EXHAUST EMISSIONS FROM HEAVY-DUTY VEHICLES

Prepared by

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PREFACE

On September 27, 1990, the State of California Air Resources Board passed a series of stringent new vehicle emissions regulations that set a critical new precedent for automobile manufacturers and the market place. This is only the beginning of what will be seen worldwide as governments become more and more concerned with the air we breathe.

This regulatory action is designed to place rigorous standards on noxious automotive emissions, particularly those that contribute to ground-level ozone as well as particulates from heavy vehicles that cause respiratory problems. For the first time, a regulatory body will force the world's automakers and engine manufacturers to take direct action in advancing non-emitting technologies.

Heavy trucks and buses, an integral component of the world's transportation system, are an important consideration in the context of the new regulations. Today, almost all heavy trucks and buses are powered by diesel engines, which are advantageous with respect to fuel economy, reliability and durability. However, conventional diesel engines emit significant quantities of carbon dioxide, nitrogen oxides, volatile organic compounds and particulate matter to the atmosphere.

Although current diesel engines cannot meet the tough new auto emissions standards, technology is now available which can. For example, the application of particulate traps substantially reduces particulate emissions, and allows the use of catalytic treatment to cut carbon dioxide and hydrocarbon emissions. As well, technological leaps and bounds have been made in the use of alternative fuels such as methanol and natural gas in heavy-duty engines.

These alternative fuel technologies are nearing maturity, but information gaps still remain. Specifically, the role of government and regulatory bodies in the task of controlling or limiting heavy-duty engine emissions is largely undefined. As well, the relevance and application of current emissions legislation to methanol engines and other alternative transportation fuels remains unclear.

In 1987, Canada, the United States, Japan, Sweden and Italy agreed to collaborate on the International Energy Agency (IEA) Annex III, to review demonstrations using alcohols in heavy engine applications. As a result of this annex, the issue of different standards and standard test procedures for measuring emissions amongst member countries arose. Thus, this report on Exhaust Emissions from Heavy-Duty Vehicles was produced.

Many countries have limits on pollutants, but the methods used to determine those limits vary widely. The IEA, as part of the IEA Agreement on Alternative Motor Fuels, recognized the need for an international forum for information exchange on heavy-duty exhaust emissions. This information exchange will assist governments in forming the regulatory environment that addresses the needs of a changing automotive market place. As well, it provides a means to examine the possible consolidation of new legislation into an international framework.

This agreement has formed a base of information on alcohol-fuelled engines and emissions from both alcohol and diesel fuels that will be valuable to government and industry alike as we work to find ways to meet the challenges that lie ahead.

Dr. Pier-Paolo Garibaldi
Chairman, Executive Committee
IEA Alternative Motor Fuels Implementing Agreement

INTRODUCTION

May 1, 1991

To All Participants

Canada is pleased to print and distribute this report, "Exhaust Emissions from Heavy-Duty Vehicles".

This report has evolved from the work being carried out by the operating agent for Annex 3, Alcohols in Large Engines, initially designed to accumulate, synthesize, analyze and disseminate information on the many truck and bus demonstrations being conducted in the member countries of the Implementing Agreement on Alternative Motor fuels. It was further authorized to include data from non-member countries where such data was in the public domain.

It soon became apparent that, with respect to emissions and emissions testing, each country had a different set of procedures and/or standards. Thus, any comparison made between fleets in the emissions and even fuel consumption areas would be marred by different measurement technologies. As the environment and clean air take their position as a major driving force, we will need to be able to make comparisons under the same set of guidelines.

This report serves to identify the different procedures and standards that prevail throughout member and certain selected countries. Of greater significance is the fact that this report might be a starting block upon which to build a set of uniform standards for emissions testing.

Originally, it was intended that the contents of this report would be distributed only to the participant countries for their consideration, as an element of the overall annex. However, the Implementing Agreement Executive Committee decided that the work was important enough to stand on its own and be published as a report under the auspices of the International Energy Agency (IEA).

Five countries agreed to Annex 3 and contributed to the contents of this report: Canada, Italy, Japan, Sweden and the United States.

In addition to the copies of the report distributed to the participants, and those sent to IEA Headquarters, the Operating Country member has a number of supplementary copies which can be requested from the undersigned.

Please ensure that the concept of universality in emissions testing and standards is widely known. This report may assist in illustrating the extent of the problem and in bringing it to the attention of those who can effect change. I or other members of the IEA Implementing Agreement on Alternative Motor Fuels will be pleased to receive your comments and suggestions on this issue. My address is:

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ABSTRACT

Increasing global interest in controlling atmospheric pollution has led legislative authorities in many countries to impose stringent regulations upon motor vehicle emissions. Standards have been in force for many years in most of the developed world, but there is still a great deal of diversity in the approaches taken. This paper presents a comparison of international emissions regulations including test cycles employed, sampling and measurement techniques, and legislated limits on pollutants. Because of the many variations in these basic criteria and their application to different vehicle types and classes, any cross-correlation of standards between countries is likely to be impossible in practice. Furthermore, there is likely to be considerable resistance to any attempt to promulgate universal standards, because many countries have tailored their regulations to cope with their own unique environmental concerns and economic situations.

