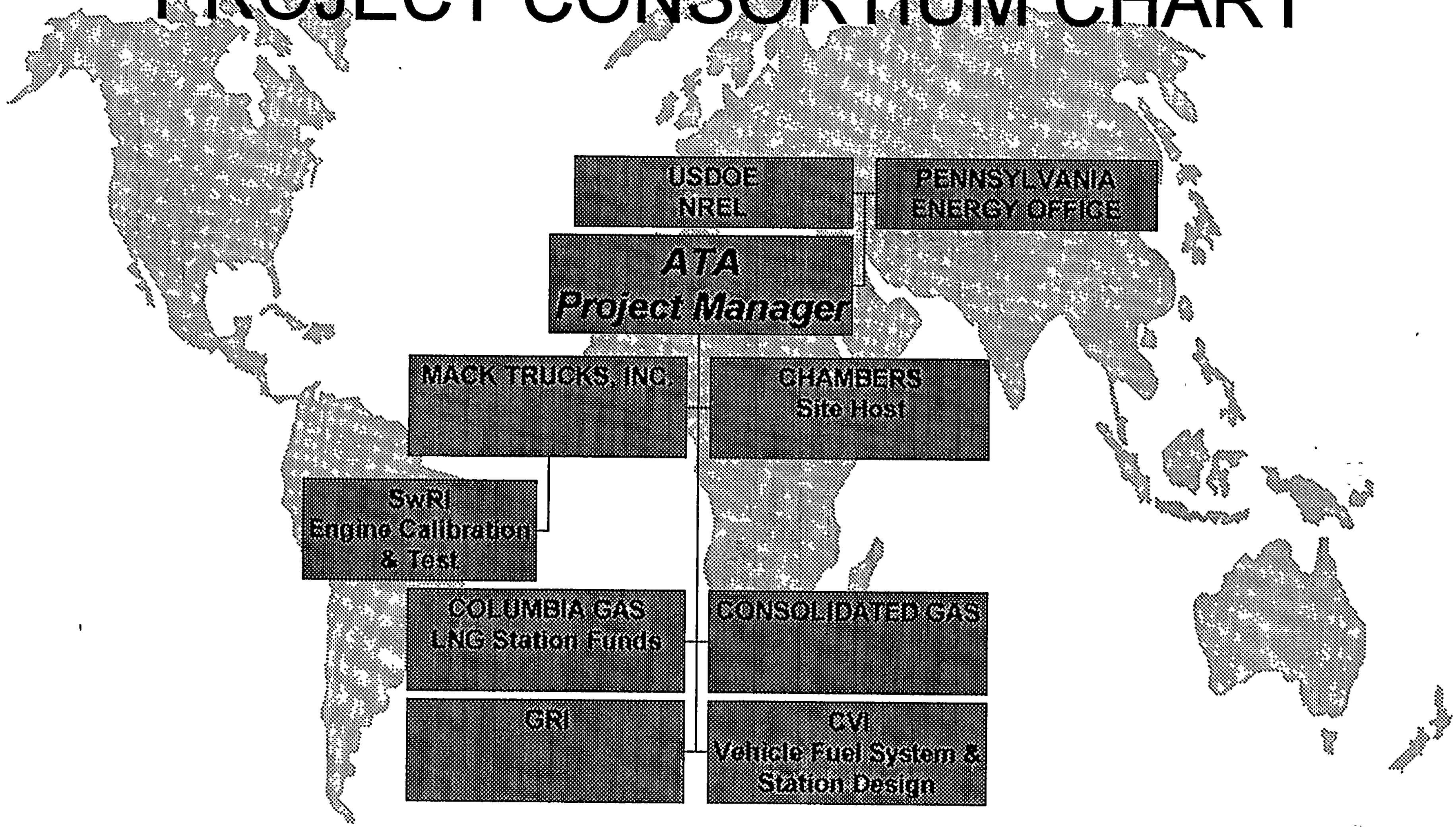
CHAMBERS LNG PROJECT

- Provide 7 LNG Fueled LE Refuse Trucks
- Install Underground LNG Refueling Station
- Improve Engine's Part-Load Efficiency
- Field Test for 3 Years
- Maximize Tank's Holding Time in the Vehicle
  - Non-Metallic Trunnion Joint

CHAMBERS LNG PROJECT - CONT.

- Perform Thorough Testing of Tanks & Supports
  - Mack's Bump Test
  - 30 ft. Drop Test
  - 10 ft. Filler Neck Drop Test
  - 30 mph Crash Test Simulation

PROJECT CONSORTIUM CHART



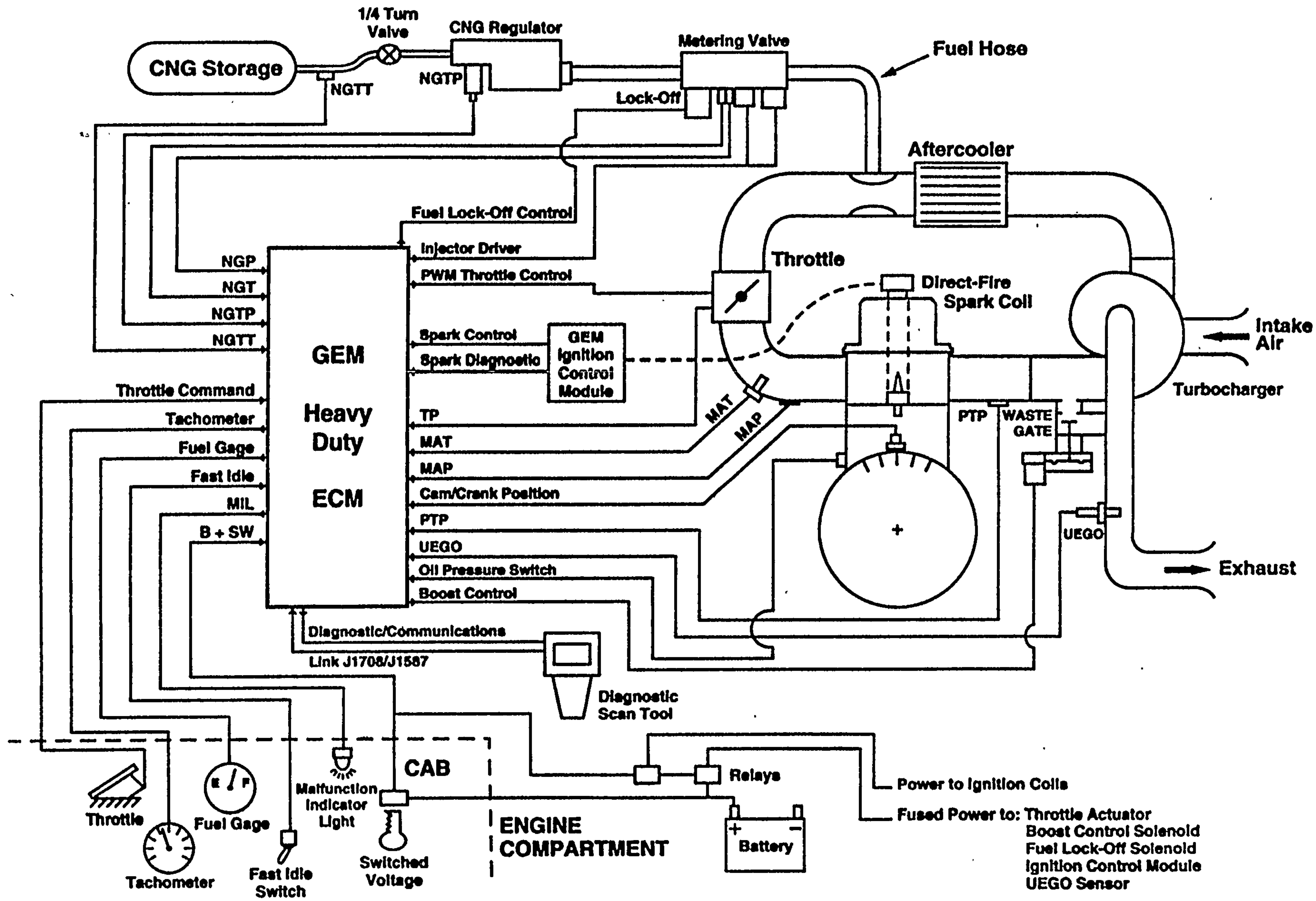
E7G 12L ENGINE GOALS

- Two Power Ratings:
  - 325 hp @ 1950 rpm; 1160 ft.lbs. P.T.
  - 350 hp @ 1800 rpm; 1260 ft.lbs. P.T.
- Good Part Load Efficiency for Refuse Industry
  - *3 Mpg D.E. in Service, Front Loader*
- Low Emissions W/O Catalyst
  - *1.9 gr/hp hr NOx SwRI Prediction*
  - *2.0 gr/hp hr THC SwRI Prediction*
  - < .05 gr/hp hr PM Goal
- Excellent Driveability
- Diesel-Like Reliability & Durability

WOODWARD/MESA ELECTRONIC FUEL SYSTEM

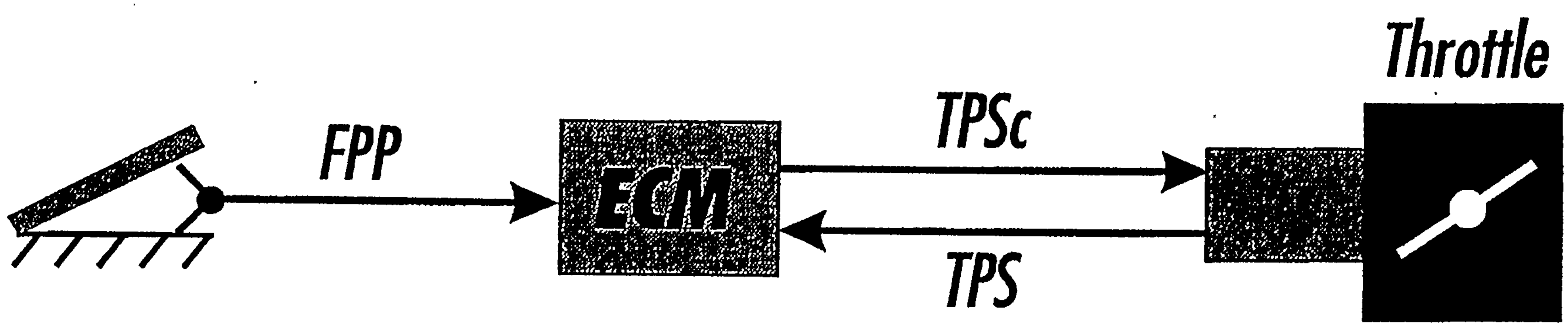
- State-of-the-Art Speed Density Control Strategy
- Closed-Loop Lean-Burn Operation with Adaptive Learn
- Advanced “Turbo-Lag” Compensation
- Full Authority Electronic Throttle
- NGK UEGO Sensor
- Electronic Wastegate Control
- High Energy Inductive Ignition System
- Full Diagnostics
- Reduced Power Engine Protection

GEM HEAVY DUTY CONTROL SYSTEM

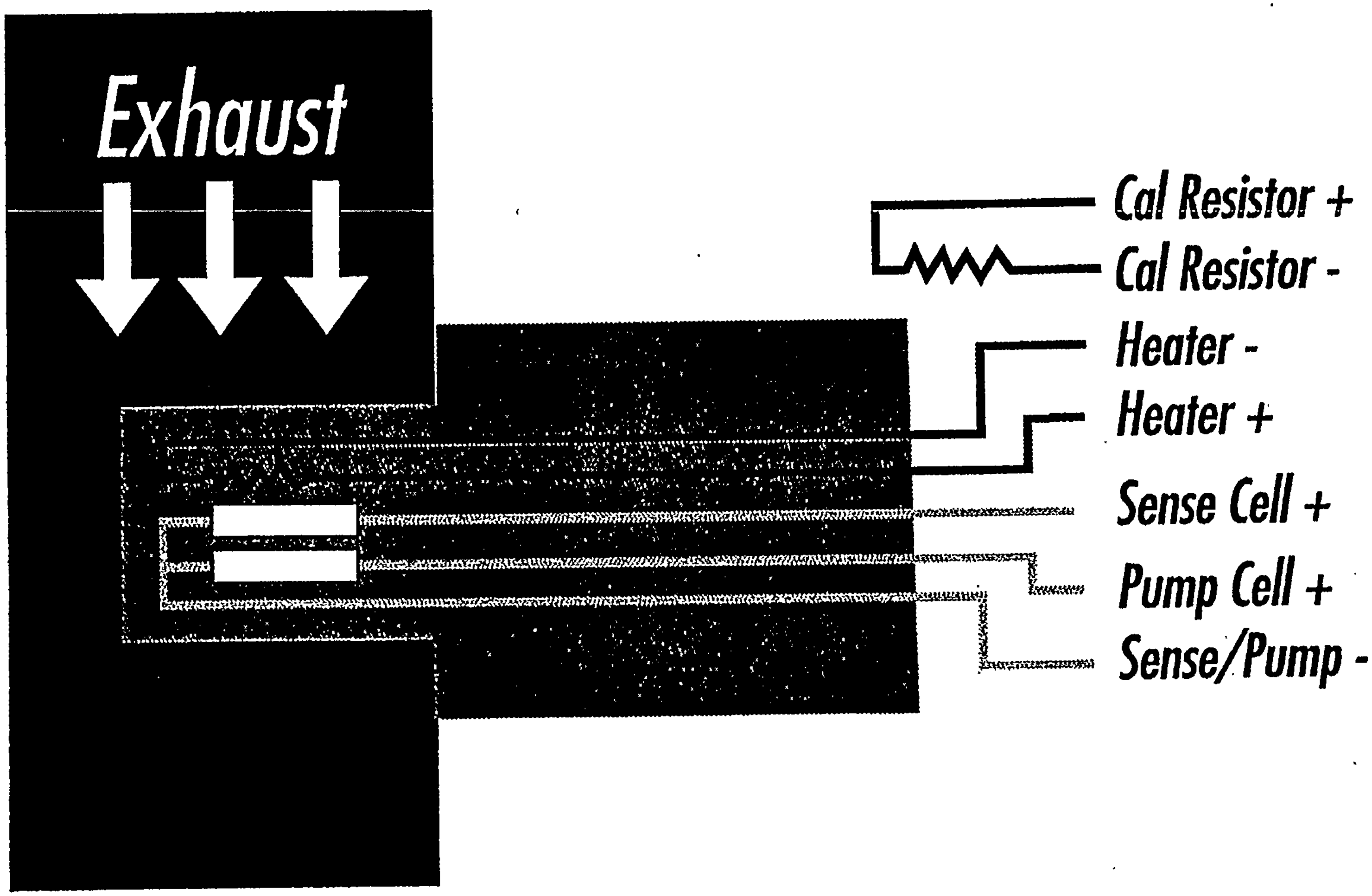


DRIVE-BY-WIRE THROTTLE SYSTEM

- Full-Authority DBW Throttle Control
- Command Signal from FPP Sensor
- Min / Max Governing
- Controlled by ECM
- Woodward Digital Throttle
- Extensive Diagnostics Provided

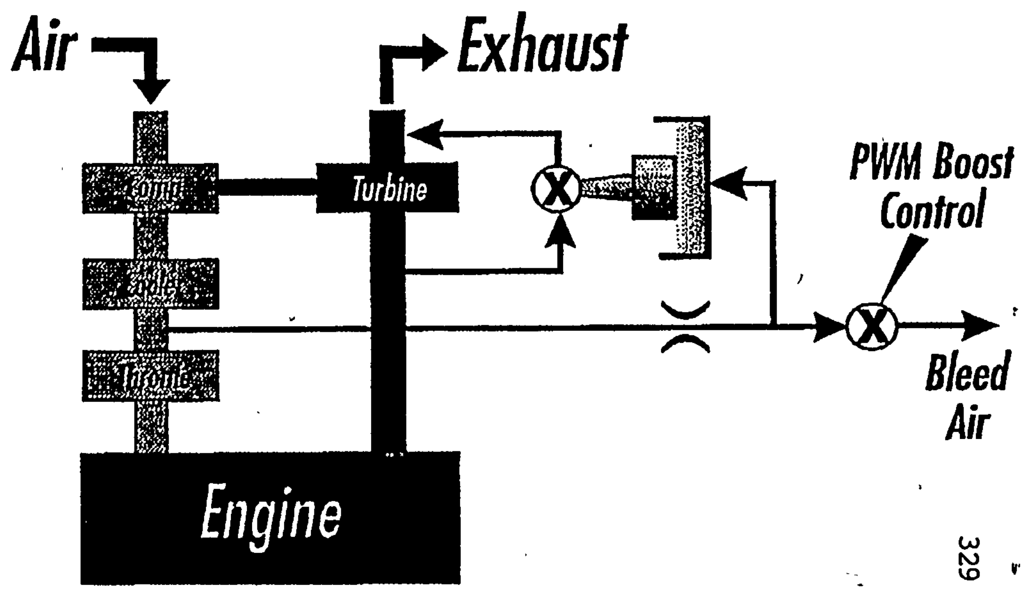


NGK UEGO SENSOR



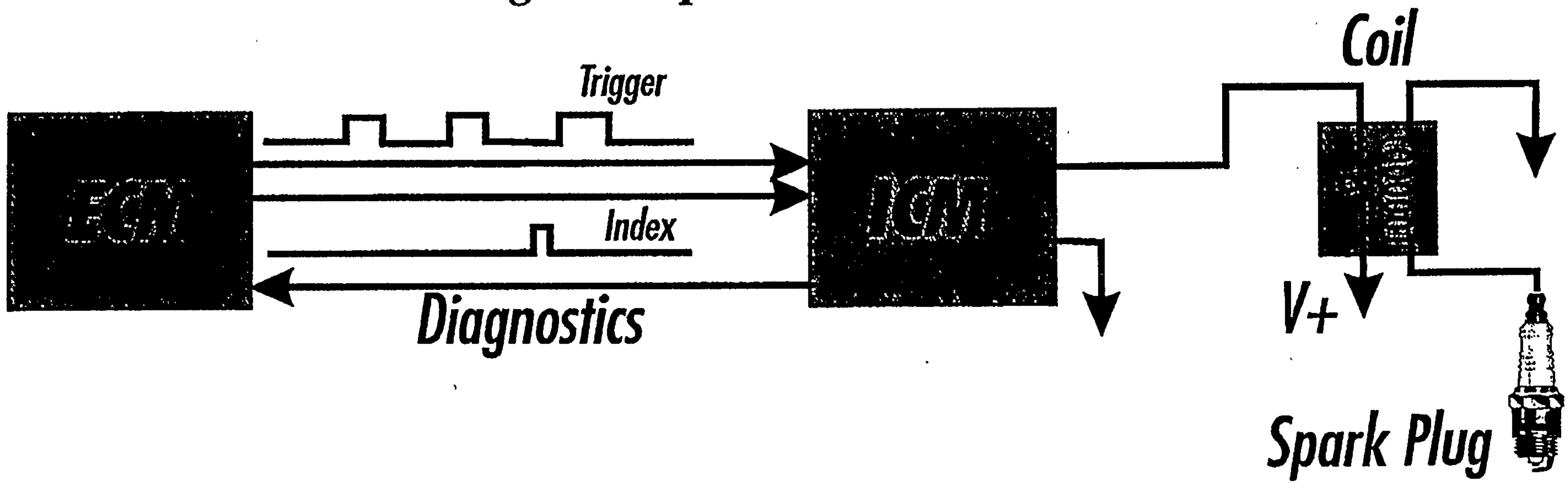
BOOST CONTROL

- **Electronic Wastegate Control**
  - torque curve shaping
  - electronic delta-P wastegate control improves part-load efficiency
- **MAP Setpoint Based on RPM and FPP**
- **"Turbo Lag Compensation" Quickly Spools Turbo**
  - 50% reduction in spool-up time
  - Based on spark and fuel control
  - Zero emissions penalty



IGNITION SYSTEM

- **Inductive, Direct-fire Ignition System**
  - one coil per cylinder
  - longer spark duration than CD, extends LML
- **ECM Spark Timing and Dwell Control**
  - based on RPM and MAP
  - separate ignition control module with drivers
  - ICM diagnostics provided



FUTURE PLANS

- Continue with Current Programs
- Progress to Production on LE Model with the E7G Engine for Late 1997
- Evaluate Potential for a Natural Gas Highway Tractor; the CH
- Work with Renault V.I. on European Applications of E7G Engine
- Continue to Incorporate New Technologies to:
  - Improve Performance
  - Reduce Cost

GEORGETOWN UNIVERSITY
Advanced Vehicle Development

Fuel Options For Fuel Cell Powered Transit Buses

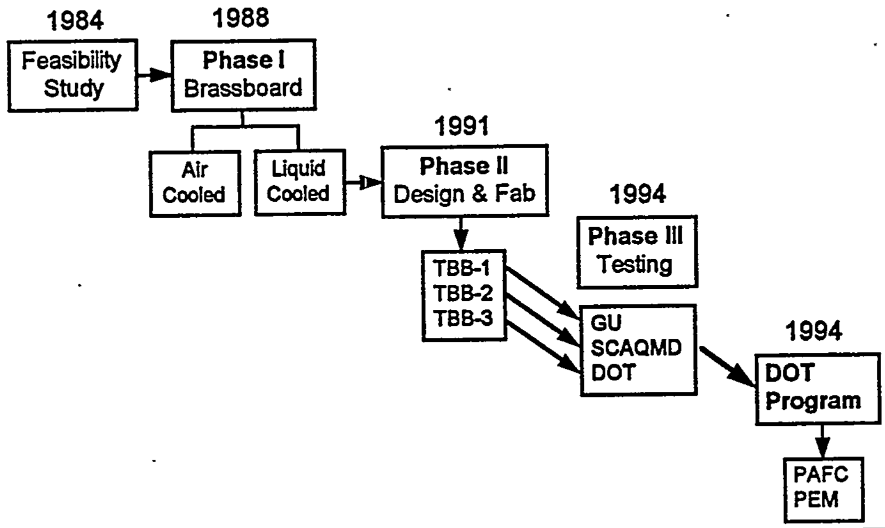
Robert R. Wimmer
Project Manager

Windsor Workshop on Alternative Fuels
Toronto, Canada
June 4, 1996

GEORGETOWN UNIVERSITY FUEL CELL POWERED TRANSIT BUS PROGRAMS

- Georgetown University (GU) has been working on Fuel Cell (FC) powered transit buses since 1983
- We are presently working on two FC bus projects
  - The 30 ft FC Powered Test Bed Bus Program
  - The 40 ft FC Powered Bus Commercialization Program
- Both buses are hybrid electric (two power sources)
  - The fuel cell provides the "average" power or energy
  - The battery pack provides the "peak" power
- This presentation will discuss FC and reformer technology, and fuel selection for the transit bus application

PROGRAM HISTORY

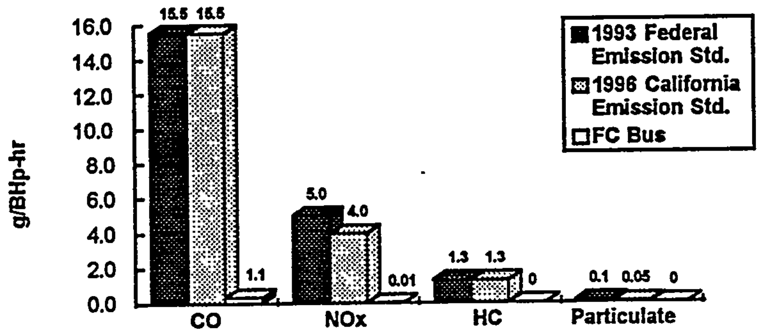


PROGRAM GOALS

- Demonstrate that FC systems can supply 100% of the energy required to successfully operate a transit bus
- Demonstrate benefits as compared to present buses
  - Higher efficiency; ie, better mileage resulting in lower fuel costs
  - Lower emissions and noise
- Develop a vehicle that meets the needs of the operator
  - No loss of performance
  - Minimum effect on present fueling infrastructure
- Demonstrate commercial viability

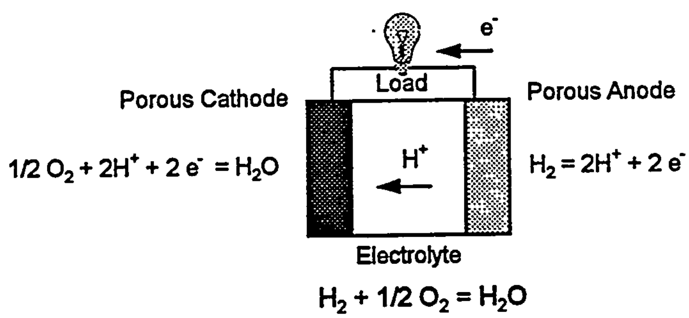
EMISSION COMPARISON

- Tested emissions for 50 kW PAFC system



WHAT IS A FUEL CELL?

- In its simplest form, a fuel cell is a solid state electrochemical device that combines H_2 & O_2 to form water and electricity



THE FUEL CELL REACTANTS

- In land based FC systems, air provides the oxygen required for the electrochemical reaction
- The hydrogen required for FC operation can be stored as a gas, liquid, hydride or bound in a compound
- These hydrogen containing compounds include methane (natural gas), alcohols, hydrocarbons and ammonia
- A "Reformer" is used to break-down these compounds

REFORMERS

- The reformer liberates hydrogen by heating the compound, possibly in the presence of a catalyst, until it cracks into simpler molecules (H_2, CO_2 & CO)
- Each fuel has unique reforming requirements
  - Temperature
  - Type of catalyst
  - Dwell time in reformer
- These variables effect system design and control
  - Efficiency over the full range of outputs
  - Control of a reformer during vehicle transients

FUEL CELLS

- There are two primary types of FCs being considered for transportation applications
- The Phosphoric Acid Fuel Cell (PAFC)
  - Most developed (Over 75 utility systems in operation worldwide)
  - Proven systems (many with over 25,000 hrs)
  - Proven operation on reformed fuel (CO tolerant)
- The Proton Exchange Membrane Fuel Cell
  - Low temperature operation (quick start-up)
  - Simpler storage requirements
  - Less tolerant of CO

FUEL SELECTION

- GU initially reviewed fuel selection in the mid 80s for the 30 ft bus program and revisited many of the same issues in 1993 for the 40 ft bus program
- GU's broad knowledge of the transit and FC industries, reforming technology, and fuels allowed consideration of a variety of factors
  - Public policy
  - The customer's requirements (Transit Operators)
  - Storage and reformer technology
  - Fuel price and availability
- These issues were all considered in selecting a fuel

ISSUES THAT IMPACT FUEL SELECTION

- Public policy was determined by the funding agencies
  - Due to concerns for energy security and balance of payments, these agencies mandated the use of a domestically produced, alternative fuel
- The transit operators use centralized refueling allowing for greater flexibility in choosing a fuel
  - A trained fueling and maintenance staff
  - A controlled repeatable demand
  - Experience with many of the candidate fuels (biases)
- Refueling time and complexity must be minimized

ISSUES THAT IMPACT FUEL SELECTION

- The operators are sensitive to capital and operating costs
  - Fueling infrastructure cost
  - Zoning, above-ground equipment and noise
  - A fuel's cost per mile
- Impacts to the vehicles are also a concern
  - Increased weight
  - Decreased range
  - Changes in the vehicle's handling
  - Fuel systems that require special care (cryogenic or gaseous)

FUEL CHOICES
- Hydrogen

- Direct H_2 FC systems are simpler, easier to control and more efficient than reformer based systems
- They also produce zero tailpipe emissions
- But hydrogen storage is problematic
  - Gaseous storage is heavy and requires excessive space
  - Current hydride storage technology is very heavy
  - Cryogenic storage raises cost, safety and boil-off concerns
- Limited fuel infrastructure

FUEL CHOICES
- Reformed Fuels

- Candidate fuels for reforming are ammonia, natural gas, ethanol, and methanol
- Although ammonia is attractive from the storage and price standpoint, its hazardous nature will prevent use in mobile applications
- Natural gas is low cost, available throughout the country and well characterized as a reformer fuel
  - Requires a high temperature reformer and a heavy fuel storage system, which results in a significant weight penalty

FUEL CHOICES
- Reformed Fuels cont.

- Because of differences in their chemical bonds, some fuels require higher reforming temperatures than others

Low Temperature Catalytic Steam (450°F)	High Temperature Catalytic Steam (1300°F)	Partial Oxidation (>2000°F)
Methanol	Natural Gas Ethanol	Gasoline Diesel

- Typically, the higher the temperature, the more complex and less efficient the reforming process

FUEL CHOICES
- Reformed Fuels cont.

- High temperature reforming produces more CO than low temperature, requiring additional shift hardware
- Although low-temperature reforming requires the least hardware, maintaining reformer bed temperature during load transients is a system control challenge
- Due to excess heat, high temperature reforming requires a less complex control system to follow transient power demands
- This excess heat must be recovered for high efficiency

FUEL CHOICES
- Price and Availability

- H_2 price is difficult to asses
  - It is not sold as a commodity
  - Limited availability increases transportation costs
  - Compression or liquefaction requires additional energy
- Although ethanol contains 30% more energy than methanol, its market price is typically 1.5-3 times higher
  - Both liquid fuels are produced in various parts of the country and are easily transportable
  - Since both are commodities, their price fluctuates

SUMMARY OF FUEL SELECTION ISSUES

	H_2	Ethanol	Methanol
FC System Weight	○	●	⊙
Fuel System Weight	●	○	⊙
FC System Efficiency	○	●	⊙
Retraining (Transit)	●	⊙	⊙
Capital Cost (Transit)	●	○	⊙
Fuel Cost	⊙	●	⊙
Fuel Availability	●	⊙	⊙

Good ○ Fair ⊙ Major Concern ●

FUEL CELL BUS SYSTEMS - 30 ft Bus

- Three 30 ft test bed buses are being tested in different parts of the country to verify performance, emissions and fuel efficiency
- The bus design consists of
  - A Fuji Electric 50 kW oil-cooled PAFC
  - A low temperature steam reformer for methanol fuel
  - A 100 kW SAFT NiCd battery pack with 180 amp-hr capacity
  - A 120 kW (peak) DC electric motor
- Areas of concern include bus weight, FC response and system control algorithms

FUEL CELL BUS SYSTEMS - 40 ft Buses

- GU has received a grant from the Federal Transit Administration to design and fabricate two 40 ft FC powered hybrid transit buses
- Both buses will use a methanol fueled 100 kW FC system and a 125 kW battery pack
- The first bus will be a preproduction prototype
  - IFC 100 kW PAFC and compact high temperature steam reformer
  - Idle to 100% output in less then 5 seconds
  - Water recovery
  - Proven production utility-stack design (PC25)

FUEL CELL BUS SYSTEMS - 40 ft Buses cont.

- The second bus will be powered by a PEMFC system being designed by Ballard Power Corporation
- The PEMFC system will make use of existing technology being used on other projects
  - High power density stack
  - An oil-heated low temperature steam reformer
  - Hydrogen separation membrane technology for removal of CO
- Both PAFC and PEMFC systems are projected to be more than 38% efficient with significant improvements in power density compared to the 30 ft bus systems

SUMMARY

- For near-term commercialization of FC systems for transit buses, methanol continues to be the fuel of choice
  - It has none of the storage problems of gaseous fuels
  - It has minimal infrastructure impact on the transit operator
  - It has a price and ease of reforming advantage over ethanol

SESSION 8

PANEL DISCUSSION

CALIFORNIA ZEV COMMERCIALIZATION EFFORTS

Moderator: Juan Osborn
California Air Resources Board

Presentation - Lois Wright, Sacramento Municipal Utility District

(Other presentations unavailable at time of publication)

California's Clean Cities

ELECTRIC VEHICLE INCENTIVE PROGRAM

Lois Wright

Electric Transportation Department
Sacramento Municipal Utility District

Program Goals

- Accelerated introduction of electric vehicles
- Market-based approach
- Uniform level of incentive statewide
- Fuel diversity
- Energy security
- Air quality
- Economic development

Program Opportunity Notice

- $250,000 available (US Dept. of Energy)
- Proposals requested from local air districts
- Required elements
  - "Clean Cities" designation or application
  - 50:50 match
  - $5,000 incentive level

Air District Participants

➢ Sacramento	$50K
➢ San Francisco Bay Area	$50K
➢ Santa Barbara	$50K
➢ San Diego	$50K
➢ Ventura	$25K

- ➢ Note: Additional $25K reserved for first Air District to award all of its funds

Administrative Options

- Sale or lease is eligible
- $5,000 incentive is payable to
  - purchaser / consumer
  - retail dealership
  - auto manufacturer

Rebate vs. "Buy Down"

	Consumer	Manufacturer
EV Purchase Price	$30,000	$30,000
Buy Down	-	($5,000)
Sales Tax @ 8%	$2,400	$2,000
Federal Tax Credit	($3,000)	($2,500)
Rebate	($5,000)	-
Income Tax on Rebate @ 28%	$1,400	-
Net EV Cost	**$25,800**	**$24,500**

Vehicle Eligibility Requirements

- Light Duty (<8500 lbs. GVW)
- Certified as Zero Emission Vehicle (ZEV)
  - by the CA Air Resources Board
- Meet EV America performance goals
- Meet Federal Motor Vehicle Safety Standards (FMVSS)

EV America Performance Goals (at 50% state of charge)

- Acceleration: 0-50 mph in 13.5 seconds
- Minimum Top Speed: 70 mph
- Gradeability: 3% @ 55 mph; 6% @ 45 mph
- Gradeability: start & ascend a 25% grade
- Range: 50 mile minimum
- Heat Durability: 120 degrees F. ambient air
- Water Durability: 20 mph in 2" of water

Air District Responsibilities

- Publicize the program
- Verify customer's eligibility
- Verify vehicle's eligibility
- Collect data from selected EV customers

$642K: Funding Sources

- $250K US Dept. of Energy
- $250K Local air districts (matching funds)
- $112K Redirected CEC-SMUD contract
  - for Sacramento incentives
- $ 30K Separate allocation
  - by Yolo-Solano Air District for incentives

Term of program

- Incentives available as of July 1, 1996
- EV purchases must be completed and invoices submitted by June 30, 1997

Summary

- Promotes successful commercialization of EVs in CA
- Establishes uniform incentive level statewide
- Increases enthusiam of Clean Cities Stakeholders for EVs
- Leverages limited funds effectively

Future Activities

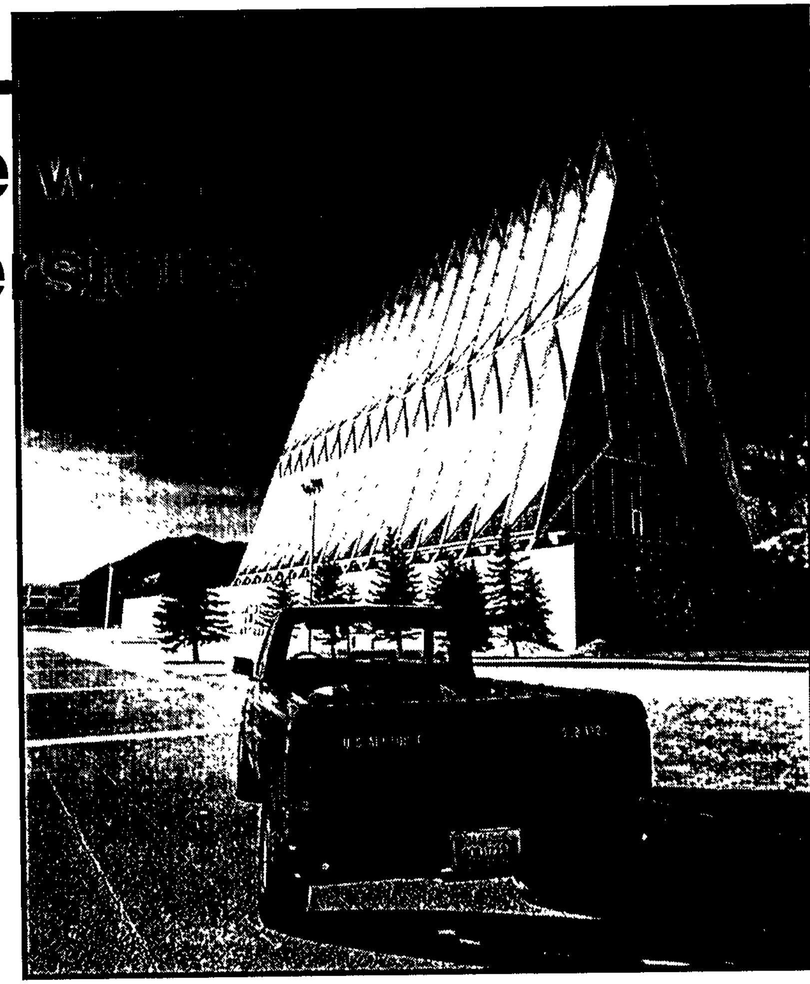
- Augment incentive program for EVs
- Develop incentive program for advanced batteries

SESSION 9

IN-USE EXPERIENCE

Chair: **Brent Bailey, National Renewable Energy Laboratory**

NREL's Experience
Aftermarket Conve



Robert C. Motta
Kenneth J. Kelly
William W. Warnock

Windsor Workshop
on Alternative Fuels

Toronto, Canada
June 3–5, 1996

SQP4-B119401

Center for Transportation Technologies and Systems

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

SQP4-B119402

Presentation Overview

- Program objectives/basis
- Steps to high quality conversions
- Results
  - Meeting EPACT requirements
  - Evaluating performance
- Summary of conclusions

Objective

- Assist Federal government in meeting the alternative fuel vehicle purchase requirements of the Energy Policy Act (EPACT) of 1992
- Ensure high-quality equipment and installations
- Evaluate performance
  - Emissions tests
  - Driver surveys

Energy Policy Act of 1992

AFV Purchase Requirements

FY 1993	5,000
FY 1994	7,500
FY 1995	10,000
FY 1996	25%
FY 1997	33%
FY 1998	50%
FY 1999	75%

Typical annual Federal vehicle purchases

- 50,000 at the start of the program
- 35,000 after Federal downsizing

1992 OEM Vehicle Availability

Manufacturer	Model	Body Style	Fuel	Type
Chrysler-Dodge	Ram van/wagon	Full-size van	CNG	Dedicated
GM-Chevrolet	C1500/C2500	Full-size pickup	CNG	Bi-fuel
GM-Chevrolet	Lumina	Mid-size sedan	Ethanol	Flex-fuel
Ford	F700	Medium-duty truck	LPG	Dedicated

Two light-duty CNG models: one van and one pickup

Steps to High Quality Conversions

1. Conversion Company
2. Hardware Requirements (Equipment and Technology)
3. Installation Procedures
4. Warranty and Training
5. Emissions and Performance Requirements

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Steps to High Quality Conversions

Conversion Company

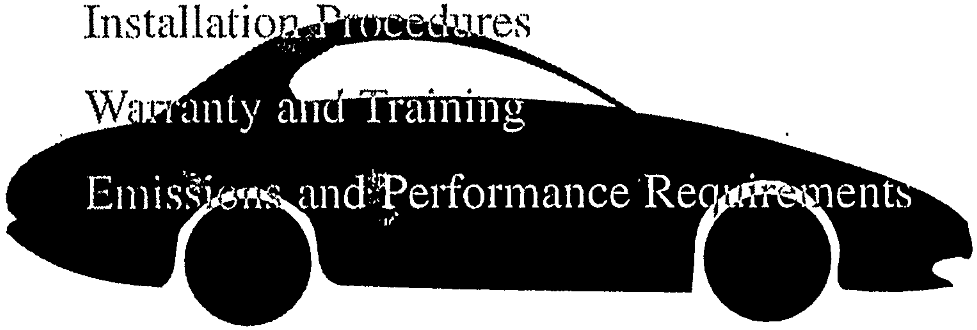
- **Competitive Procurement/Evaluation Criteria**
  - **- 70% Technical Merit**
  - **- 30% Cost**

Hardware Requirements (Equipment and Technology)

Installation Procedures

Warranty and Training

Emissions and Performance Requirements



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Steps to High Quality Conversions

Hardware Requirements (Equipment and Technology)

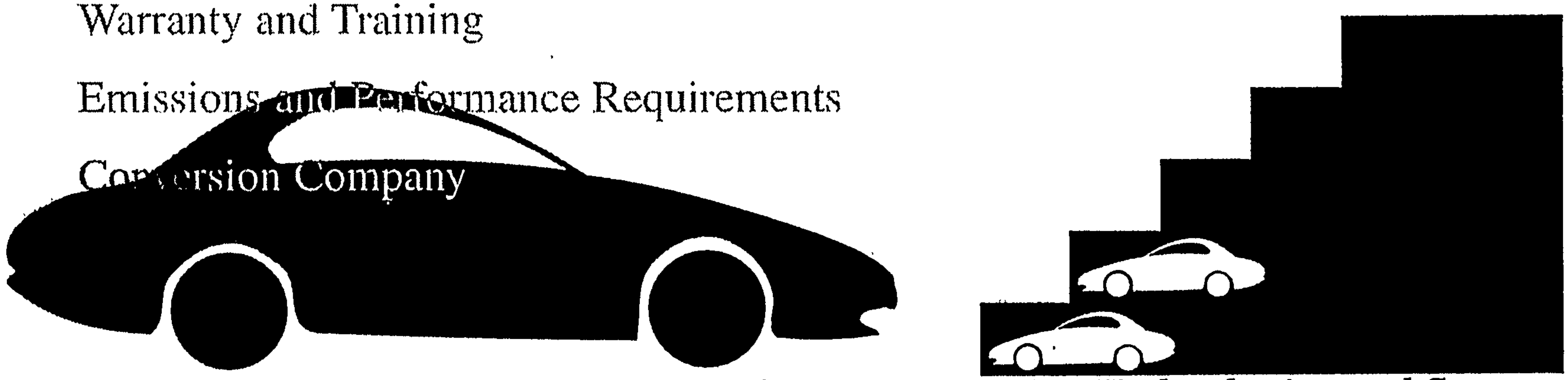
- **Closed loop feedback control**
- **AGA NGV2 Fuel cylinders - CNG**

Installation Procedures

Warranty and Training

Emissions and Performance Requirements

Conversion Company



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Steps to High Quality Conversions

Installation Procedures

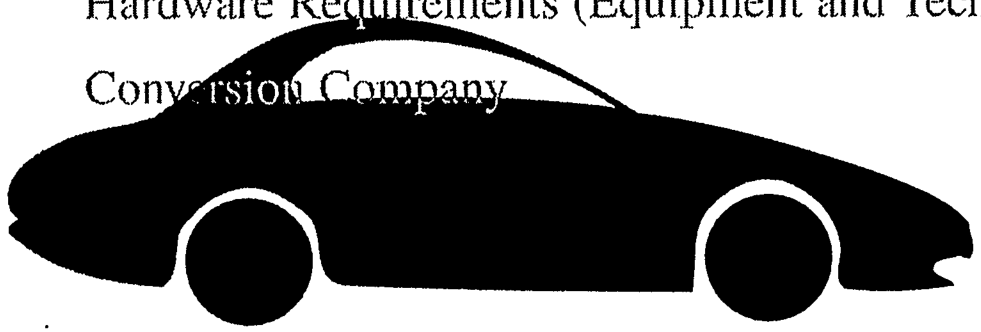
- **Best Industry Practice - NFPA Standards**
- **On-site inspection by NREL**

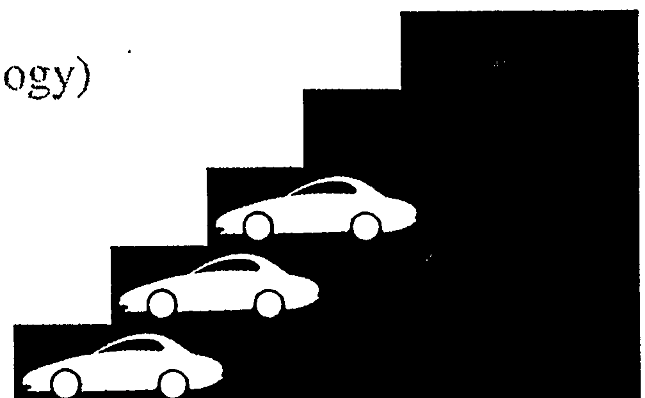
Warranty and Training

Emissions and Performance Requirements

Hardware Requirements (Equipment and Technology)

Conversion Company





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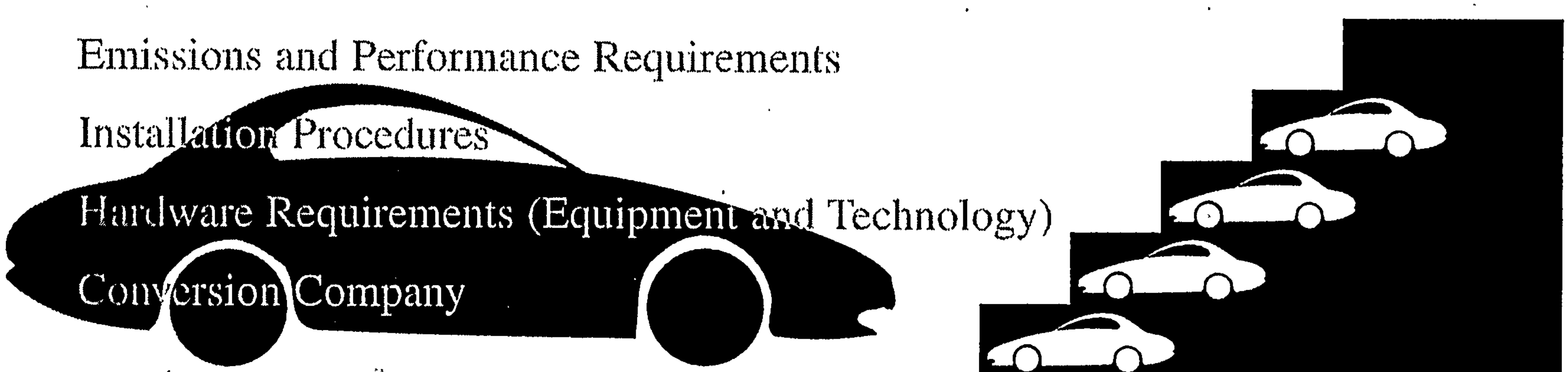
Steps to High Quality Conversions

Warranty and Training

- **3 years/36,000 miles conversion system parts and labor**
- **Damages to OEM equipment**
- **Training site personnel**



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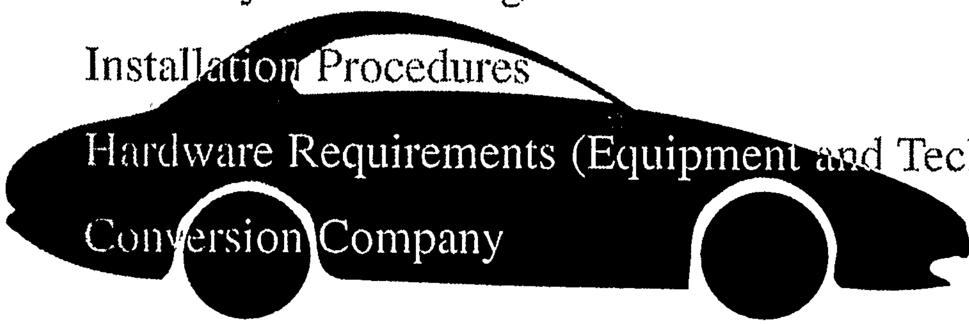
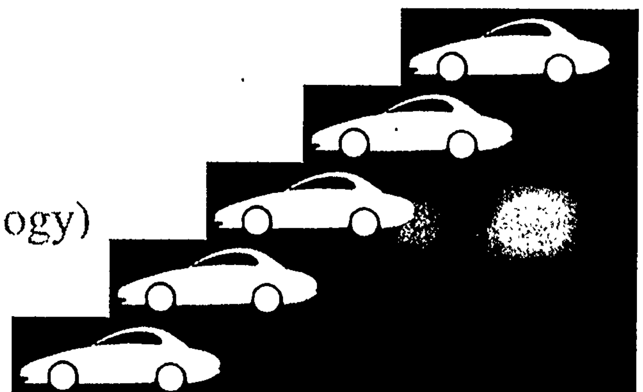
Steps to High Quality Conversions

Emissions and Performance Requirements

- Applicable emissions standards (EPA/CARB)
- CNG range > 70 miles; LPG range > 170 miles
- Initial conversions test driven by NREL
- Emissions tests and driver surveys





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Results

880 High-Quality
Conversions in the
Federal Fleet

SQP4-B119414

Center for Transportation Technologies and Systems

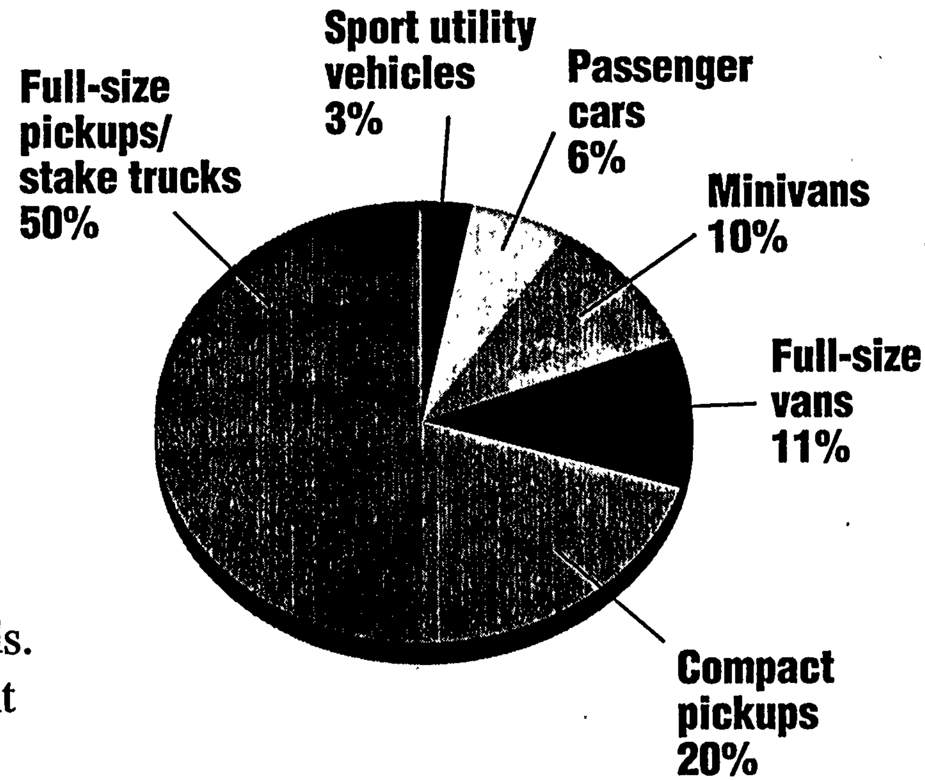
Results

- Conversion Kit Selections
  - CNG: GFI and IMPCO kits
  - LPG: IMPCO ADP kits
- Average System Cost
  - CNG: $4,500
  - LPG: $2,800

Results

90 % Vans or Pickups

90% Bi-fuel



Note: Type of vehicles converted was based on fleet demands. They closely follow current OEM availability

SQP4-B119416

Center for Transportation Technologies and Systems

1996 OEM Vehicle Availability

Manufacturer	Model	Body Style	Fuel	Type
Chrysler-Dodge	Ram van/wagon	Full-size van	CNG	Dedicated
Chrysler-Dodge	Ram pickup	Full-size pickup	CNG	Dedicated
Chrysler-Dodge/ Plymouth	Caravan/Voyager	Minivan	CNG	Dedicated
Ford	Contour	Compact sedan	CNG	Bi-fuel
Ford	Taurus	Mid-size sedan	Methanol	Flex-fuel
Ford	Taurus	Mid-size sedan	Ethanol	Flex-fuel
Ford	Crown Victoria	Full-size sedan	CNG	Dedicated
Ford	F150/F250	Full-size pickup	CNG	Bi-fuel
Ford	Econoline	Full-size van	CNG	Bi-fuel
Ford	F150/F250	Full-size pickup	LPG	Bi-Fuel
Ford	F700	Medium-duty truck	LPG	Dedicated