Methanol fuelling is now widely recognized as a potential means of reducing pollution from motor vehicles particularly because of its soot-free combustion and low overall emissions levels. This paper presents an overview of the current work in progress on design, manufacture and testing of heavy-duty methanol engines for trucks and buses as well as a survey of the application of catalytic converters for exhaust emissions control on these engines. A review of progress in emissions control measures for diesel fuelled engines is included for comparison purposes.

Prior to methanol being phased-in as a diesel fuel substitute, regulatory bodies will have to address its compatibility with existing emissions control standards. In the meantime, researchers and manufacturers must continue developing their engines. The variations in emissions test procedures create a confusing background against which to measure progress in emissions reduction technology. This problem is aggravated by the trend to design modern engines for manufacture and marketing on an international basis. Any moves towards greater commonality between emissions test cycles would therefore be welcomed by both independent researchers and engine manufacturers. The paper concludes with a proposal for a Standardized Emissions Research Cycle, which might be used to allow ready comparison between numerous emissions control strategies at present under development.

GLOSSARY OF ABBREVIATIONS

BSAld	Brake Specific Aldehyde Level
BSCO	Brake Specific Carbon Monoxide Level
BSFC	Brake Specific Fuel Consumption
BSForm	Brake Specific Formaldehyde Level
BSHC	Brake Specific Hydrocarbon Level
BSNOx	Brake Specific Oxides of Nitrogen Level
BSP	Brake Specific Particulate Level
BTDC	Before Top Dead Centre
CARB	California Air Resources Board
CFC	Chlorofluorocarbon
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CUTA	Canadian Urban Transit Association
CVS	Constant Volume Sampling Technique
DDC	Detroit Diesel Corporation
DDEC	Detroit Diesel Electronic Control System
DI	Direct Injection
EPA	Environmental Protection Agency
ECE	Economic Commission for Europe
EF	Emissions Factor
EGR	Exhaust Gas Recirculation
EVAP	Evaporative Emissions
FEV	FEV Ltd.
FTP	Federal Test Procedure (U.S.)
GM	General Motors Corporation
GVWR	Gross Vehicle Weight Rating
HC	Hydrocarbon
HD	Heavy-Duty
HDD	Heavy-Duty Diesel
HDG	Heavy-Duty Gasoline
HFID	Heated Flame Ionisation Detector
ICI	Imperial Chemical Industries
JARI	Japan Automobile Research Institute
LDT	Light-Duty Truck
LDV	Light-Duty Vehicle

MAN	Maschinenfabrik Augsberg-Nurnberg
MILE	Methanol in Large Engines (Canada)
MOT	Ministry of Transport (Japan)
MV1	Identification Number of JARI Test Bus
NGK	NGK Insulators Ltd.
NGV	Natural Gas for Vehicles or Natural Gas Powered Vehicle
NOx	Oxides of Nitrogen
OMHCE	Organic Mass Hydrocarbon Equivalent
PEEC	Programmable Electronic Engine Control (Caterpillar)
RTS	Bus model built by Transportation Manufacturing Corporation (TMC)
SCAQMD	South Coast Air Quality Management District (California)
SFC	Specific Fuel Consumption
SHED	Sealed Housing Evaporative Emissions Determination (U.S.)
SwRI	Southwest Research Institute (Texas)
VFC	Vehicle Fuel Consumption

I PREAMBLE

There is an ever-increasing public concern about the quality of the environment in which we live today. This concern has resulted in legislation controlling the use or release of substances deemed toxic or harmful to mankind and the environment. Exhaust emissions from vehicles are one source of pollution that has been and continues to be studied and regulated. Concern over pollution from motor vehicles will become a more critical issue in the future as vehicle populations continue to grow, particularly in developing nations.

The demand for automobiles in North America, Western Europe and Japan has been fairly stable in recent years and is only expected to increase by about 20% over the next decade. In the remainder of the world, demand is projected to grow by 75% (1). This growth can be attributed to the development and modernization taking place in the rest of the world along with the associated increase in net wealth. As a result, the global emissions load or output can be expected to increase.

The anticipated increase in the global engine population will heighten current dependence on hydrocarbon fuels (gasoline and diesel) and emphasize the need to more closely control or limit the amount of pollutants released on a per engine basis. Future reductions in harmful emissions will come from two directions: legislated limits on emissions in terms of specific output per engine, and technological improvements such as electronic engine controls, new materials, exhaust catalysts, and alternative fuels. Legislation placing limits on exhaust emissions and minimum average fleet fuel economy has been the driving force behind many technological improvements made in developed countries so far.

Most emissions testing by engine manufacturers and developers is carried out from the perspective of conforming to exhaust emissions regulations in the target market for the engine. Regulated emissions include hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NOx). Certain jurisdictions limit smoke and/or particulate matter from diesel engines. In addition to the regulated emissions, there has been much public controversy over the past year concerning the global concentration of carbon dioxide (CO_2). Increasingly, engine manufacturers and developers, along with legislators, will have to be concerned with all exhaust emissions.