Eight light-duty CNG/LPG models available

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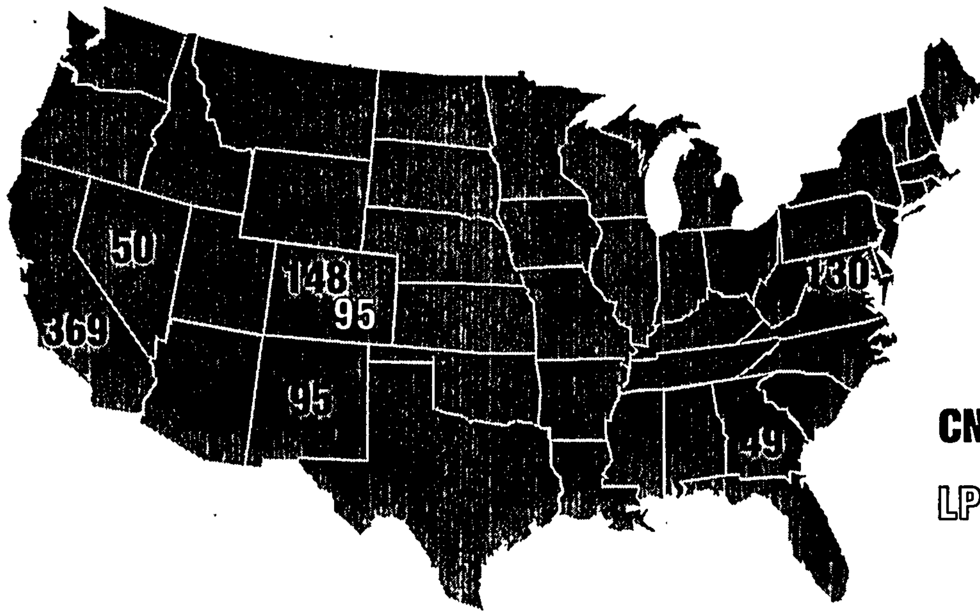
Results

Placement of CNG/LPG vehicles in six states
Including nine Clean Cities



CNG Conversions

LPG Conversions

SQP4-B119418

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Results

Variety of Federal Agencies

Agency	CNG	LPG	Total Vehicles
Air Force	368	0	368
Marines	219	0	219
Navy	97	0	97
National Institutes of Health	66	0	66
Forest Service	2	24	26
Other Federal Agencies	89	15	104
Totals	841	39	880

Emissions Testing

- Part of larger evaluation program
- 8 models/16 vehicles tested
- Specially blended test fuels
  - CNG—93% methane
  - LPG—HD5 transportation fuel
  - RFG—California Phase II reformulated gasoline
- EPA Federal Test Procedures
  - RFG before conversion
  - RFG shortly after conversion
  - CNG/LPG shortly after conversion

Importance of Evaluating Aftermarket Conversions

- 330,000 on the road
- 10,000 conversions per year

Emissions Results Legend

○	Large emissions decrease (>50%)
◒	Moderate emissions decrease (10%–50%)
NC	No change (<10%)
◓	Moderate emissions increase (10%–50%)
●	Large emissions increase (>50%)

Emissions Results:

Washington, D.C. CNG Conversion Vehicles—**Kit make: GFI**

Vehicle Model	Model Year	After Conversion (RFG) NO_X	After Conversion (RFG) CO	After Conversion (RFG) NMHC	After Conversion (CNG) NO_X	After Conversion (CNG) CO	After Conversion (CNG) NMHC
Acclaim	1992	NC	◒	◒	●	○	○
Acclaim	1992	NC	◓	NC	●	◒	◒
Astro	1992	◒	NC	NC	◒	●	◒
Caravan	1992	◒	●	◓	●	●	◒
Caravan	1992	◒	◒	NC	●	●	◒
Safari	1993	NC	◒	NC	◒	NC	○
Safari	1993	NC	◒	◒	◒	◒	○
Taurus	1994	◓	NC	◒	●	●	NC
Taurus	1994	NC	◓	◓	●	●	NC

Emissions Results:

Denver. CNG Conversion Vehicles—**Kit make: GFI**

Vehicle Model	Model Year	After Conversion (RFG) NO_X	CO	NMHC	After Conversion (CNG) NO_X	CO	NMHC
B250	1994	NC	NC	NC	◒	◓	○
B250	1994	◒	NC	NC	◒	●	○
C1500	1994	NC	◒	NC	◒	●	○
C1500	1994	NC	NC	NC	◒	●	○

Emissions Results:

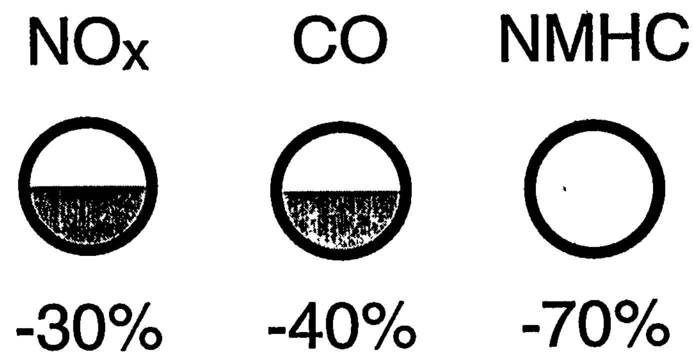
Denver LPG Conversion Vehicles—**Kit make and model: IMPCO ADP**

Vehicle Model	Model Year	After Conversion (RFG) NO_X	After Conversion (RFG) CO	After Conversion (RFG) NMHC	After Conversion (CNG) NO_X	After Conversion (CNG) CO	After Conversion (CNG) NMHC
F150 pkup	1994	◒	●	●	NC	○	●
F150 pkup	1994	NC	●	●	NC	○	●
Taurus	1994	NC	◒	NC	●	○	◓

OEM Results: Dodge B250 Van

Dedicated CNG versus Standard Gasoline

Average of approximately 40 of each



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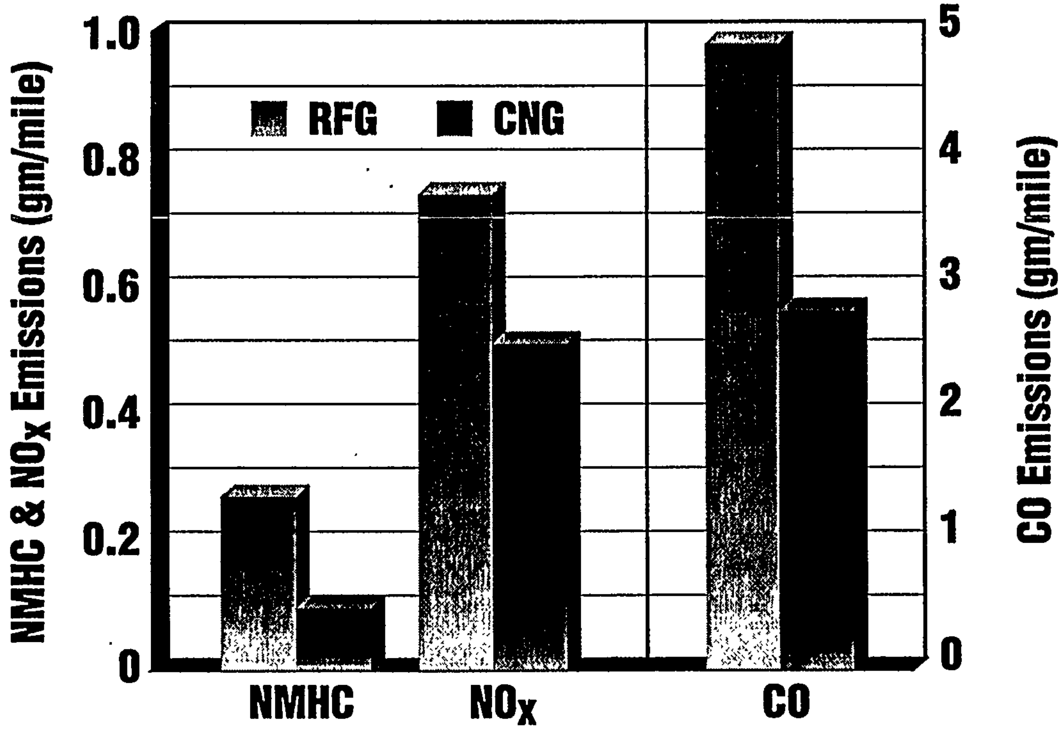
OEM Results: Dodge B250 Van



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Emissions Test Results -
Other Considerations for Aftermarket Conversions

- Potential Positives
  - Ozone-forming potential
  - Exhaust toxics/particulate matter
  - Off-cycle emissions considerations
- Potential Negatives
  - Conversion of new, relatively clean (Tier 1) models
  - Use of less advanced kits (non-feedback)
  - Poor/untested installations
  - Deterioration

Conclusions

- Program was successful in helping to meet EPACT requirements
- Developed a systematic approach for fleets to ensure "high-quality" conversions
- Emissions results from conversions have raised some serious concerns
- OEM tests show emissions benefits "across the board"
- Fleets should require verification of emissions performance with FTP testing when considering aftermarket conversions
- Initial driver survey data are currently being tabulated

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

SQP4-B119301

Center for Transportation Technologies and Systems

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

SQP4-B119302

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

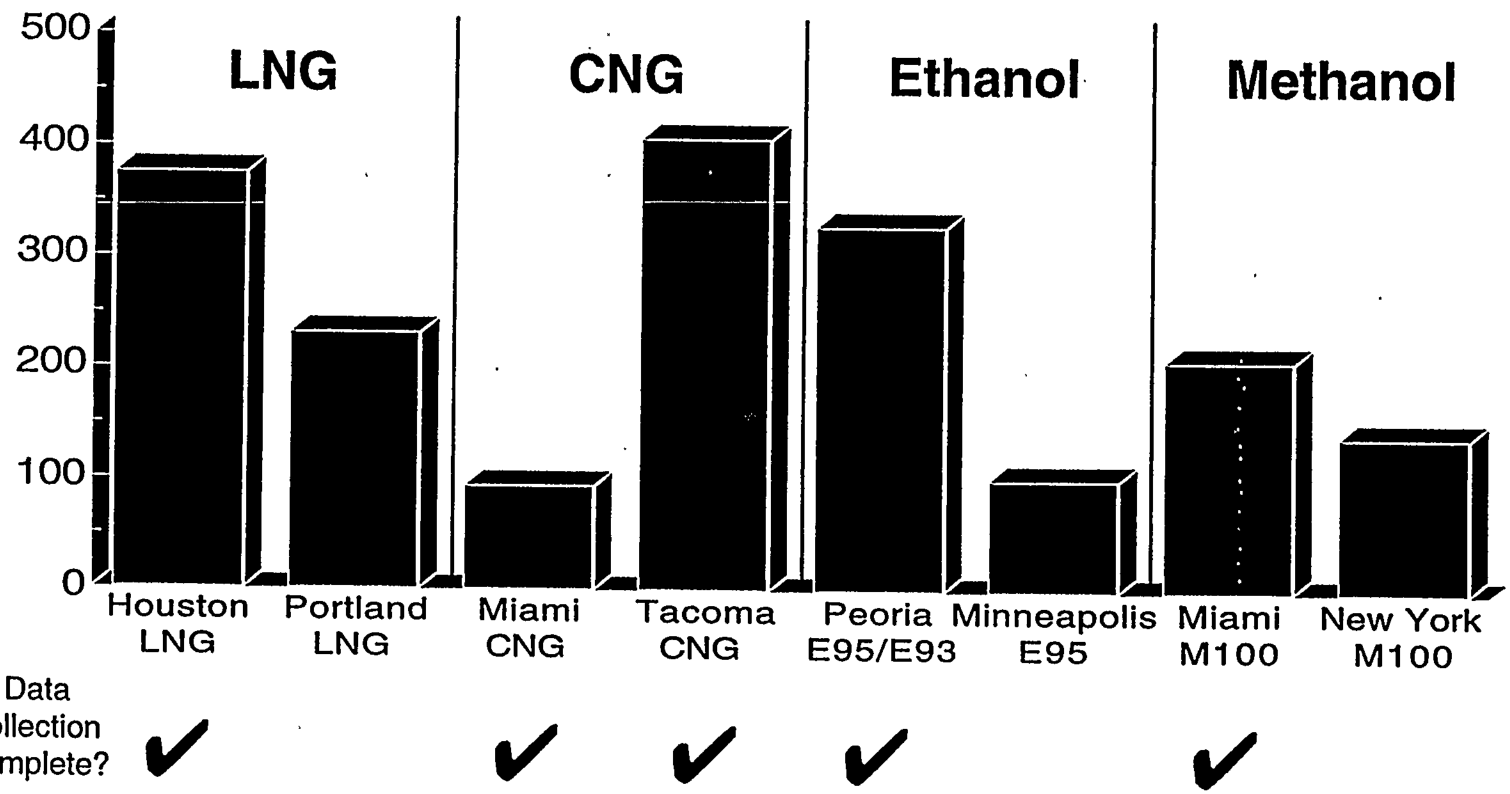
Program Design

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/	5								5
	Series 50								5	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)



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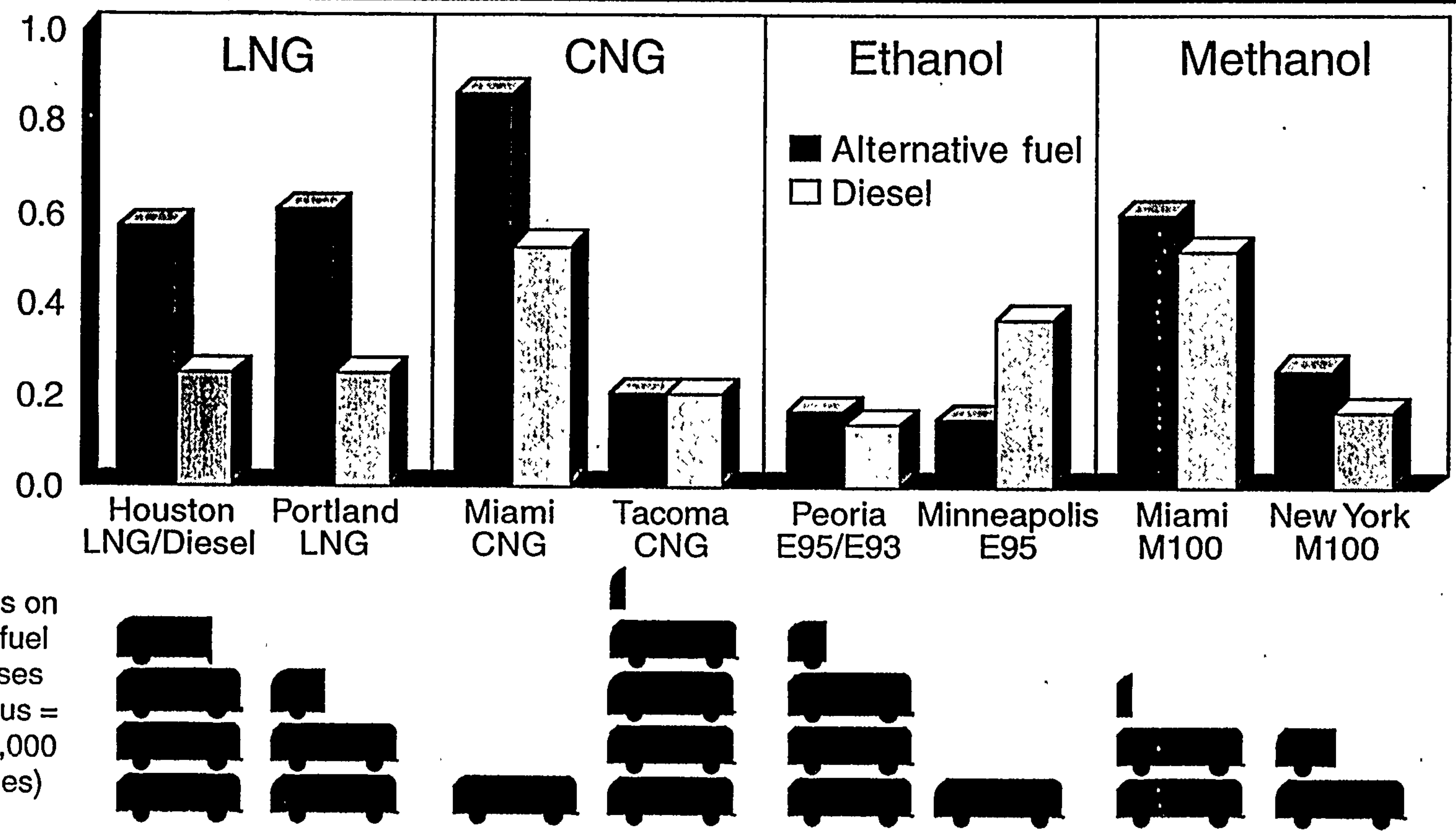
Results

- Reliability
- Operating Costs
- Emissions

Reliability

Vehicle Reliability—Road Calls/1000 Miles



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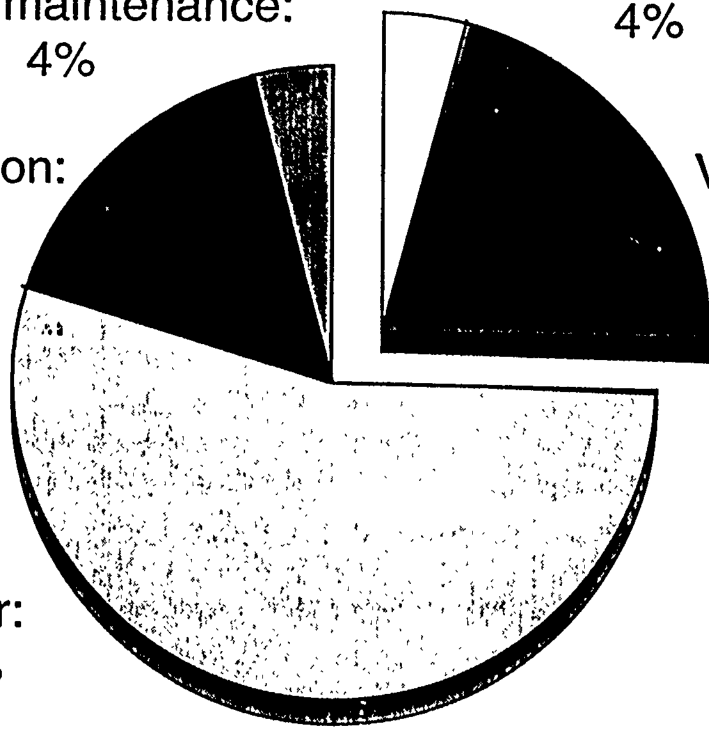
Operating Costs

Cost Breakdown for Transit Bus Operations



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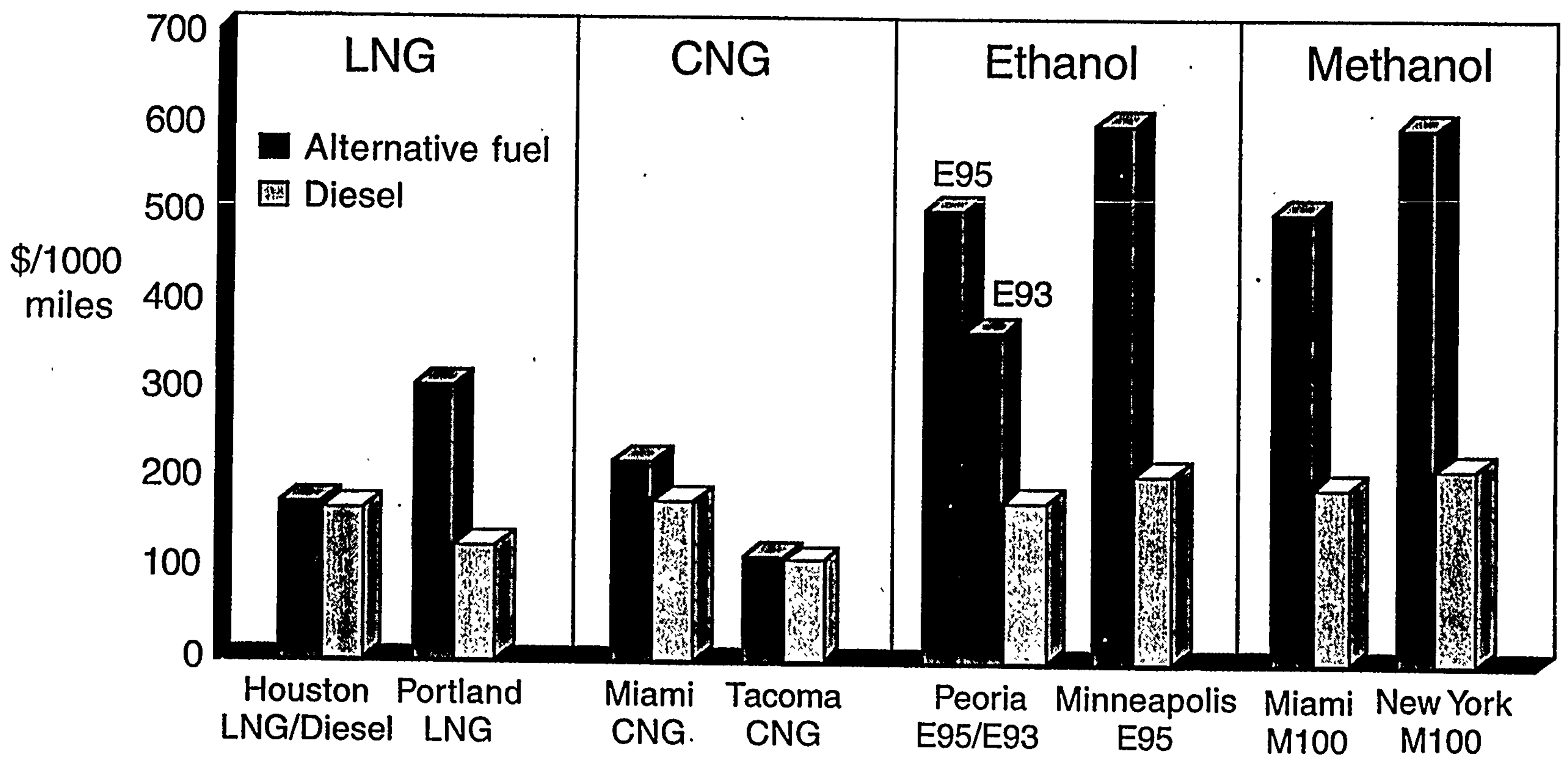
Fuel Costs/1000 miles



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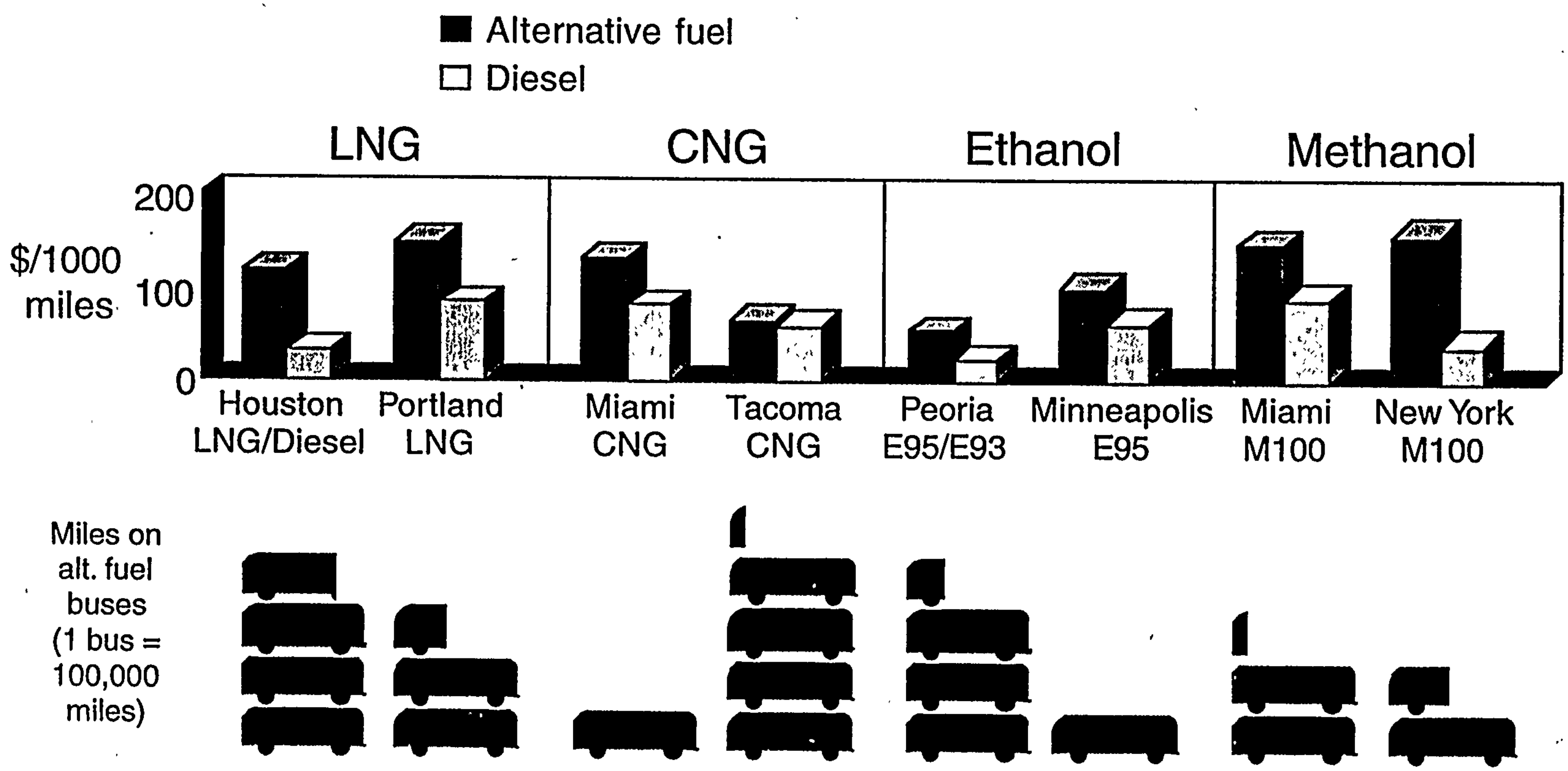
Maintenance Costs/1000 Miles
(Alternative Fuel-Affected Systems Only)



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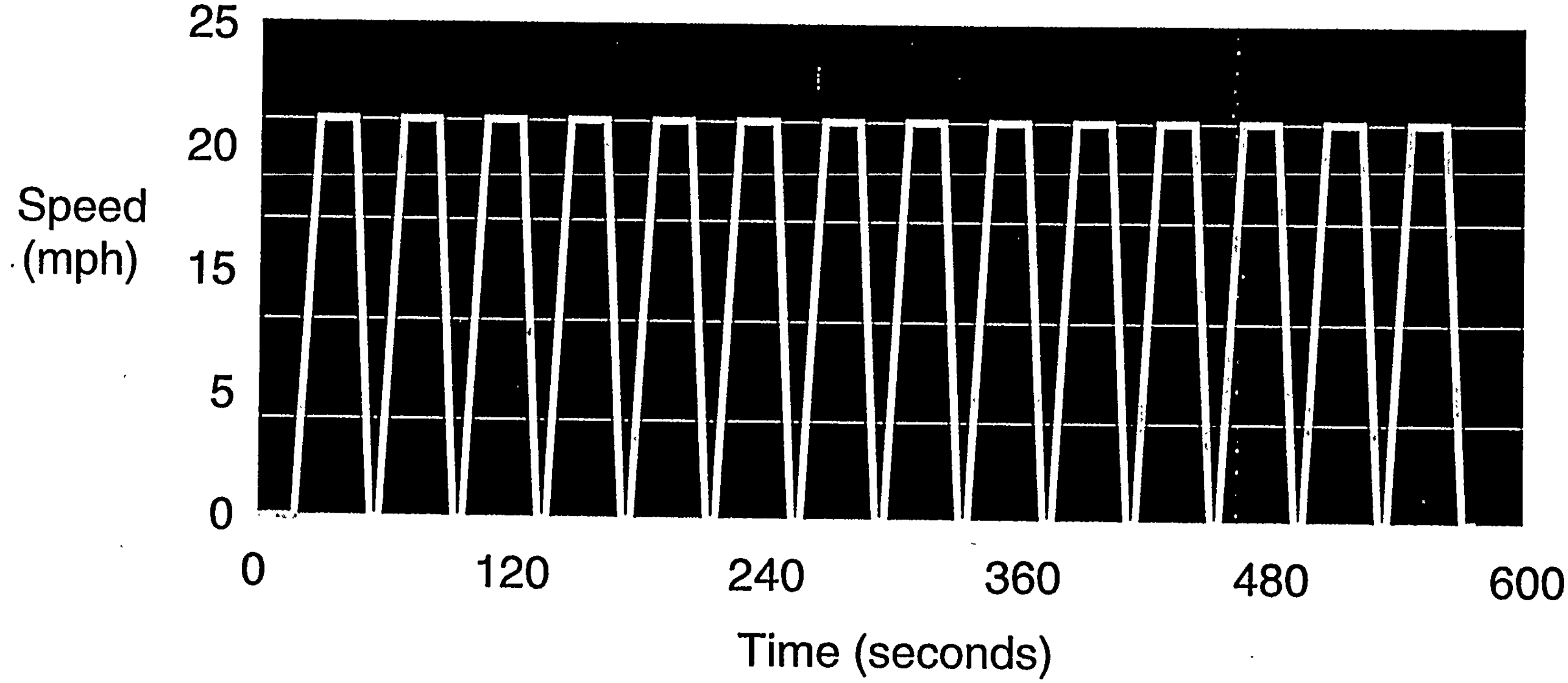
Emissions Results

Emissions Test Procedures

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

Chassis Dynamometer Test Cycle



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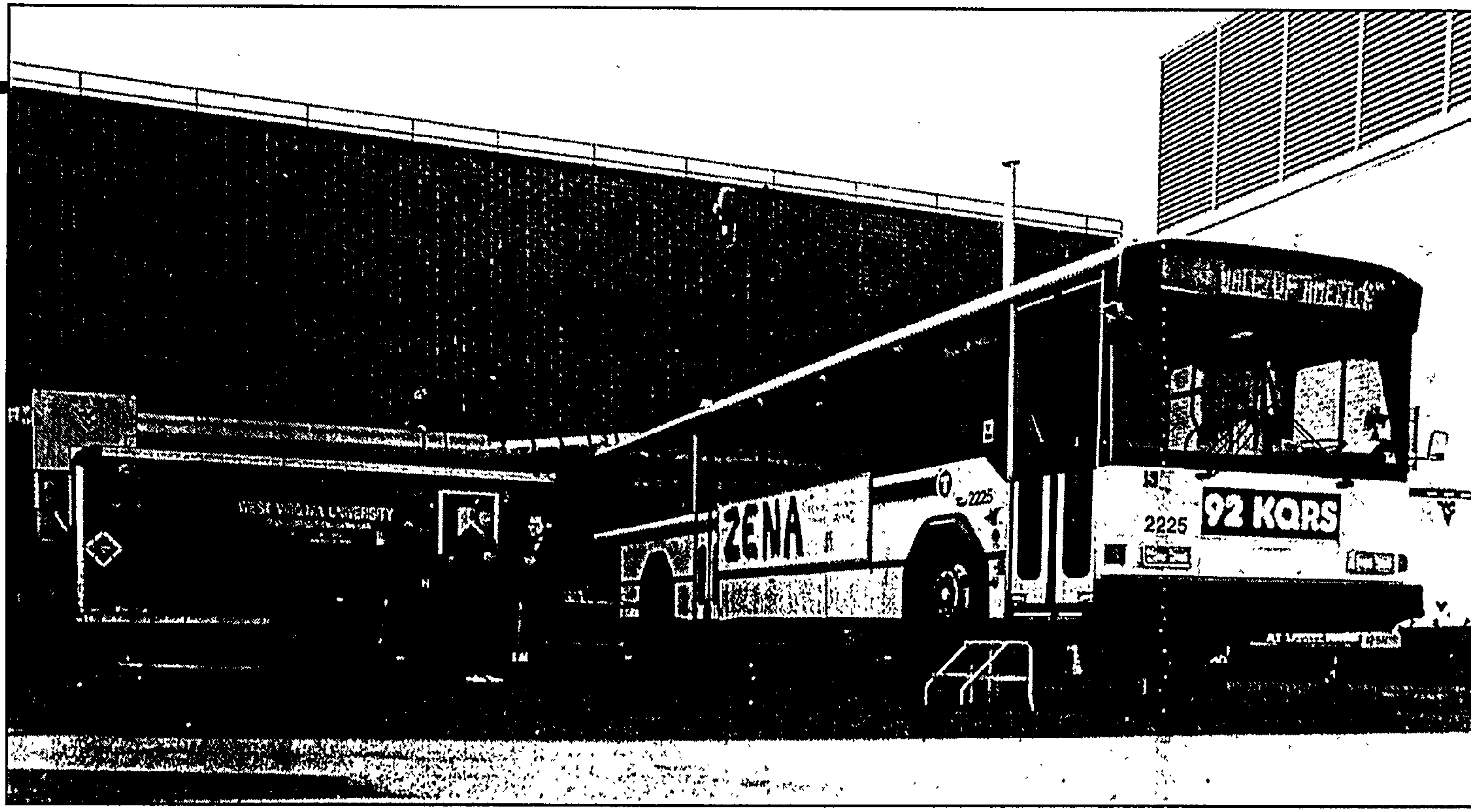

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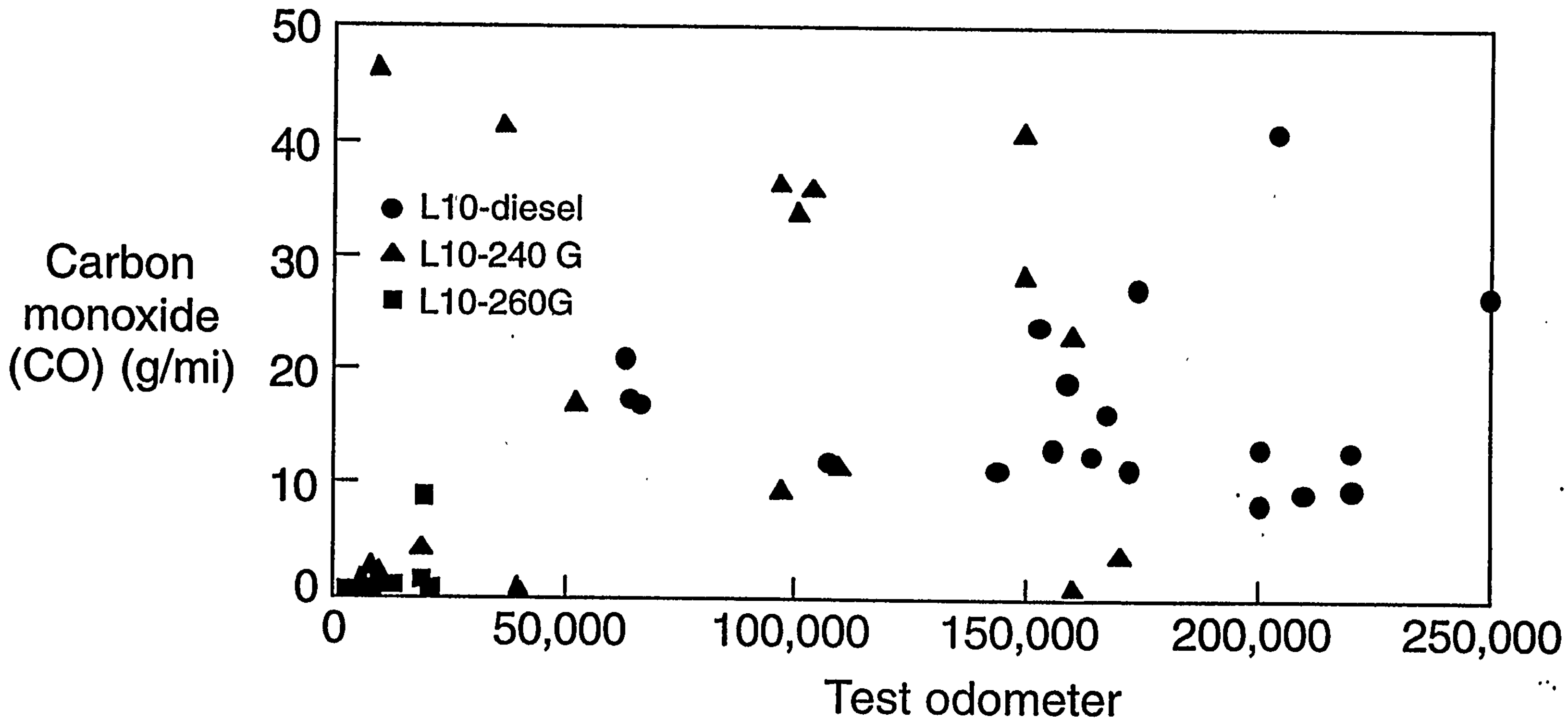
Emissions Test Results

- 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



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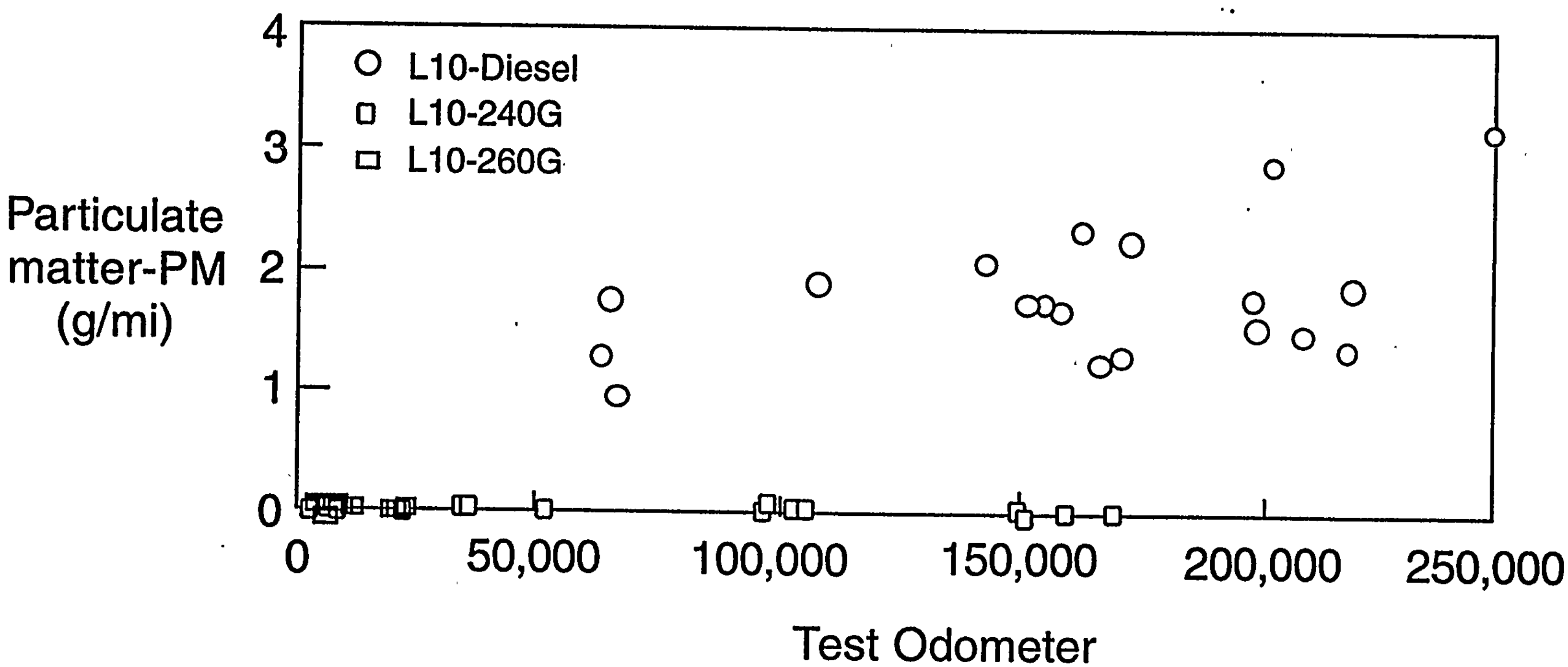
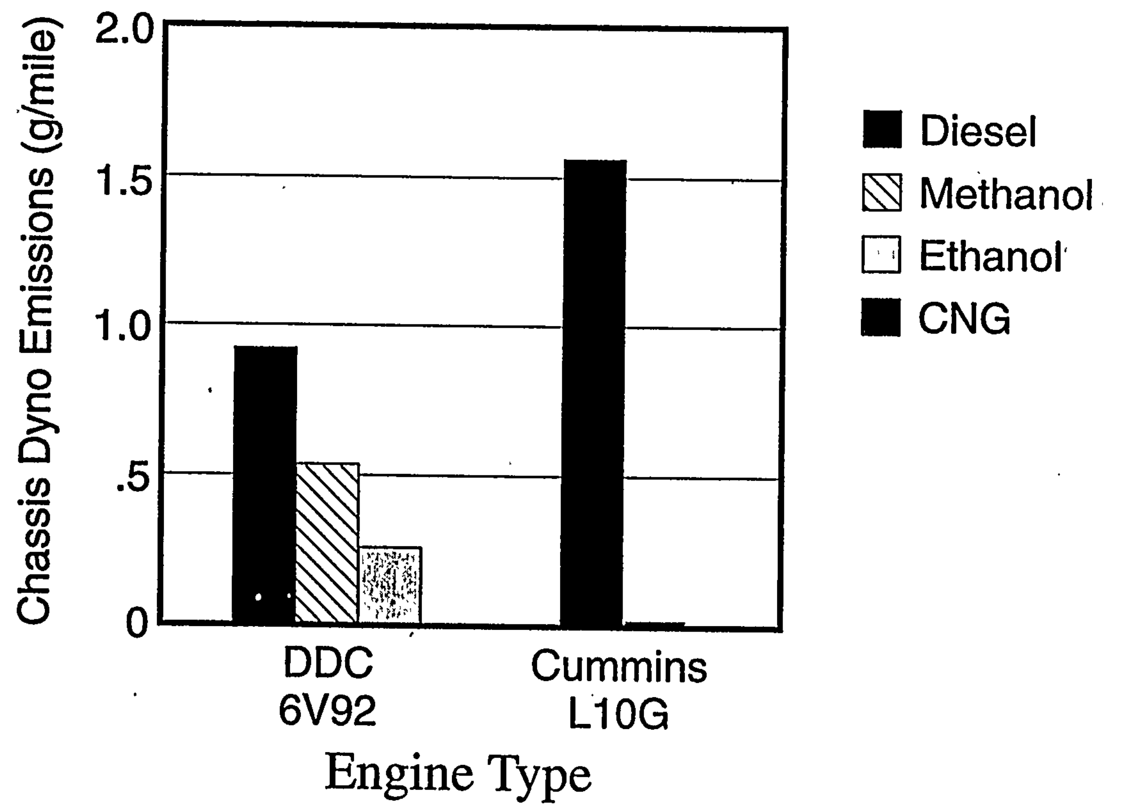
Sample Emissions Results—
Particulate Matter from CNG and Diesel Buses



Average Particulate Matter Emissions



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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

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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.

$$OMHCE = (FIDHC) - 0.768(C_2H_5OH) + 0.4621(HCHO) + 0.6298(CH_3CHO) + 0.6023(C_2H_5OH)$$

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

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Table 1: Details of Buses Tested

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

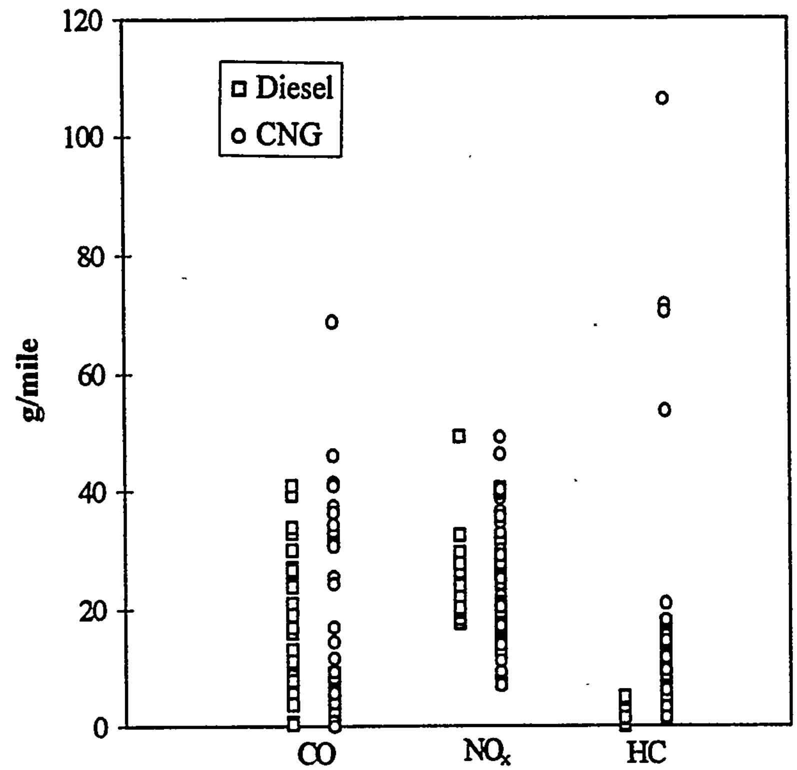

Figure 2: Testing of Bus PT-478 at Tacoma, Wa.

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.

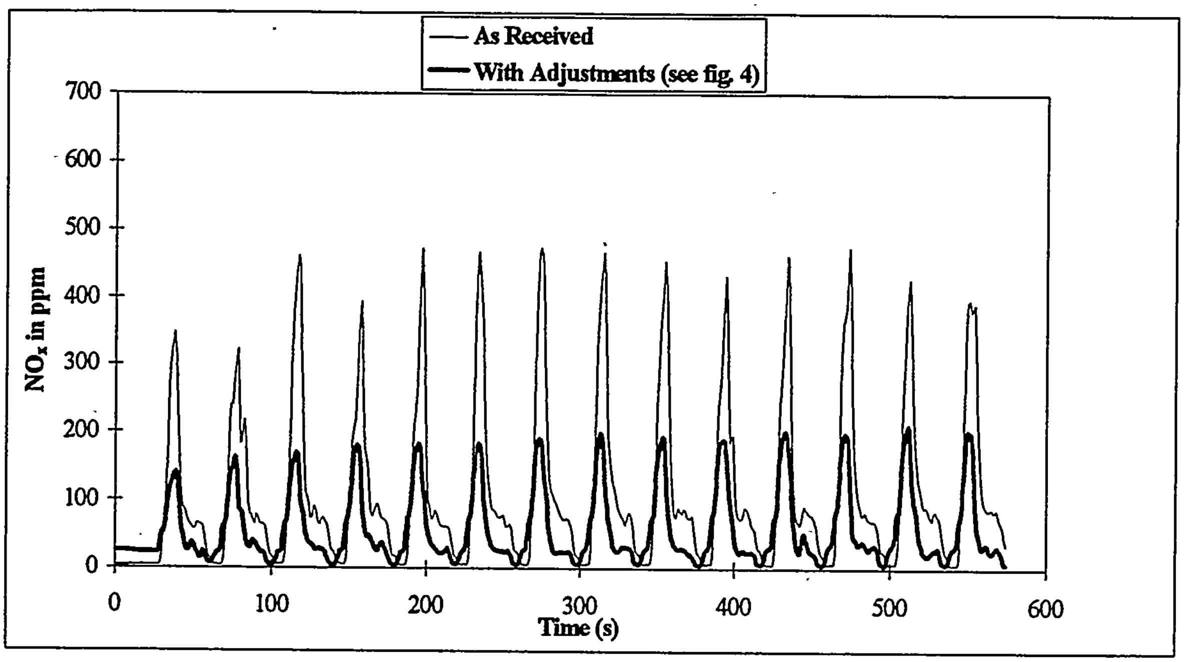

Figure 6: Comparison Between Continuous CO Emissions for a Cummins L-10 Powered Natural Gas Bus (PT-481), First Tested As-received and then with Adjustments.

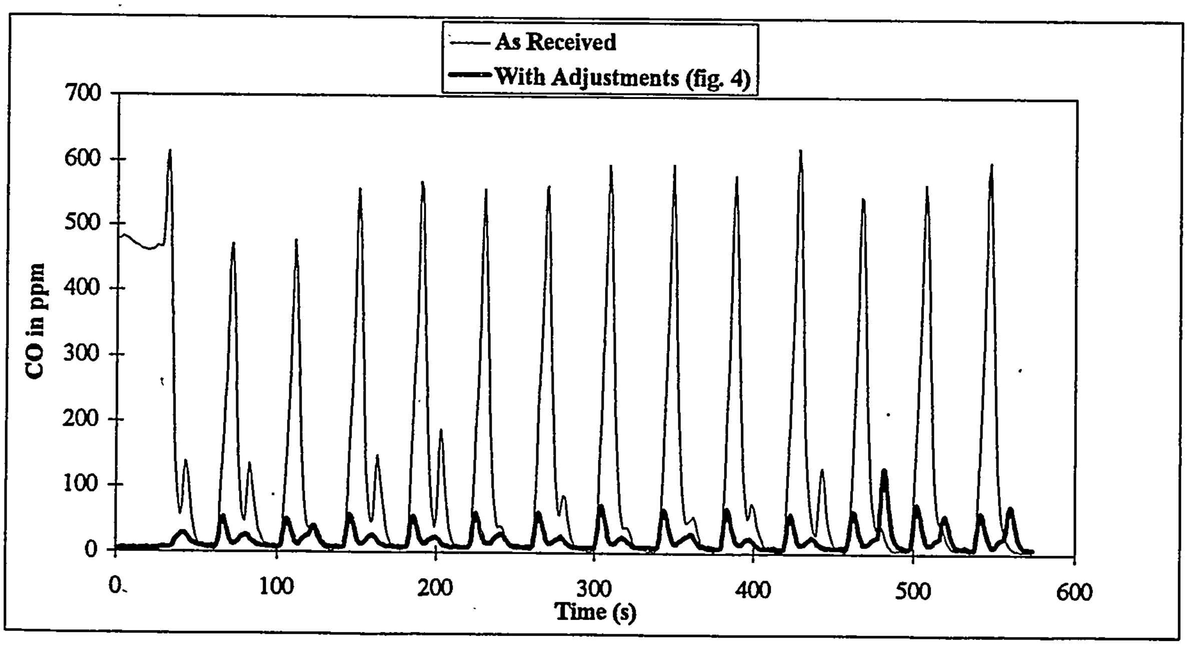

Figure 7: Testing of Bus 1507E at Peoria, Ill.

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

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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

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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.

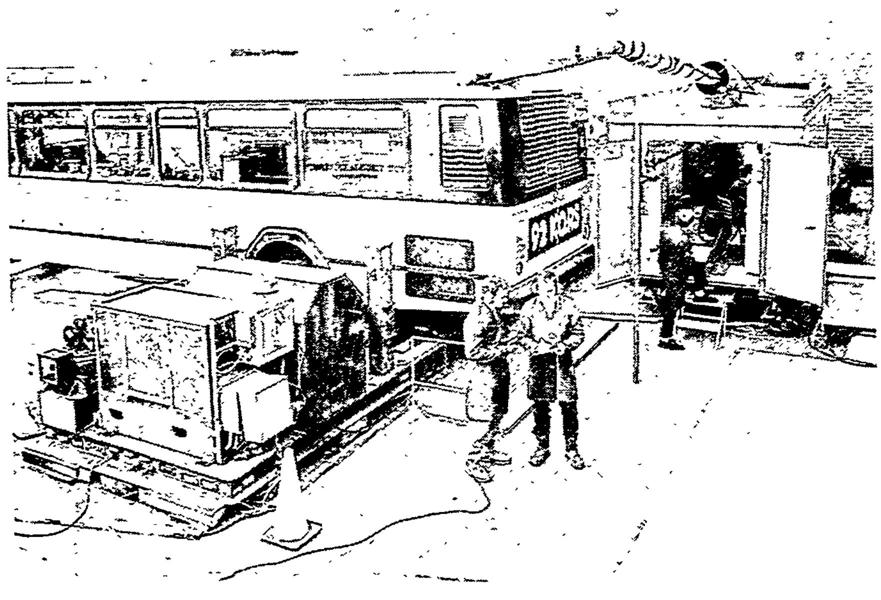
LABORATORY CAPABILITIES

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

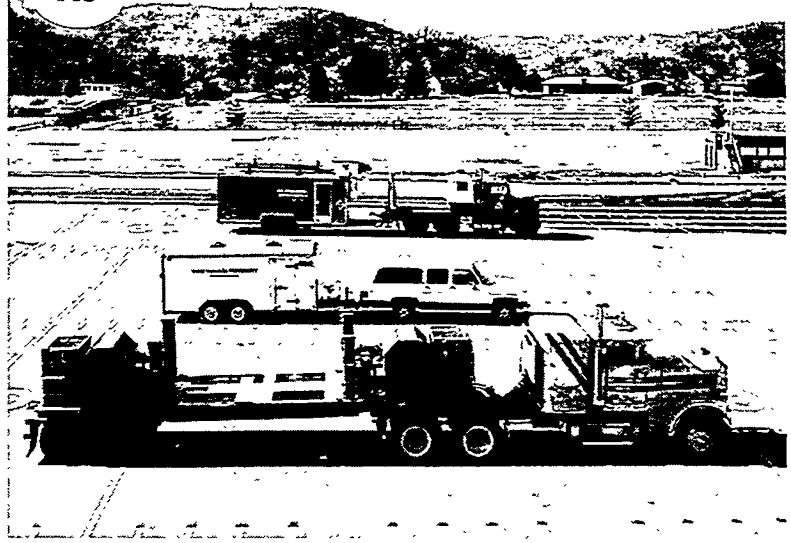
This photograph shows the laboratory in operation at a test site. The vehicle to be tested is placed on the flat bed chassis dynamometer and the exhaust from the vehicle is collected, diluted, and sampled and analyzed to measure the levels of the constituents of the exhaust.

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

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

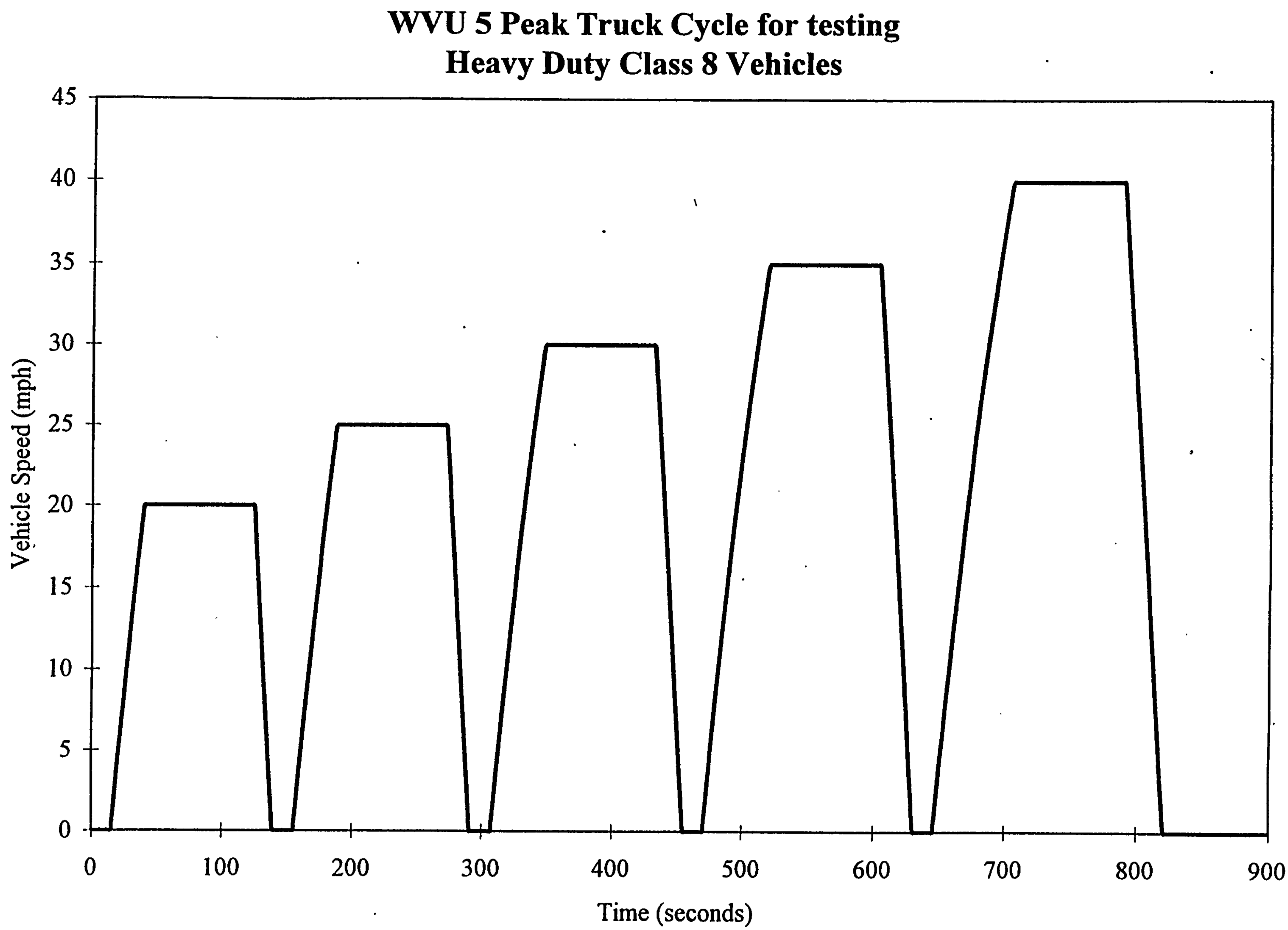
Fleet Owner Full Name	AG Processing, Inc.
Fleet Address	804 Second Ave., P.O.Box 220
Fleet Address (City, State, Zip)	Sheldon, IA 51201
Vehicle Type	Tractor
Vehicle ID Number (VIN)	2HSFHDPR9RSO90633
Vehicle Manufacturer	INTL
Vehicle Model Year	1993
Gross Vehicle Weight (GVW) (lb)	80000
Vehicle Total 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)

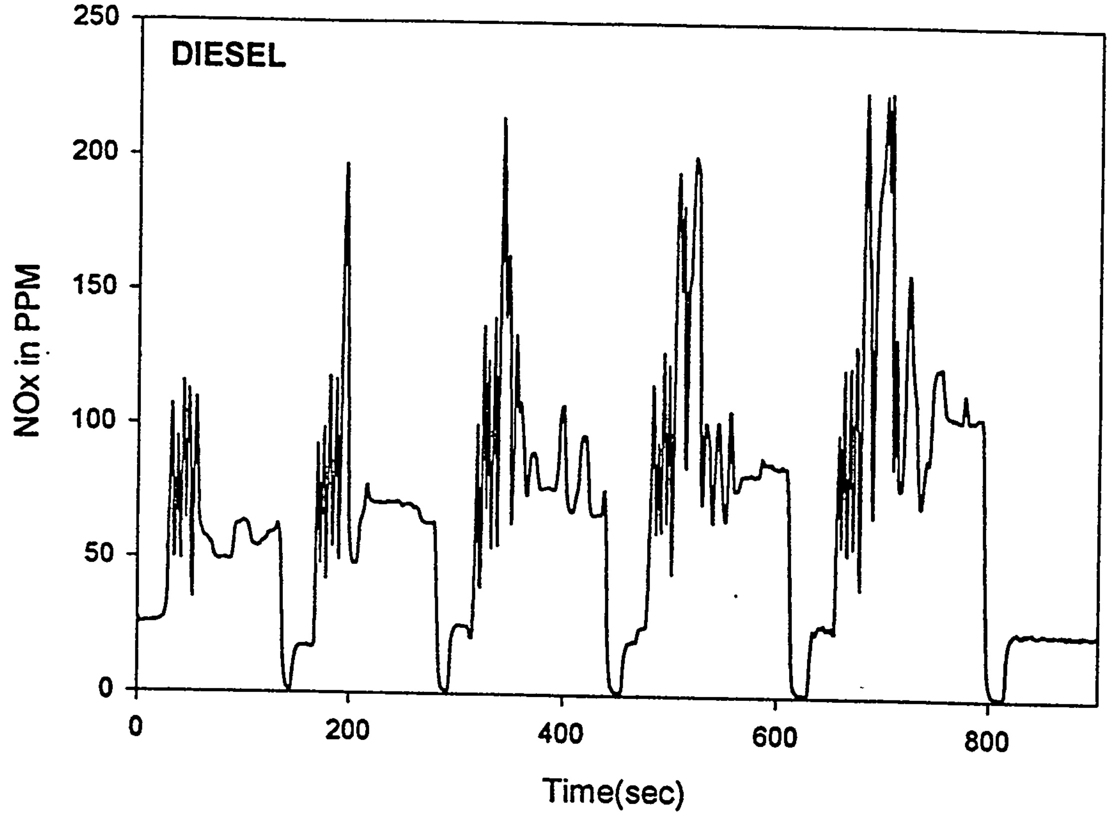
Run Seq. No.	CO	NOx	FIDHC	PM
466-1	3.4	17.6	0.24	0.29
466-2	3.8	16.9	0.25	0.25
466-3	3.0	16.9	0.25	0.25
466-4	3.8	17.4	0.22	0.22
466 Average	3.5	17.2	0.24	0.25
Std. Dev.	0.24	17.2	0.24	0.25
CV%	11.4	2.1	5.2	10.3

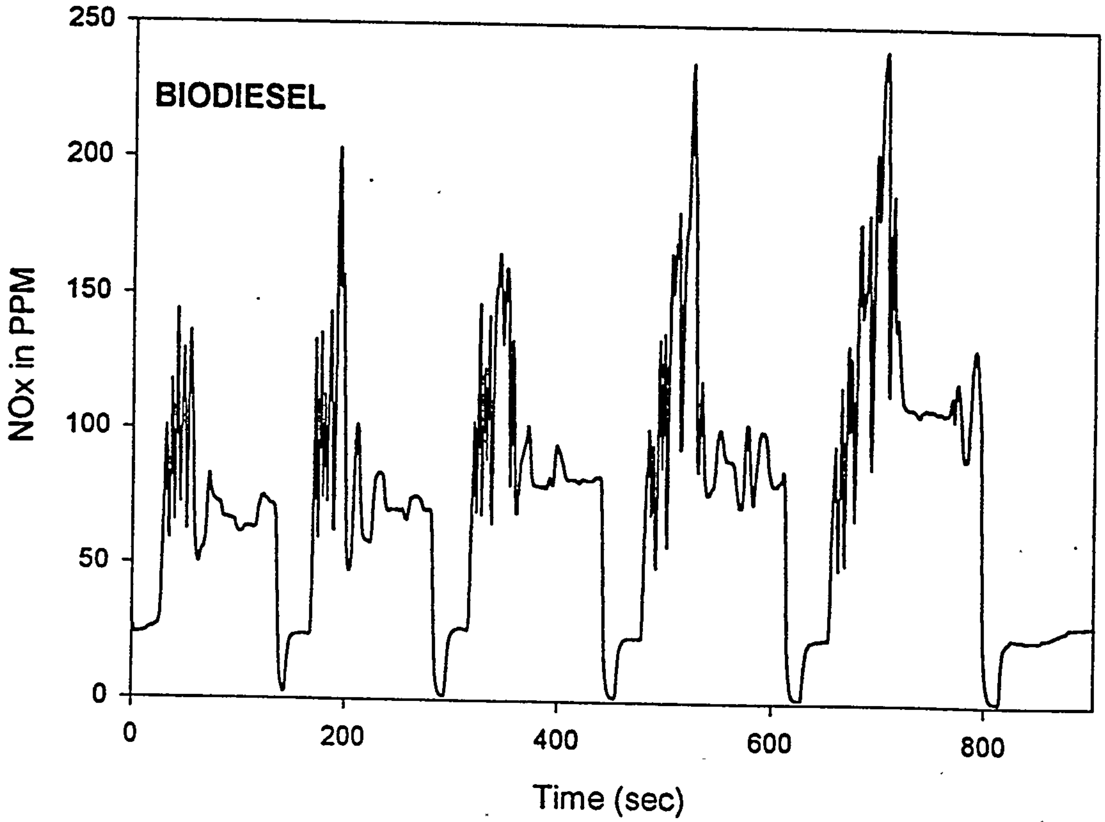
DIESEL EMISSIONS RESULTS (g/mile)

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
Vehicle Speed (mph)
0
5
10
15
20
25
30
35
40
45
Time (seconds)
0
100
200
300
400
500
600
700
800
900

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

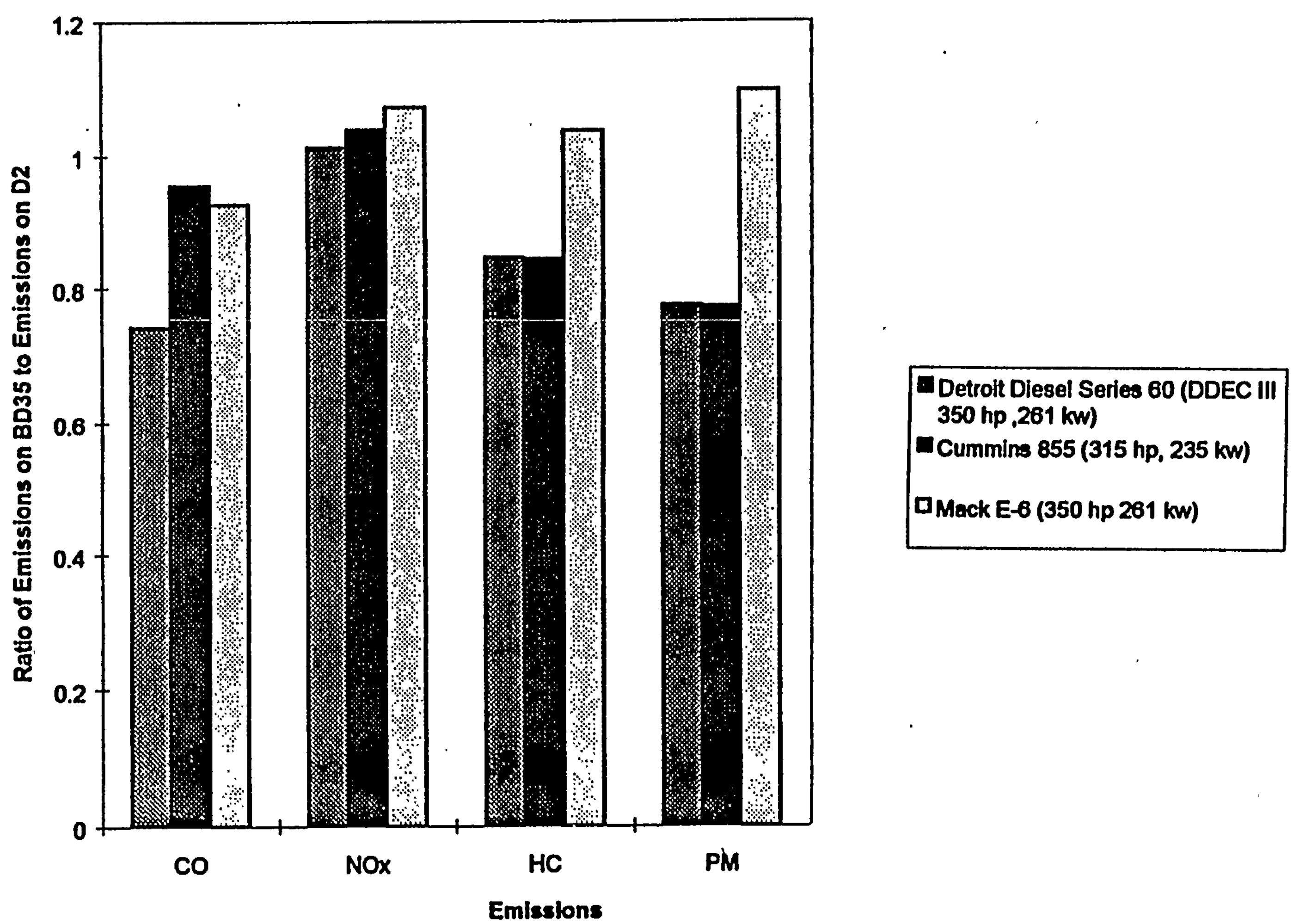




Demographics of tractors tested in Sheldon, Iowa, each on conventional No. 2 Diesel and on biodiesel (a blend of soy-derived ester (35%) and #2 diesel (65%)).

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

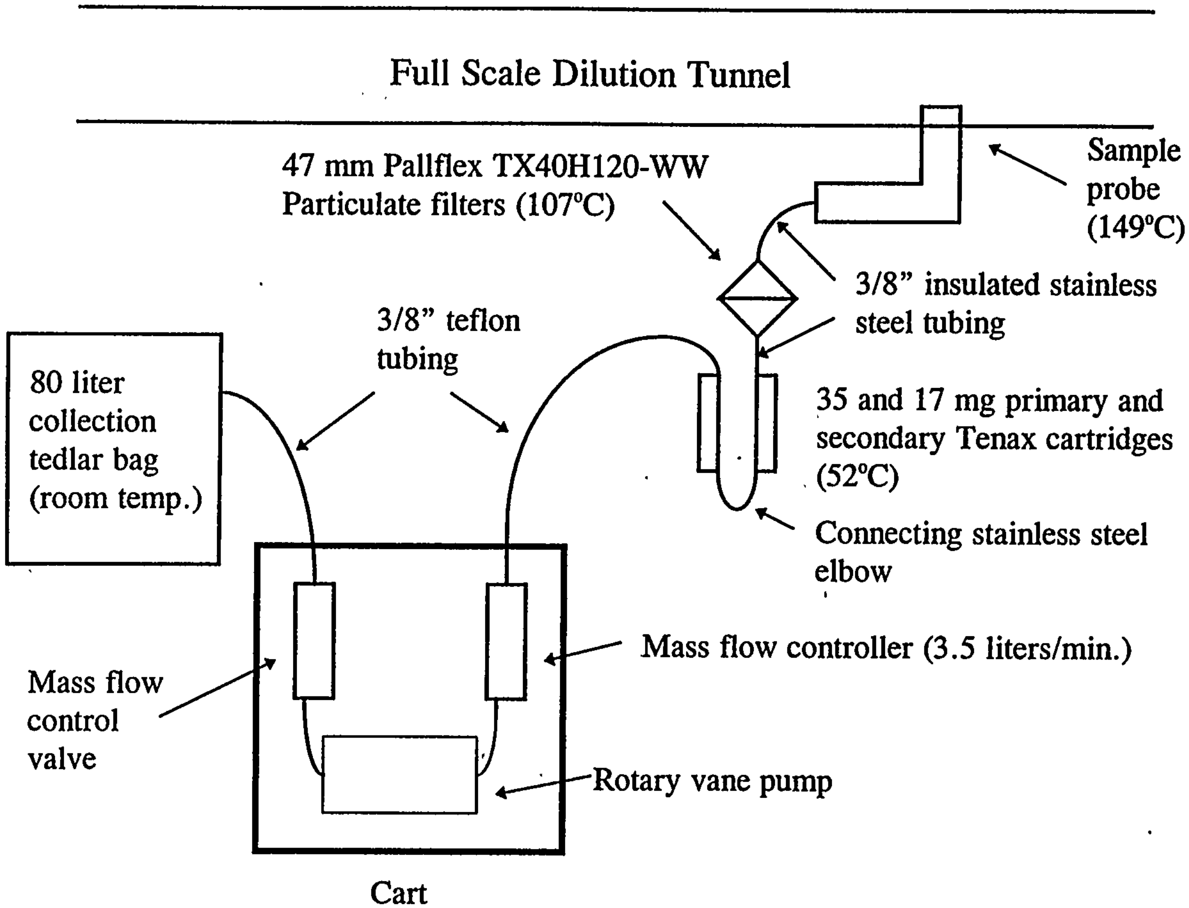


Speciation of Reactive Components of Lean Burn CNG Exhaust Emissions

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



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

Test Fuel Composition

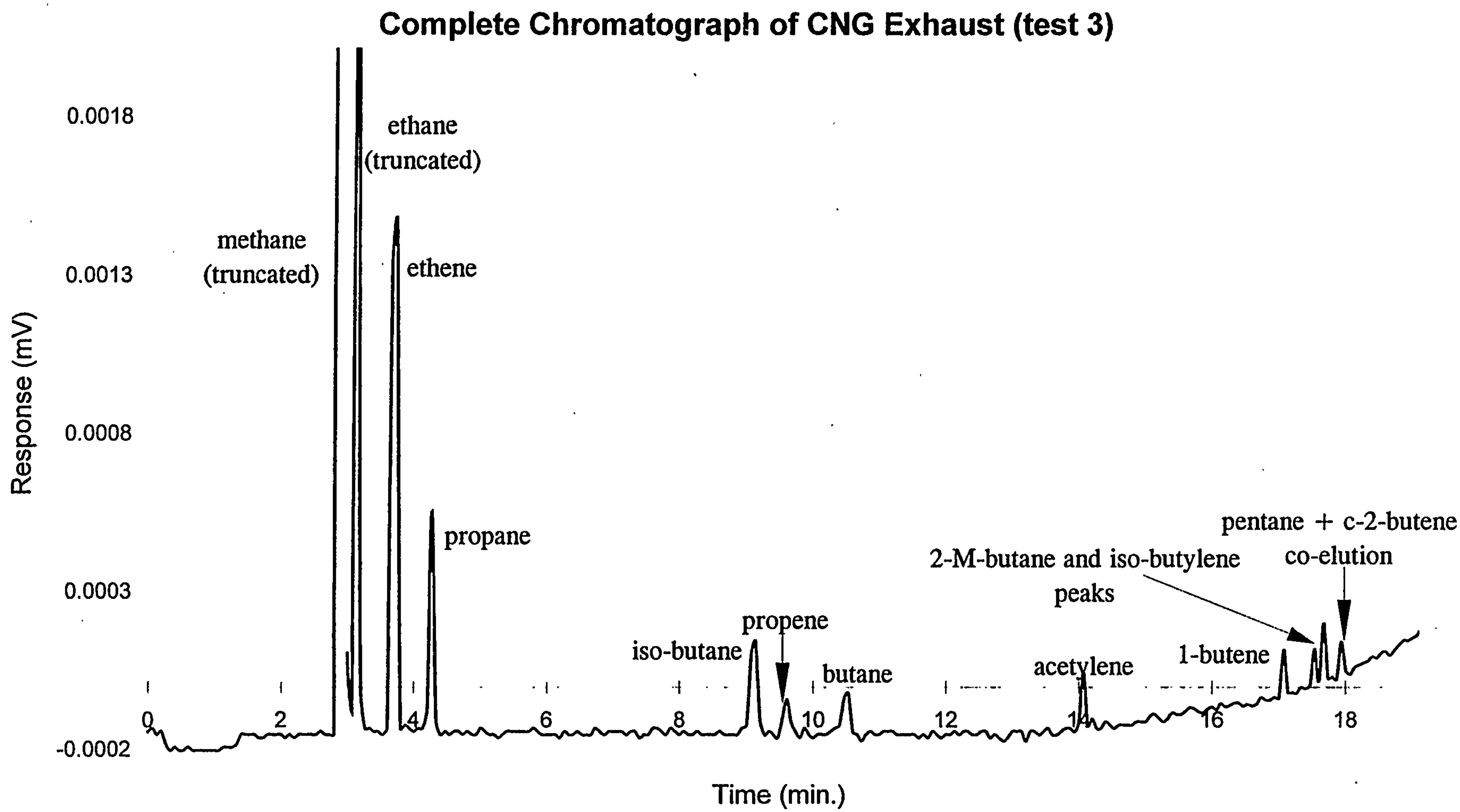
CNG	methane 91.0%; ethane 6.45%; propane 1.08%; i-butane 0.159%; n-butane 0.216%; i-pentane 0.071%; n-pentane 0.049%; hexane 0.064%; N_2 0.903%
Methane	methane 99.2%; ethane 0.060%; propane 0.167%; N_2 0.376%; CO_2 0.181%
Propane	methane 1.76%; ethane 10.5%; propane 85.6%; i-butane 0.859%; n-butane 0.081%;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

(% by volume)

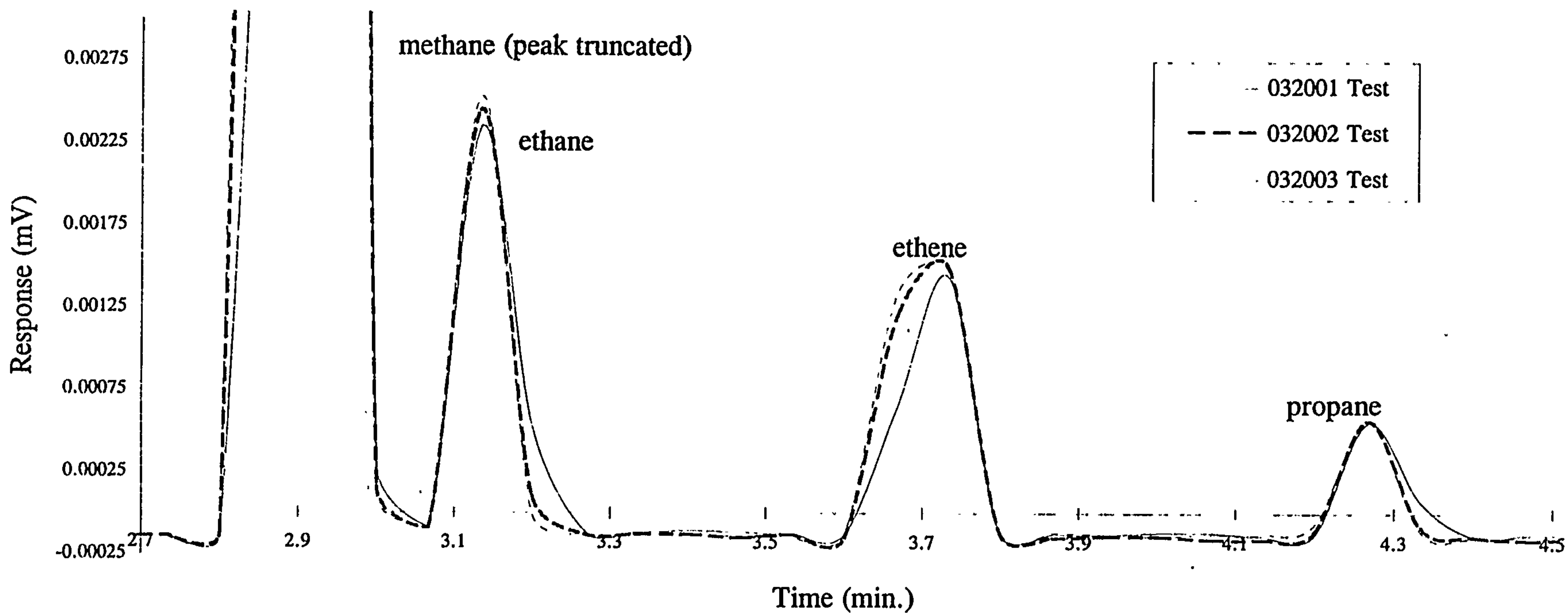
Speciated Hydrocarbons Present in the Exhaust

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

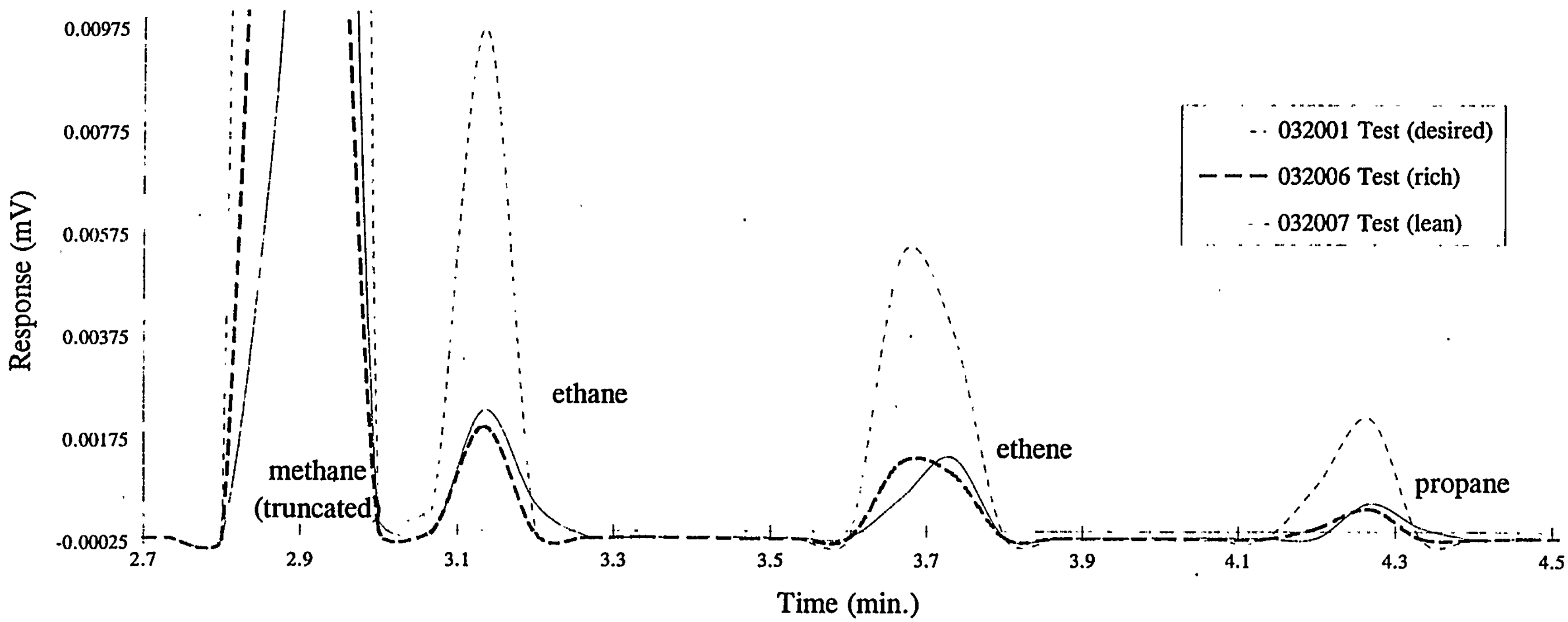
* small response detected


Complete Chromatograph of CNG Exhaust (test 3)
0.0018
0.0013
0.0008
0.0003
-0.0002
Response (mV)
methane
(truncated)
ethane
(truncated)
ethene
propane
iso-butane
propene
butane
acetylene
1-butene
2-M-butane and iso-butylene
peaks
pentane + c-2-butene
co-elution
0
2
4
6
8
10
12
14
16
18
Time (min.)

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
Dr. Nigel N. Clark
Dr. Christopher M. Atkinson
Dr. Donald W. Lyons

Research Staff
Gregory E. Mott, Engineering Scientist
Richard J. Atkinson, Instrumentation Engineer
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.

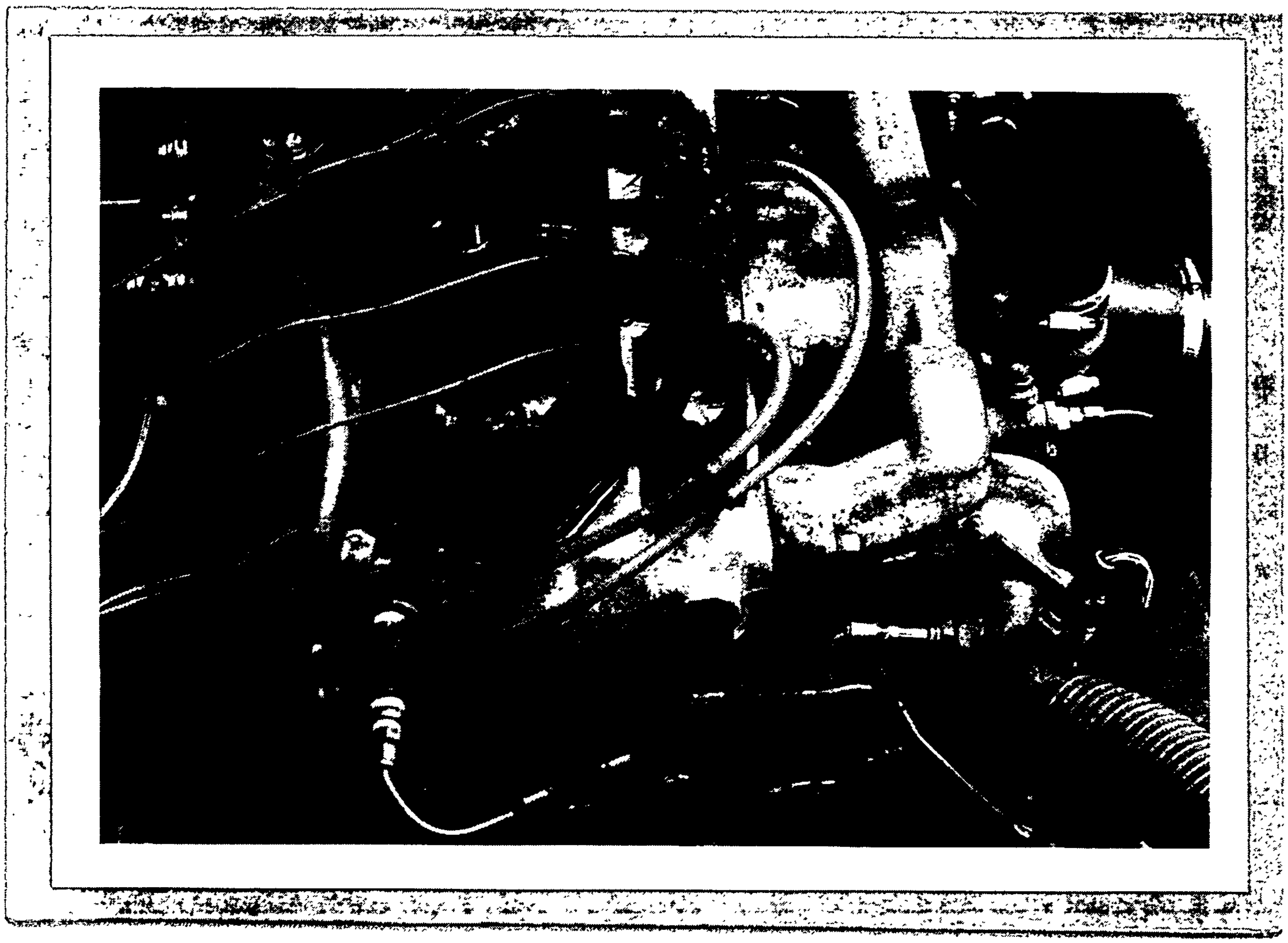
A Hercules turbocharged lean burn natural gas engine fitted with a GFI Compuvalve and an Altronics spark ignition system are being used as a test bed for the research. Closed loop fueling control is accomplished by means of feedback to the Compuvalve from a wide range EGO sensor. Two types of EGO sensor, 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.

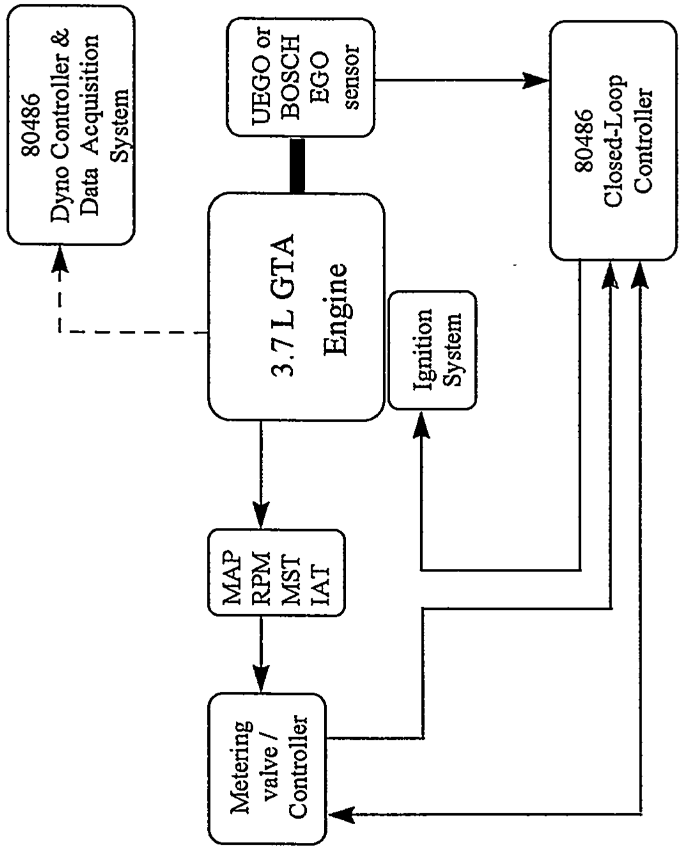
Effects of fuel composition on engine operation was investigated by operating the engine on four different fuel compositions in both open and closed loop modes and at fixed operating setpoints. The fuels varied widely in composition from pure methane to pure propane but retained similar heating values. 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.

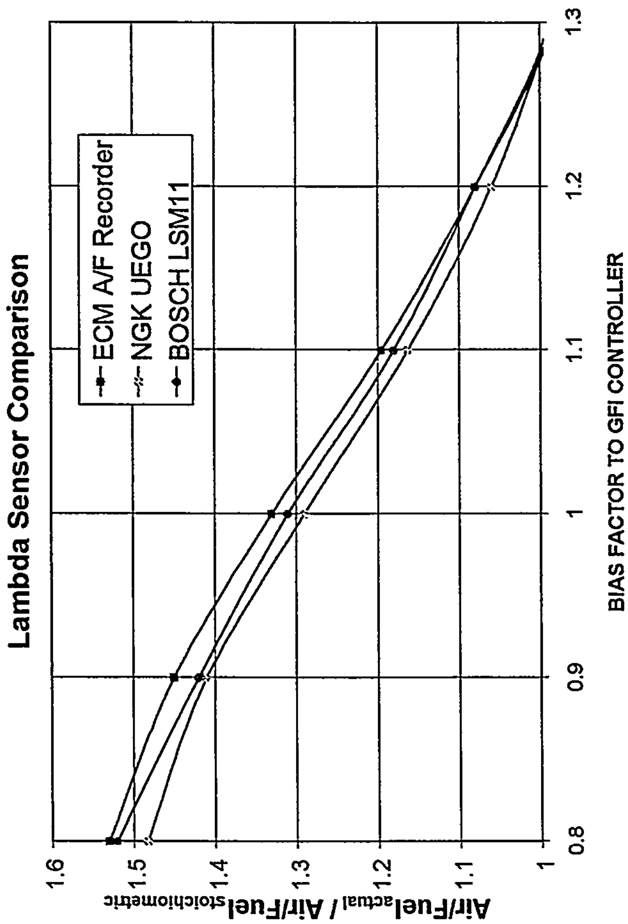
Engine knock detection is being addressed as a means of engine protection. Block resonance has been determined with and without engine knock using accelerometers and non-resonant sensors while the onset of knock has been verified with in-cylinder pressure traces. The dependence of block resonant frequency 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.

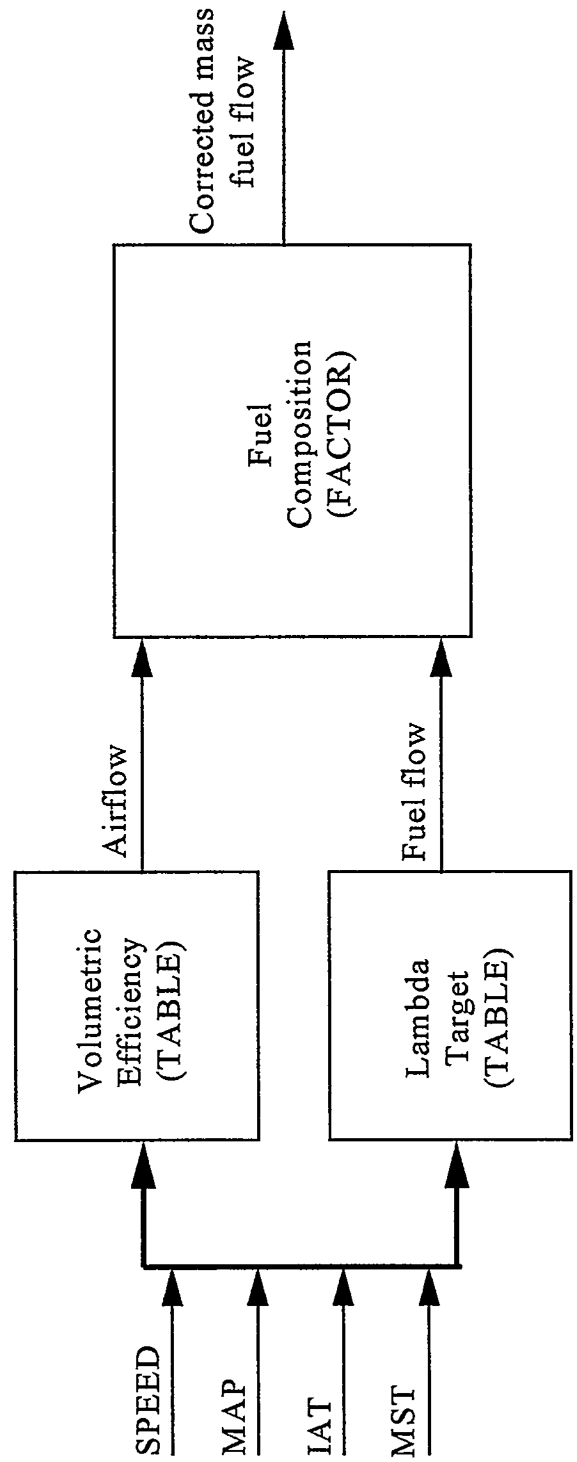
A study is currently underway to improve engine operation by the addition of exhaust gas recirculation (EGR). EGR will be investigated as a means of oxides of nitrogen (NOx) reduction by introducing different amounts of exhaust gases into the turbocharger intake. Exhaust gas has a lower oxygen concentration 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.

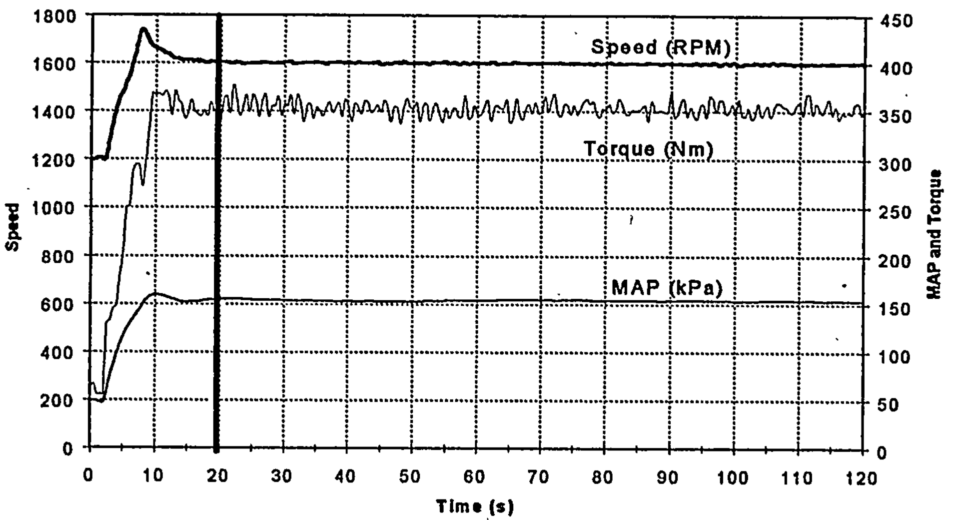


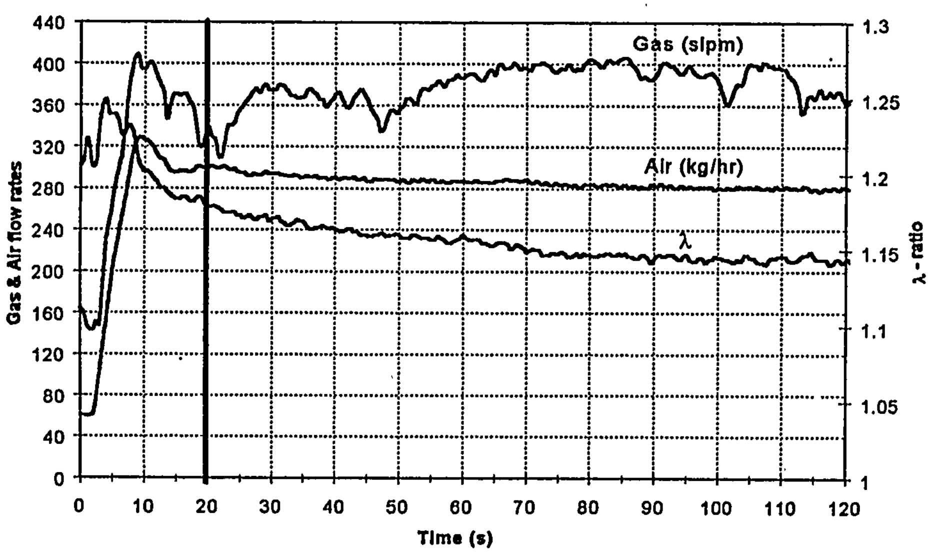

80486
Dyno Controller &
Data Acquisition
System
UEGO or
BOSCH
EGO
sensor
3.7 L GTA
Engine
Ignition
System
80486
Closed-Loop
Controller
MAP
RPM
MST
IAT
Metering
valve /
Controller


Lambda Sensor Comparison
ECM A/F Recorder
NGK UEGO
BOSCH LSM11
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

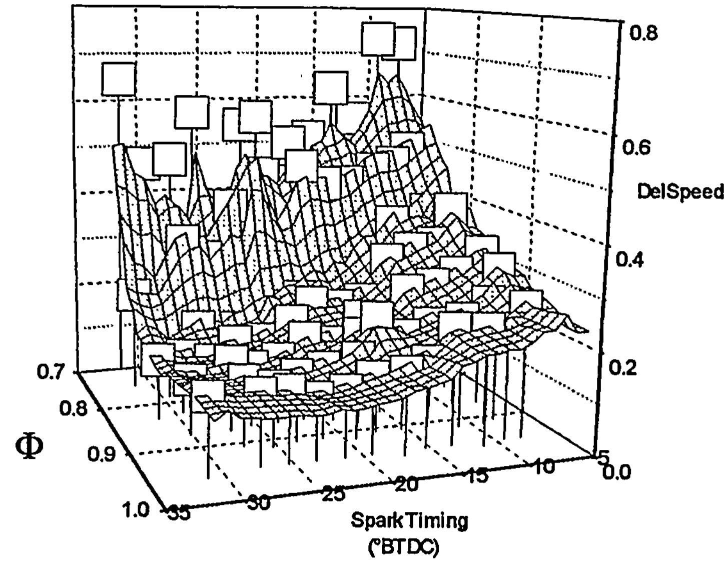

Corrected mass
fuel flow
Fuel
Composition
(FACTOR)
Airflow
Fuel flow
Volumetric
Efficiency
(TABLE)
Lambda
Target
(TABLE)
SPEED
MAP
IAT
MST

Volumetric Efficiency Deviation

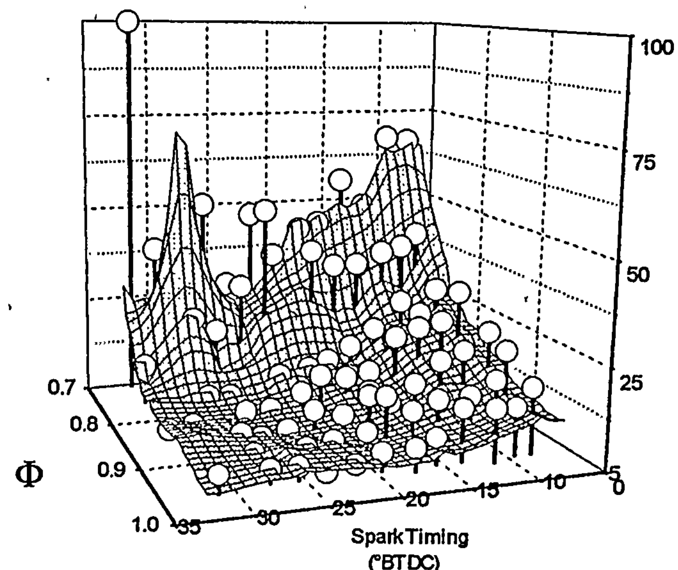




Lean Limit of Combustion



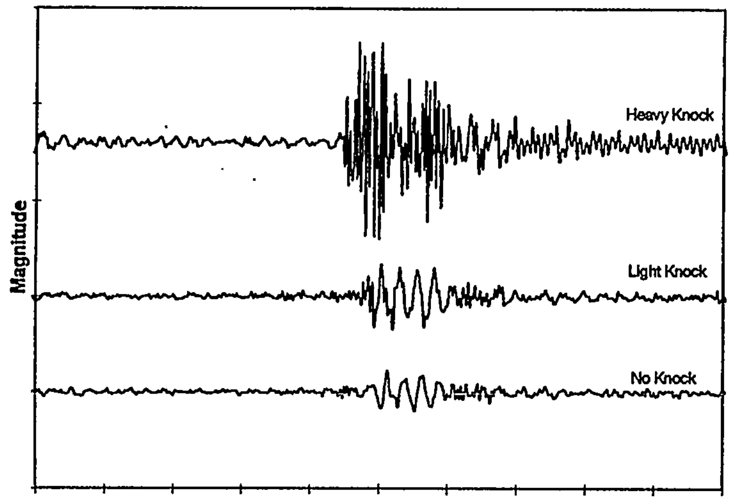
Crankshaft speed variation

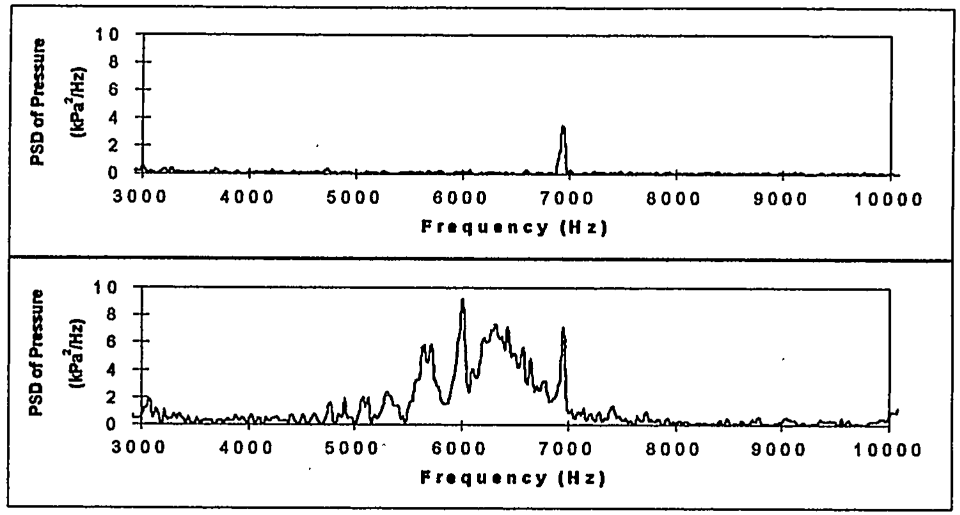


CoV(IMEPg) and speed variation normalized

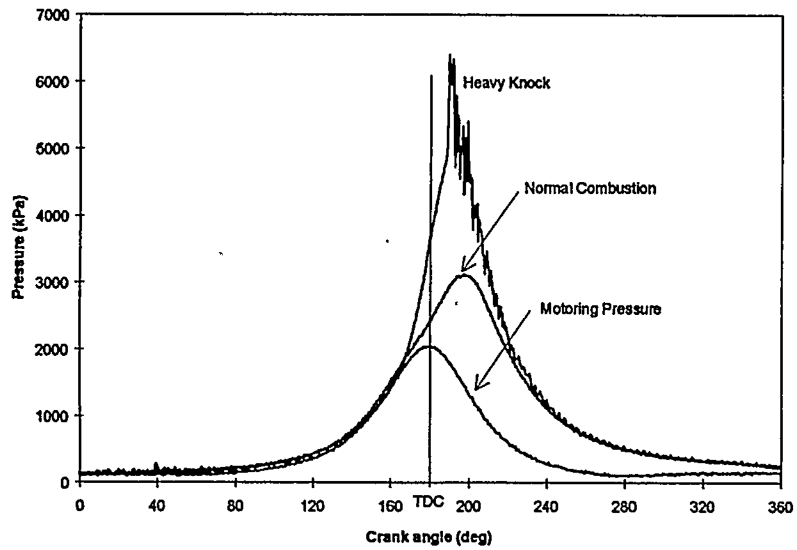
Knock Detection

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	CO	CO_2	NO_x	WORK	BSFC	VALID
				(g/BhpHr)	(g/BhpHr)	(g/BhpHr)	(g/BhpHr)	(Bhp Hr)	(lb/HpHr)	
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

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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

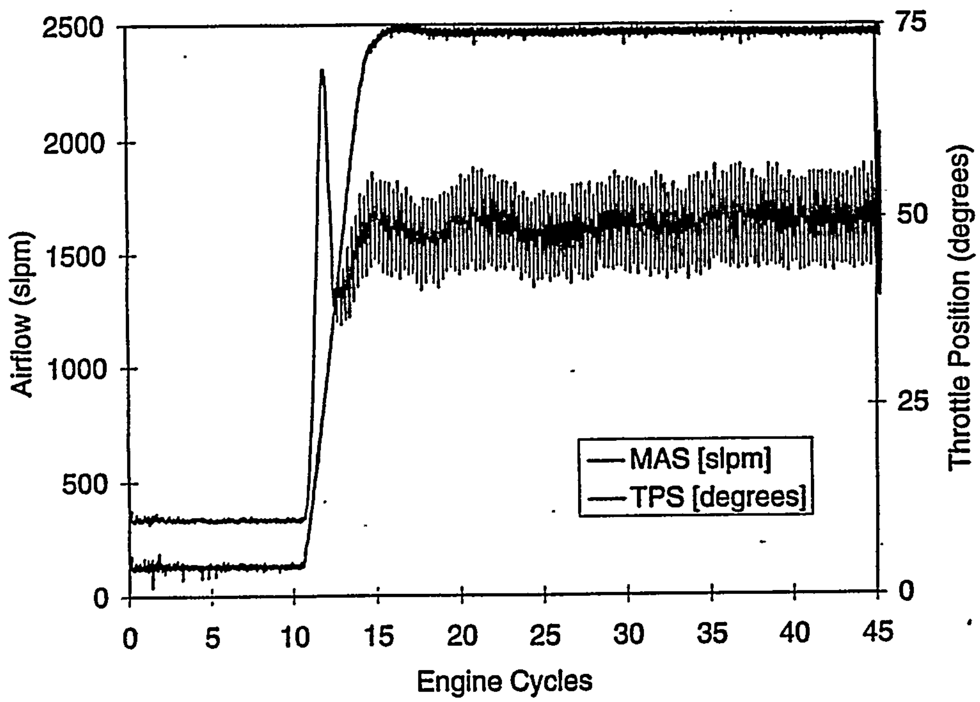
The transient response of each system was characterized by measuring the in-cylinder fuel-air equivalence ratio, ϕ, each engine cycle using a fast flame ionization detector sampling about 7 mm from the spark plug gap.

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 ϕ 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.

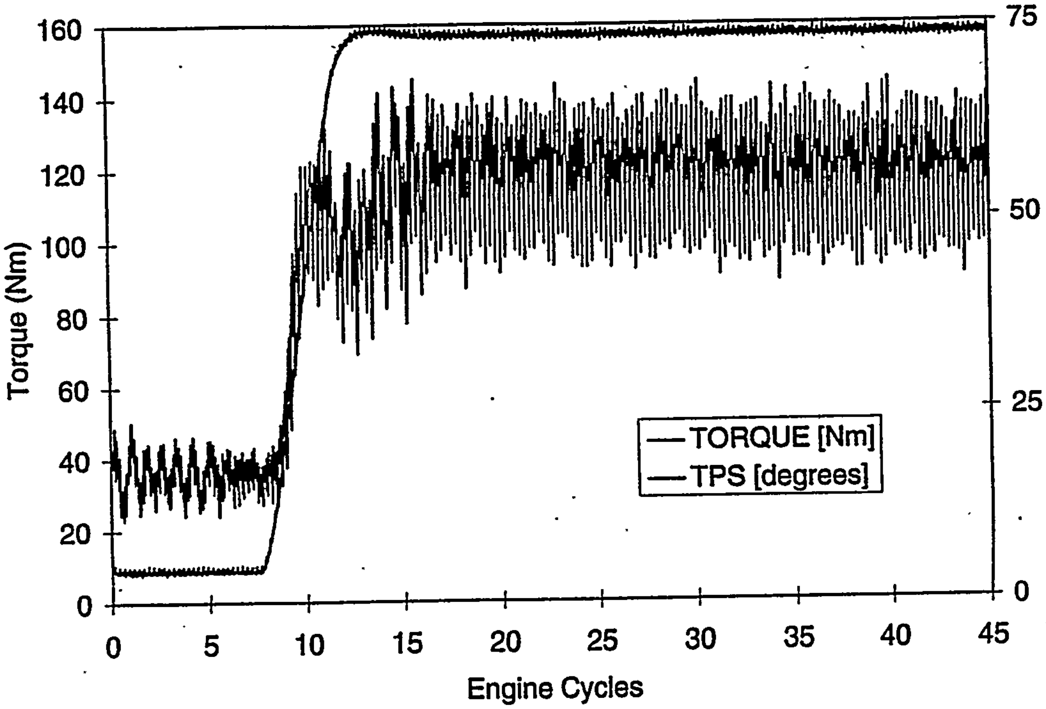


REPRESENTATIVE TEST RESULTS

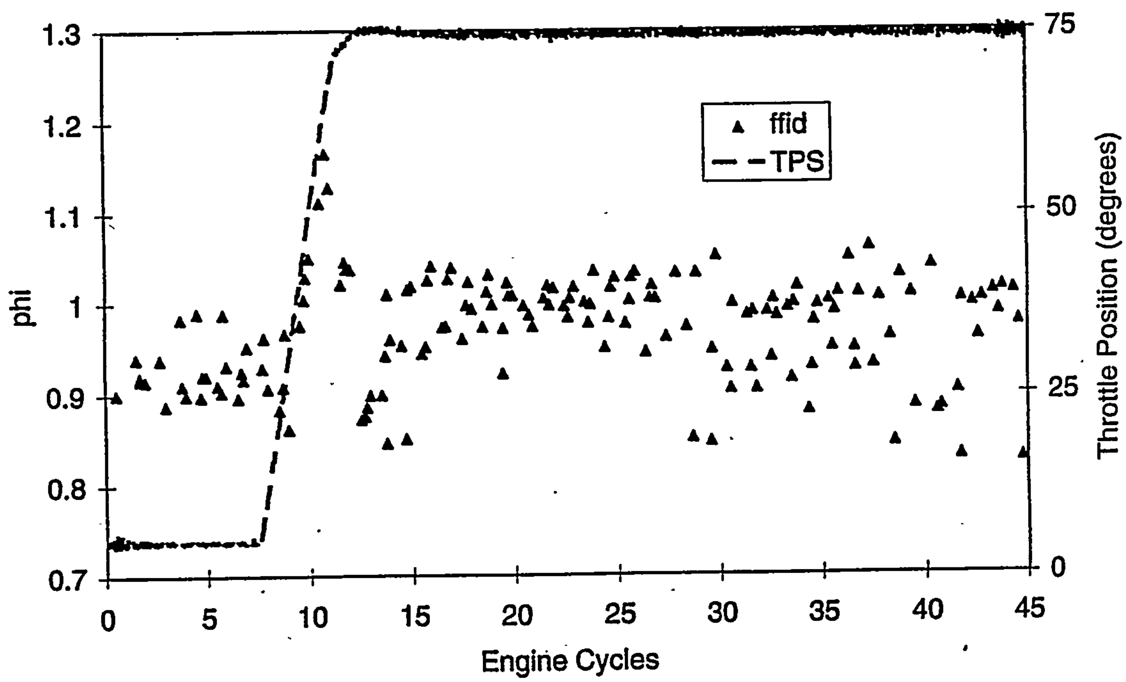
Due to space limitations, only data for the variable restriction mixer will be presented here.

Throttle tip-in

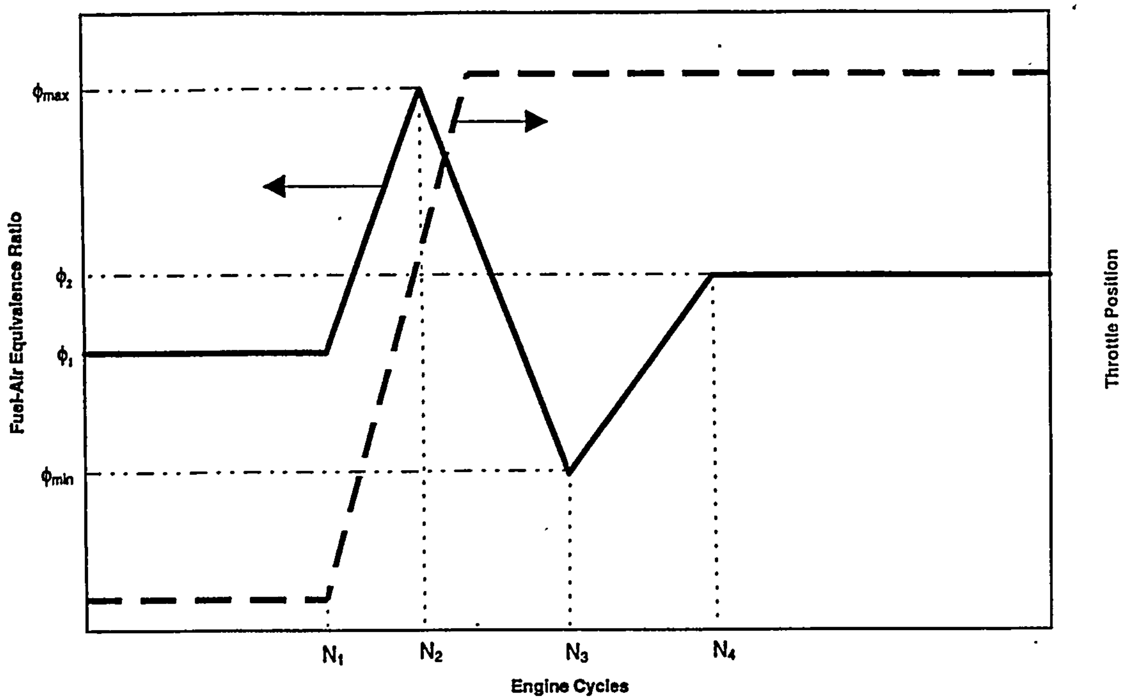
The torque response of this system is quite good, with a quick torque rise from about 35 N-m to 110 N-m, a brief stumble, and then a slower rise to the final torque of 120 N-m.



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 ϕ 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 ϕ 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 ϕ_1 and ϕ_2, seem to be much more significant in some cylinders than others.

Cylinder	ϕ_1	STD ϕ_1	NTK ϕ_1	ϕ_{max}	STD ϕ_{max}	ϕ_{min}	STD ϕ_{min}	ϕ_2	STD ϕ_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 φ*
			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 φ response (only marginally better than the variable restriction mixer).
- The variable restriction mixer gave the best throttle tip-out φ 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

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FURTHER INFORMATION

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

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A CASE FOR BIOFUELS IN AVIATION

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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

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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. Base-line 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.

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Federal Aviation Administration (FAA)
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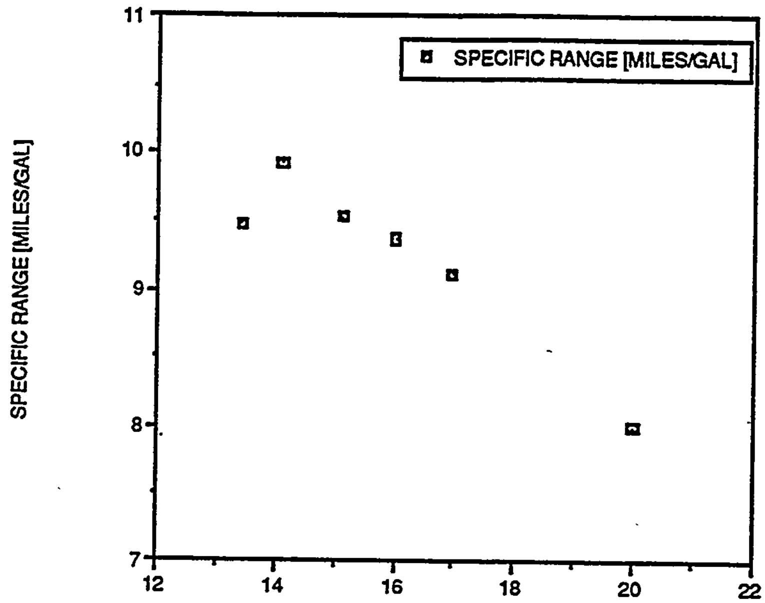
ETBE FLIGHT TEST DATA PITTS S-2B 1 MAY 1995
24"MAP, 2400 RPM, 2000 FT



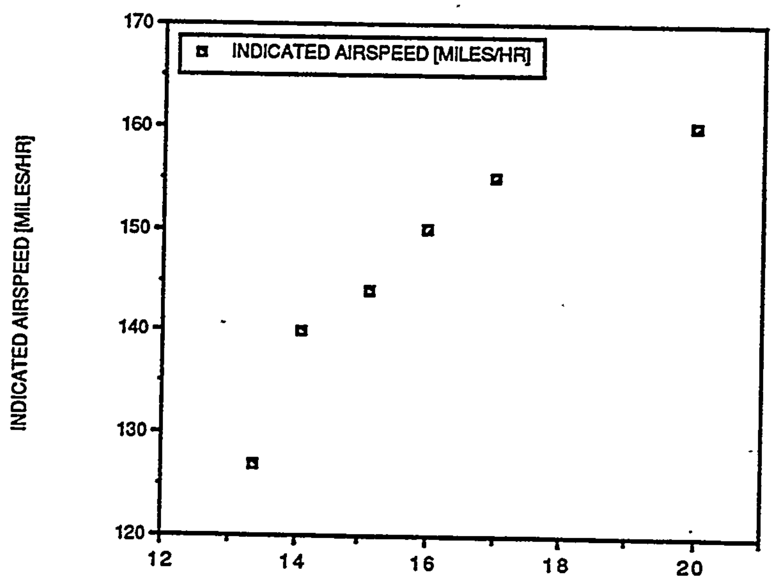
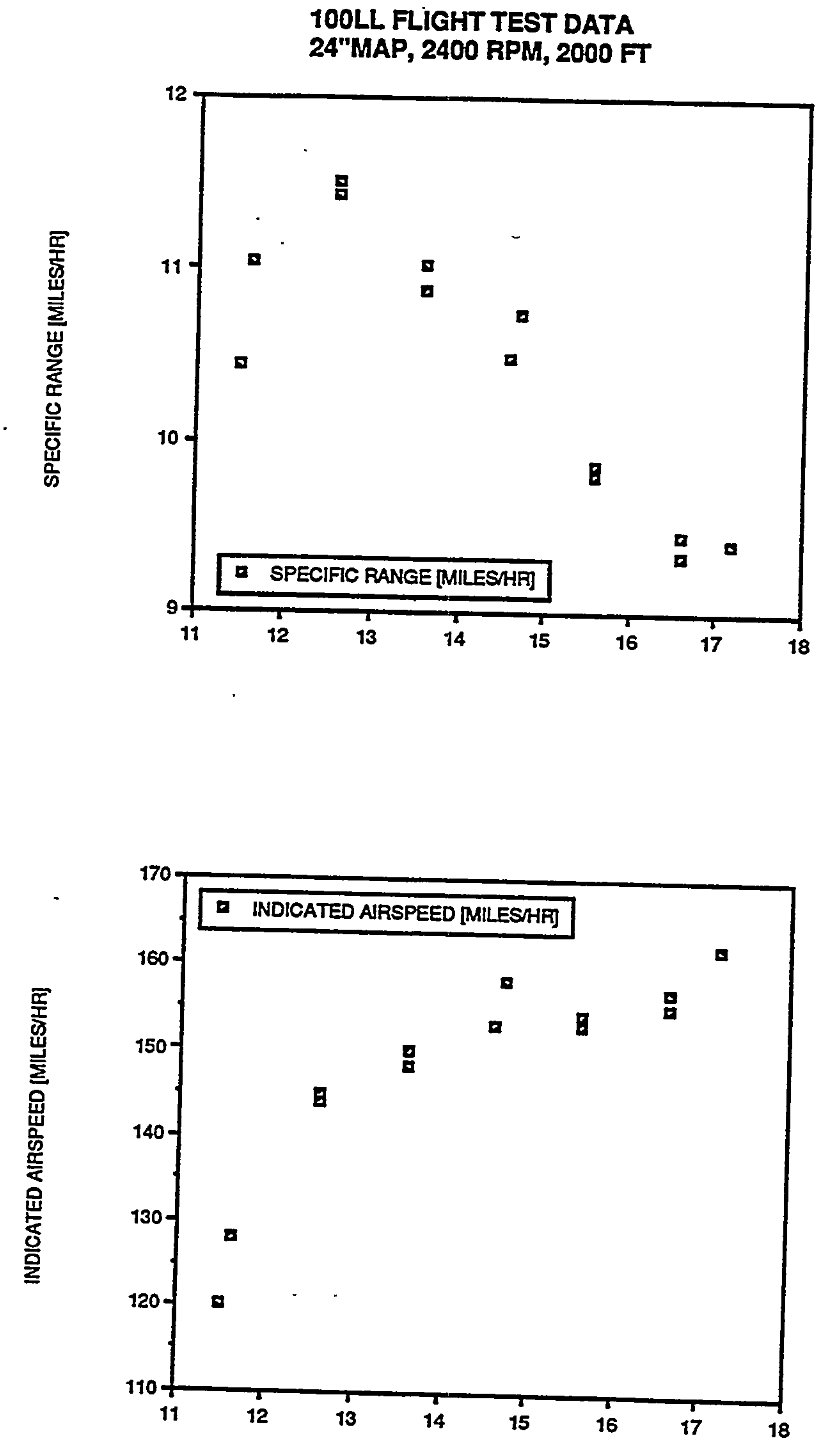
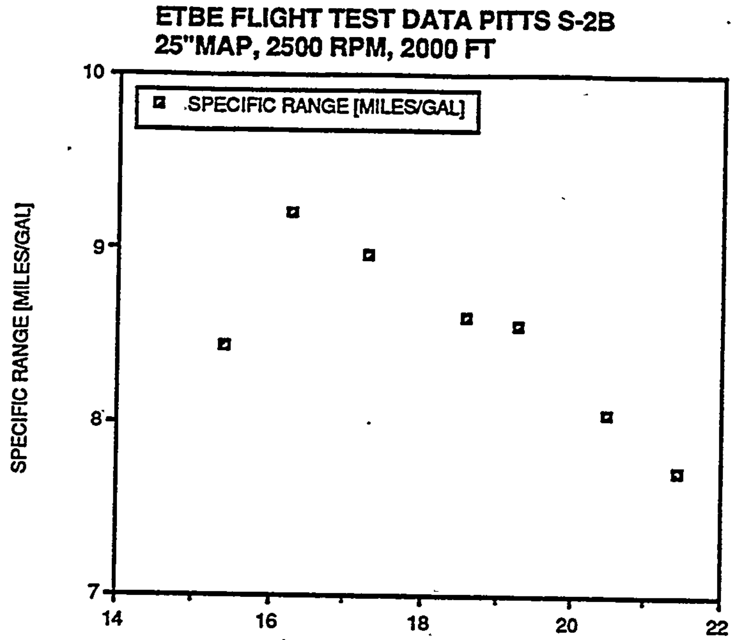


Figure 1



100LL FLIGHT TEST DATA
24"MAP, 2400 RPM, 2000 FT
SPECIFIC RANGE [MILES/HR]
SPECIFIC RANGE [MILES/HR]
12
11
10
9
11
12
13
14
15
16
17
18
INDICATED AIRSPEED [MILES/HR]
INDICATED AIRSPEED [MILES/HR]
170
160
150
140
130
120
110
11
12
13
14
15
16
17
18

Figure 2


ETBE FLIGHT TEST DATA PITTS S-2B
25"MAP, 2500 RPM, 2000 FT
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SPECIFIC RANGE [MILES/GAL]
10
9
8
7
14
16
18
20
22

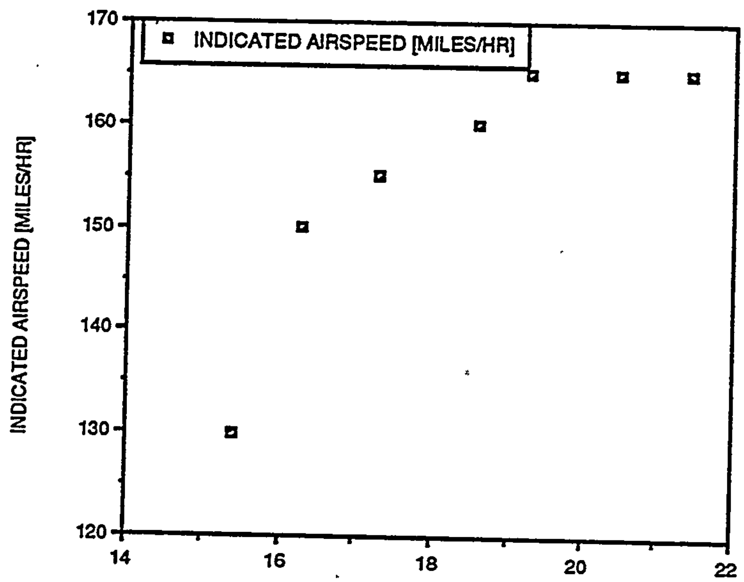
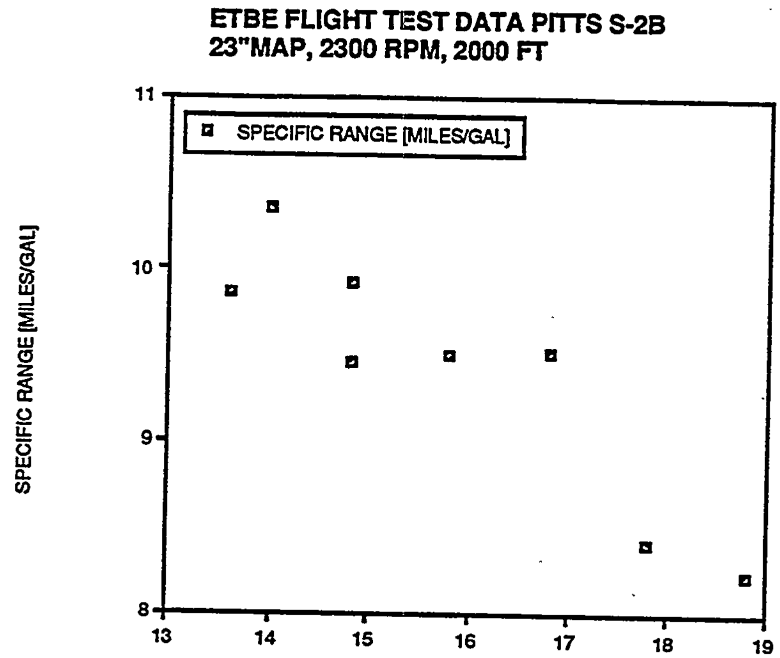

INDICATED AIRSPEED [MILES/HR]
INDICATED AIRSPEED [MILES/HR]
170
160
150
140
130
120
14
16
18
20
22

Figure 3


ETBE FLIGHT TEST DATA PITTS S-2B
23"MAP, 2300 RPM, 2000 FT
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SPECIFIC RANGE [MILES/GAL]
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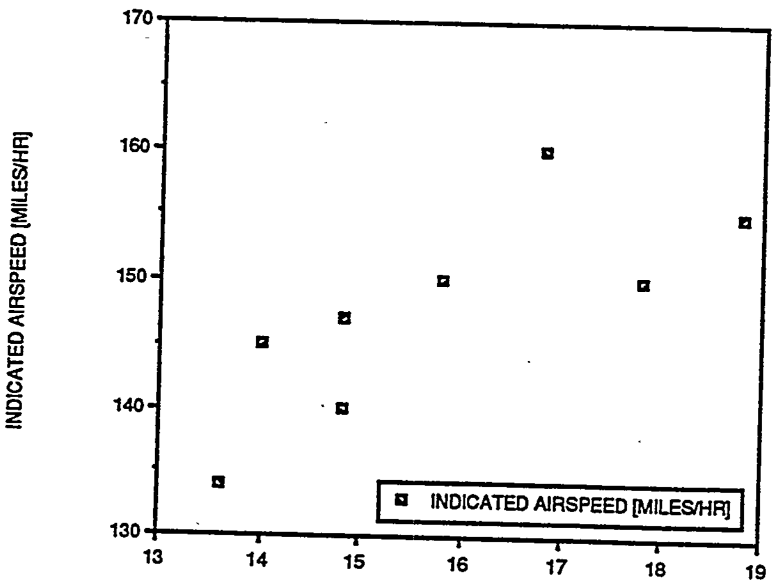
9
8
13
14
15
16
17
18
19


INDICATED AIRSPEED [MILES/HR]
INDICATED AIRSPEED [MILES/HR]
170
160
150
140
130
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18
19

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

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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

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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.

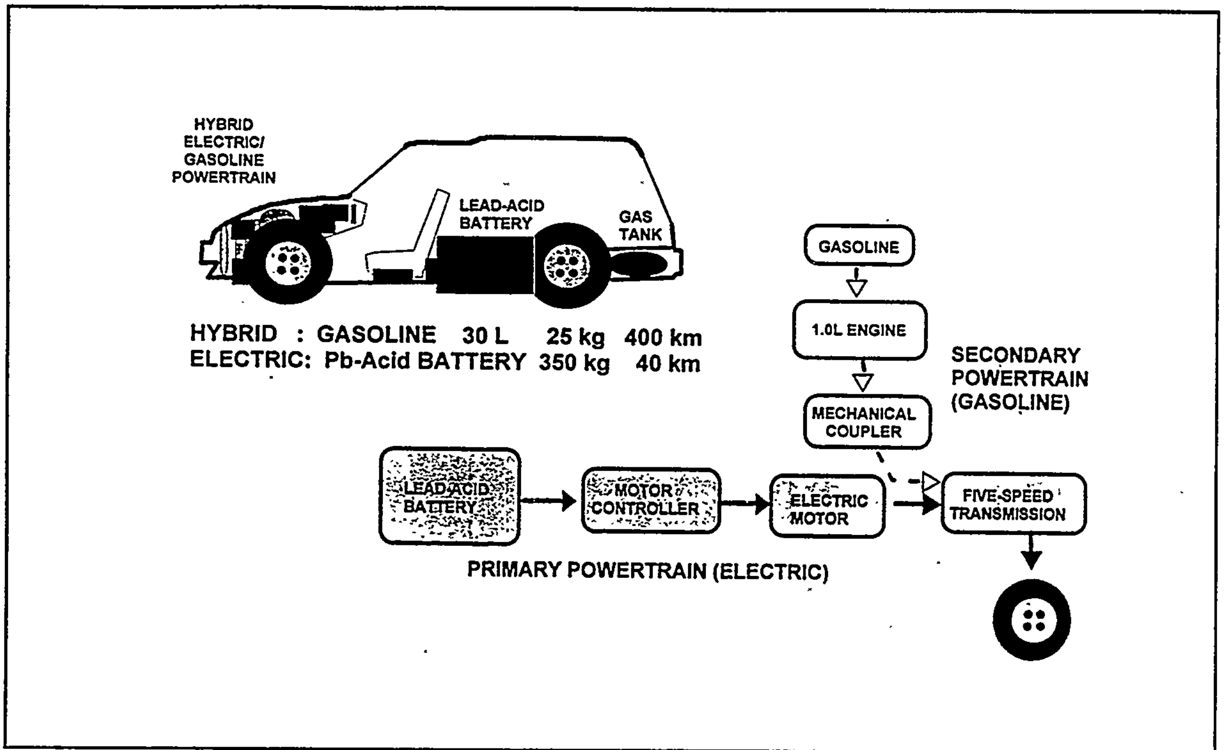

Figure 1. General Schematic of Hybrid Electric Vehicle and Electric / Gasoline Powertrain

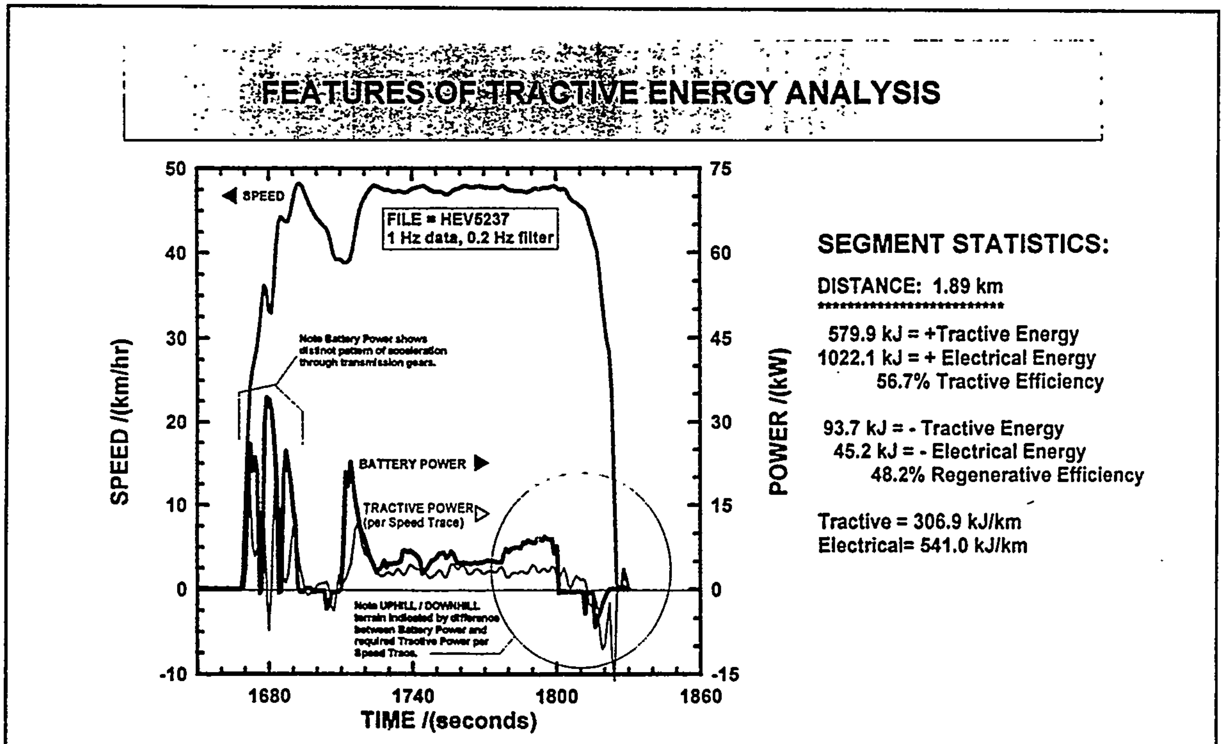

Figure 2. Recorded Speed, Battery Power, and Tractive Power Required Traces for the HEV

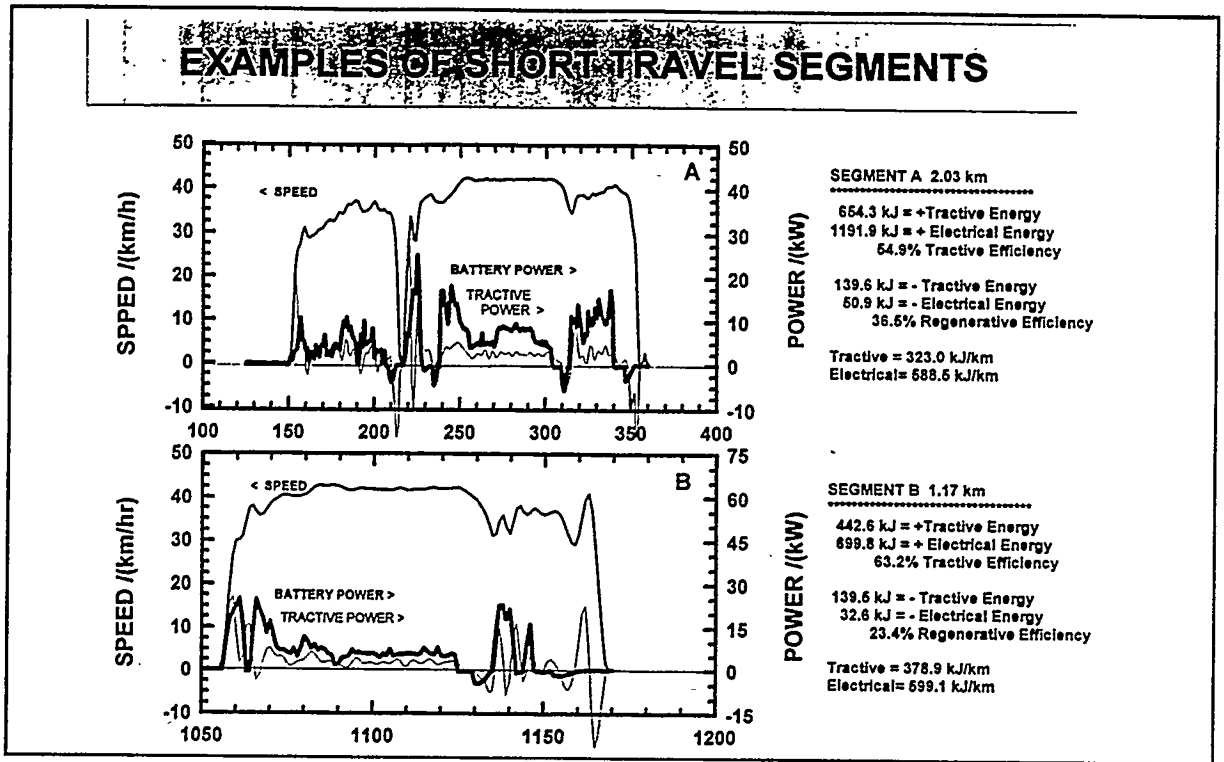

Figure 3. Further Examples of Tractive Power Analysis Traces for HEV Operation

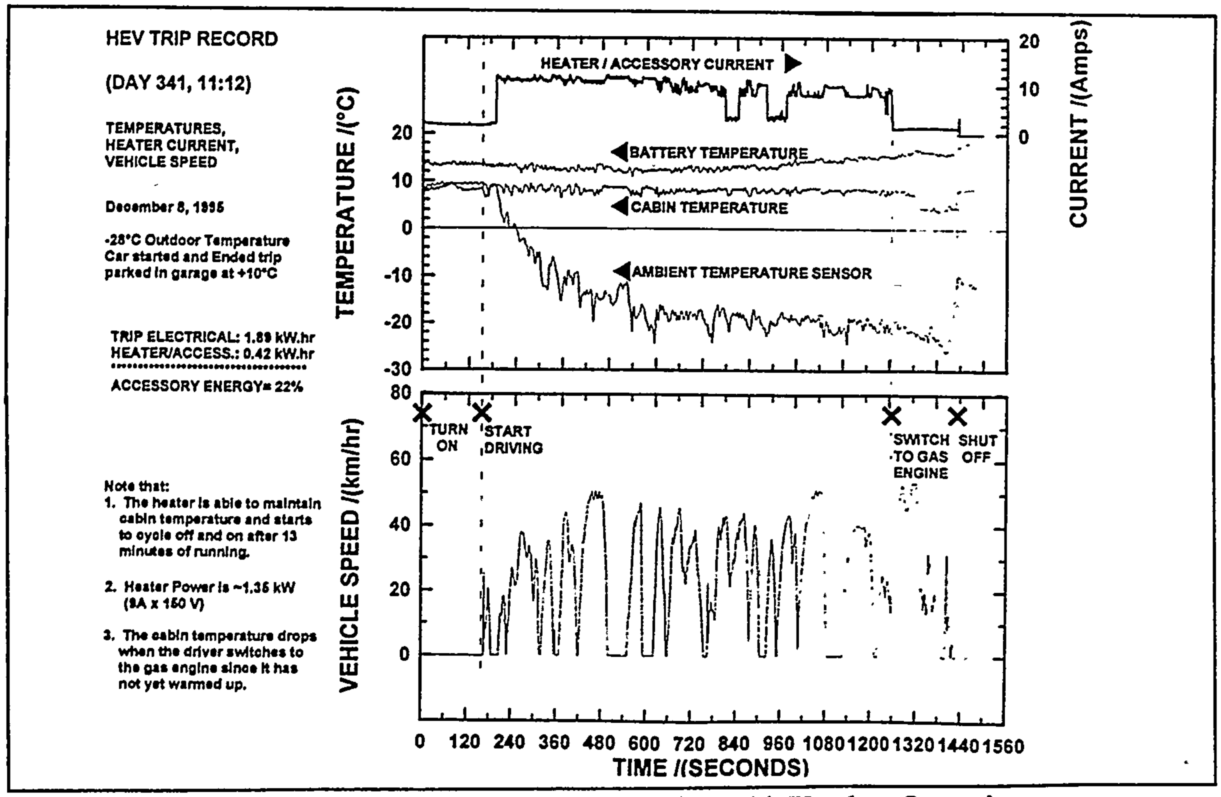

Figure 4. Heater Performance and Energy Use in Cold Weather Operation

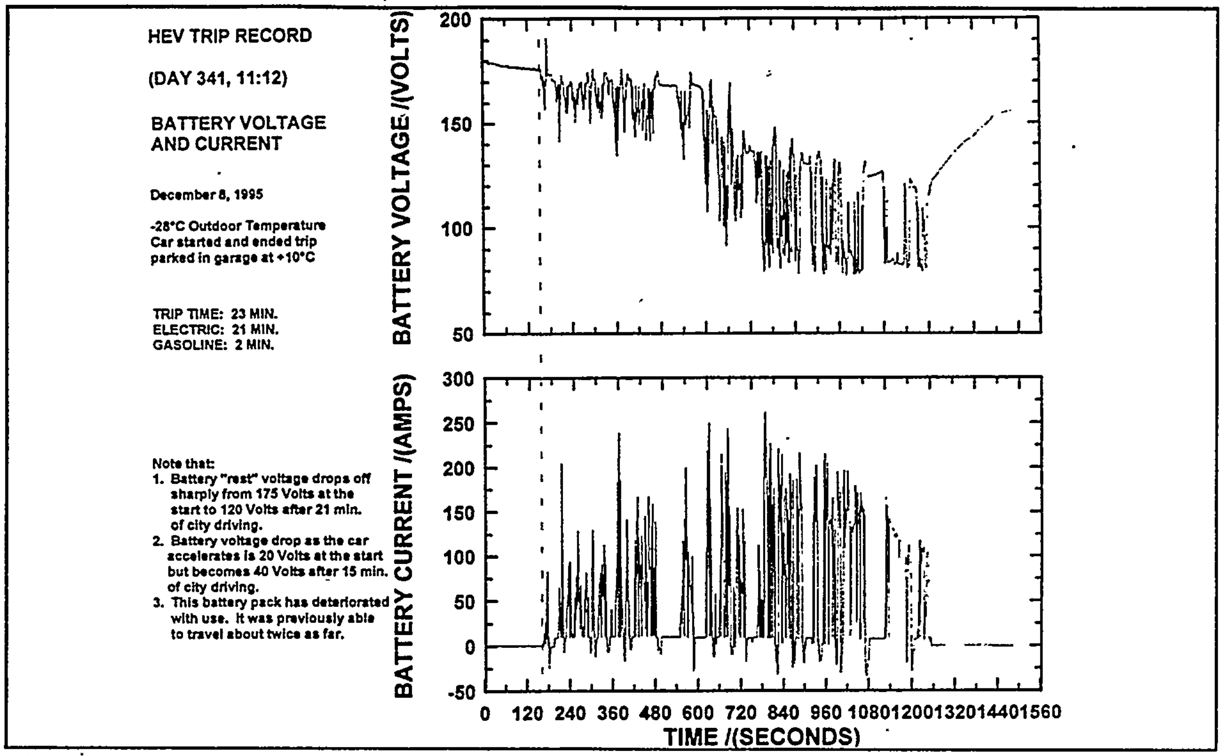

Figure 5. Illustration of Battery Voltage and Current Behaviour During a Typical Discharge

(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

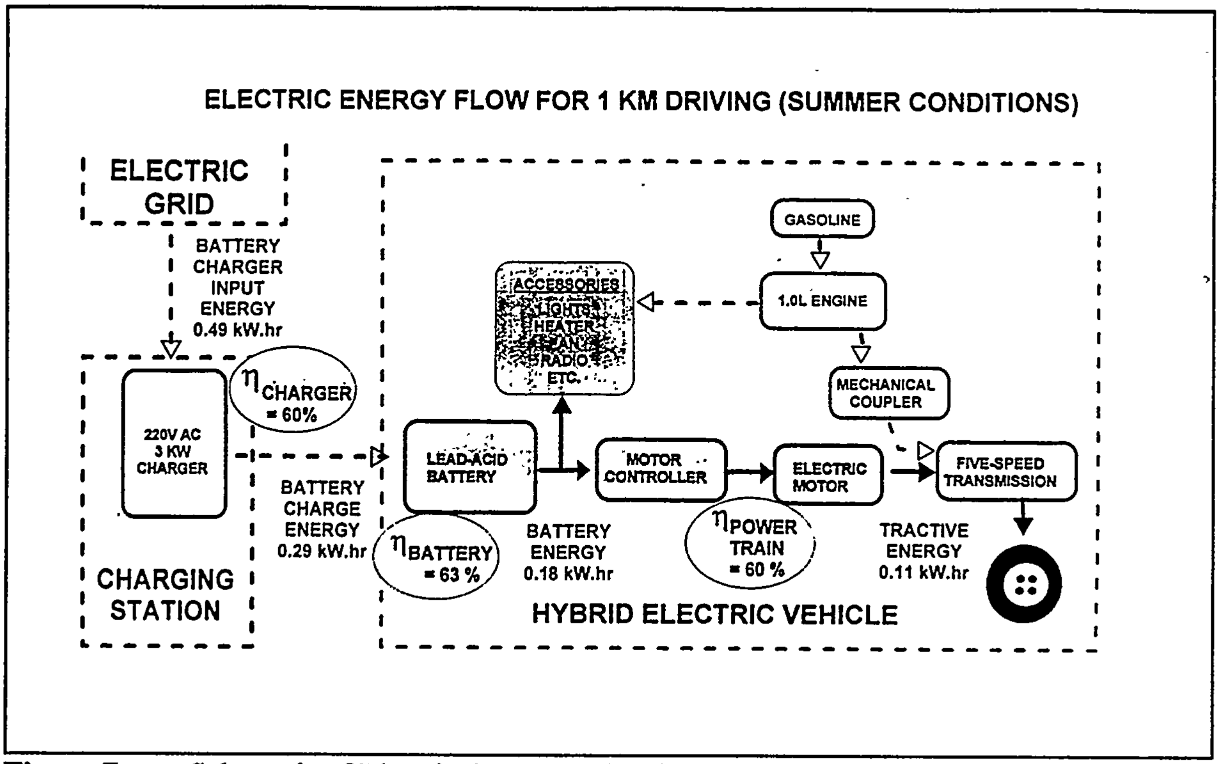

Figure 7. Schematic of Electrical Energy Flow in the HEV Including Measured Efficiencies

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)

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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.

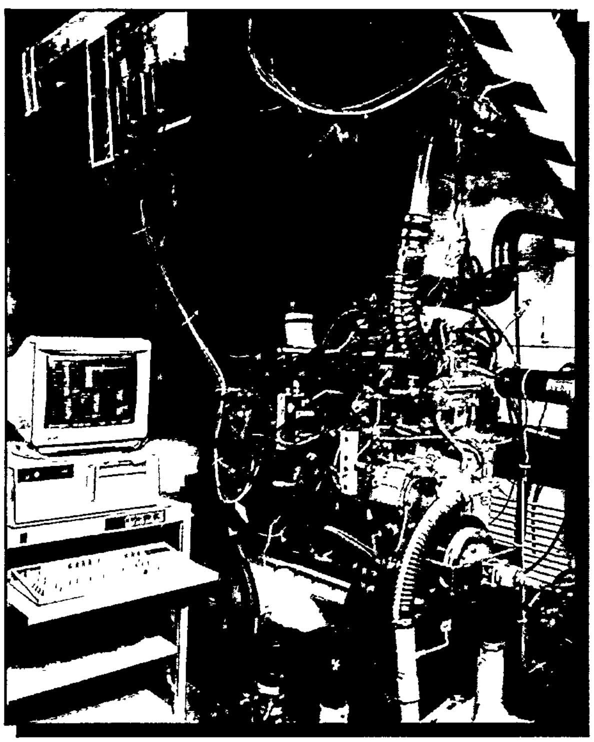

Figure 1

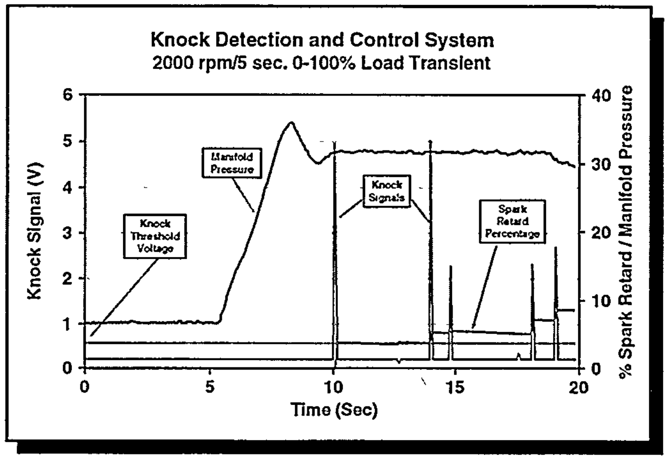

Figure 2

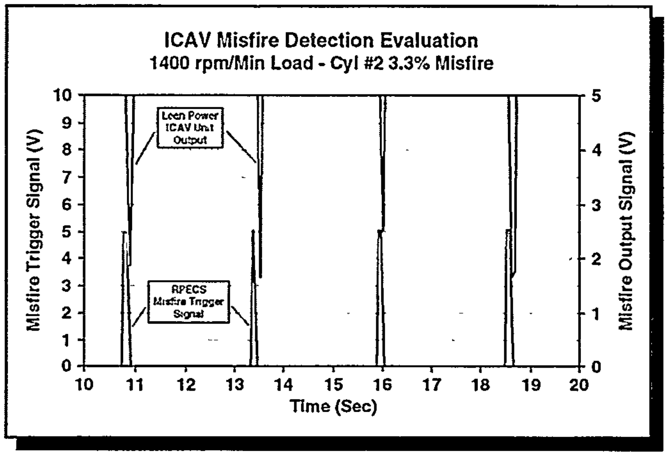

Figure 3

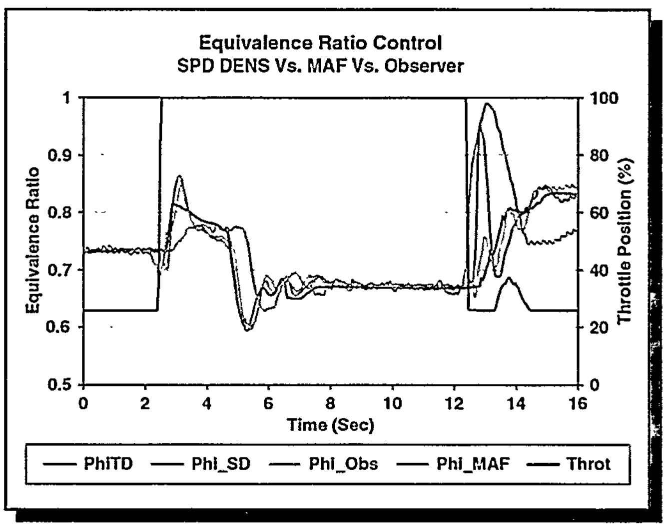

Figure 4

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

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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.

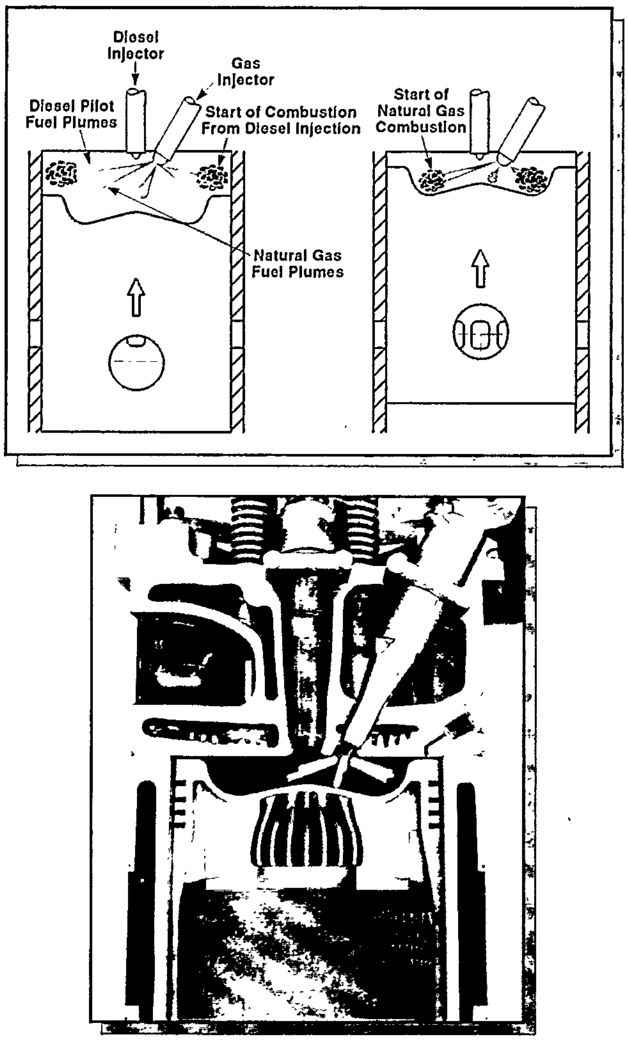

Figure 1

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

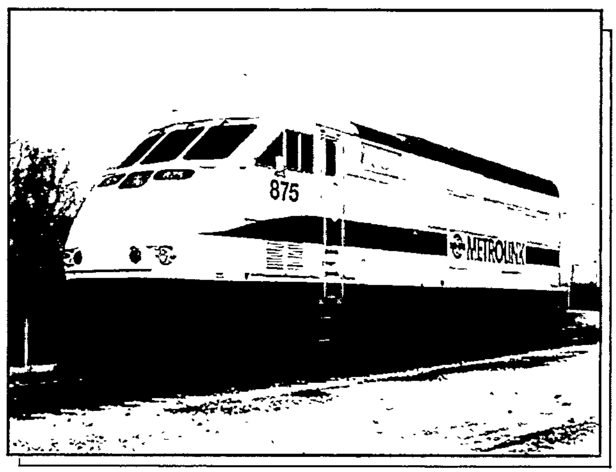

Figure 3

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

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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 ($\sigma < 0.6$) 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.

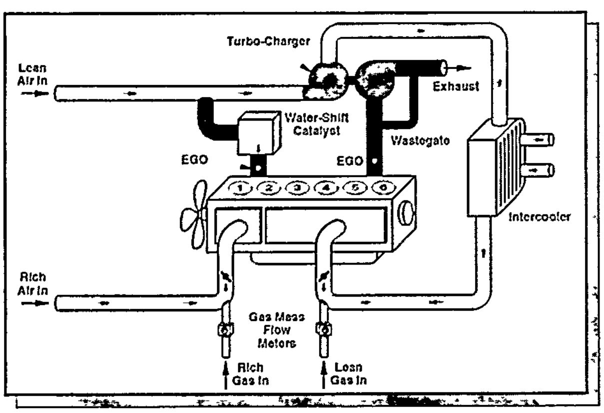

Figure 1

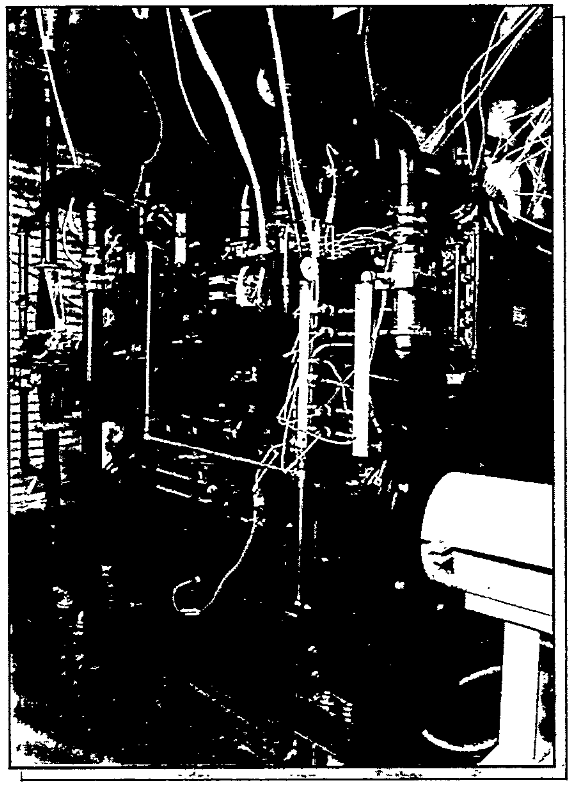

Figure 2

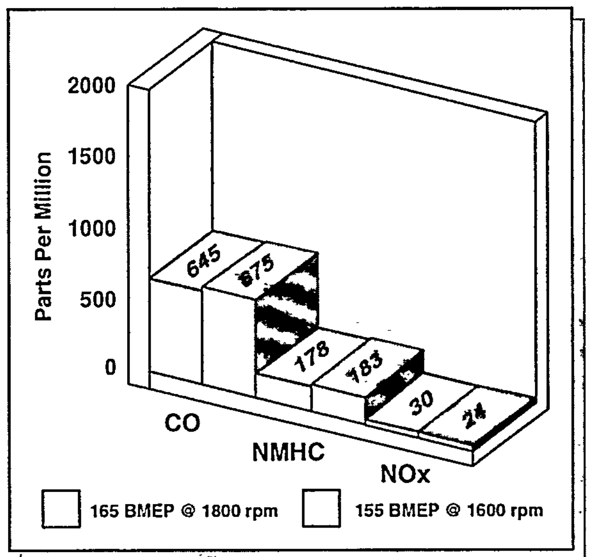

Figure 3

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.

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