This report focuses on heavy-duty (HD) diesel engine exhaust emissions and emissions regulations. Section II of the paper examines the role that legislation can play in controlling or limiting vehicle exhaust emissions. Although there is a global trend towards more stringent emissions standards in this particular class of engine, the approach of the United States and Canada is different from that of Europe or Japan. Section III of the paper examines methanol as a potential vehicle fuel for engine builders seeking to meet future heavy-duty diesel emissions regulations, particularly the U.S. Environmental Protection Agency's (EPA) 1991 and 1994 standards. Subsection IIIA reviews the relevance and application of current emissions legislation to methanol engines. Subsection IIIB summarizes heavy-duty methanol engine development activities of major international manufacturers, and associated fleet trial programs. As interest in heavy-duty alcohol-fuelled engines increases, attention is also being focussed on using catalysts to control exhaust emissions. Subsection IIIC summarizes recent work in this field. Subsection IIID completes the overview of methanol work by presenting some representative engine exhaust emissions test results. Testing has usually been performed in conformance with particular local emissions regulations. Some potential methods of correlating data obtained under different test protocols are discussed.

Section IV is an overview of the current situation regarding diesel-fuelled engines, and the technologies available to meet the 1991 and 1994 U.S. EPA standards. Very significant progress is evident in this area. The use of low sulphur fuel and particulate traps, together with advanced injection systems, has enabled manufacturers to achieve the necessary emissions reductions. It is now expected that production diesel-fuelled engines will be available for 1994.

Section V examines the actual impact on emissions of substituting different types of fuels. Heavy-duty engine emissions are normally reported on a specific power output basis (e.g. grams/bhp hour). This type of criterion is somewhat removed from the real world of vehicle operations. In order to provide some measure of the true practical effect of the substitution of various alternative fuels in diesel engines, comparison is made between on-road emissions for diesel, diesel with particulate trap, methanol and natural gas urban buses.

II CURRENT EXHAUST EMISSIONS LEGISLATION

There is a great deal of diversity in the approach to regulating vehicle exhaust emissions. This is because regulations for the control of vehicle emissions are a balance between air quality concerns and overall economic concerns for any given region. As a result, there has emerged a proliferation of emissions standards each serving a different geopolitical region. There has been some alignment of these regulations, but to date this has been largely based on the economic associations of various regions. Examples of this are in Canada and the U.S., whereby Canada is contemplating enacting future legislation so that it maintains parity with the U.S., and the European Economic Community, which has established a minimum standard within itself. While member nations are free to impose more stringent regulations, a minimum baseline has been established. In both of these examples, the net effect has been to permit manufacturers to export their product without having to go through the expense of retesting or qualifying their product to another standard. The potential results are reduced development and production costs.

Exhaust emissions regulations can be broken down into three specific areas (2):

- driving or test cycle;
- method of sample collection and measurement;
- emissions limits, their applicability and exemptions or waivers.

There are many different combinations that may arise depending on the regulations enacted in any specific area. Countries may end up enacting a similar test cycle, yet the regulated emissions levels may be adjusted upwards or downwards relative to other regions. Exhibit II-1 presents a matrix of test cycles used around the world. Even within the table, it is difficult to absolutely categorize a specific vehicle or engine class on a uniform basis. Vehicle or engine classes have uniquely evolved depending on the country or region.

From the matrix, it can be seen that the test cycles employed represent one of two philosophies; a series of repetitions of a composite of typical driving modes for light-duty vehicles (Europe and Japan) or a simulation of an actual road trip (U.S. and Canada). In the case of heavy-duty engines, with the exception of the

U.S. and Canada, all the other countries listed use a multimode steady state emissions test. The use of composite driving cycles or multimode steady state was the initial approach until 1972 when the U.S. adopted CVS-72 (constant volume sample test, 1972, also known as the Federal Test Procedure, FTP). This test was subsequently revised in 1975 to include a hot start phase and a repetition of the first 505 seconds of the cold driving cycle. In 1985, the 13 mode test was superseded by a transient cycle for heavy-duty engines in the U.S. Since that time, Canada has followed suit. The reasoning behind the change was to create a test cycle that would be more representative of the many nuances that occur in typical vehicle operation. Unlike a composite mode test, a transient test cycle is made up of continuously changing engine loadings and speeds to simulate a typical type of service that may be experienced by vehicles in a given class. Thus the transient cycle can be thought of as being made up of a series of points describing engine speed and load overtime. A more complete discussion of a comparison between a steady state test and a transient test cycle follows in a subsequent section.

While test cycles for light-duty vehicles and trucks are based on chassis dynamometer tests, there is variation in the method of testing heavy-duty engines. The transient test cycle in the U.S. stipulates the use of an engine dynamometer. The test cycle was developed based on combination of urban and highway driving. The diesel transient cycle can be divided into four discrete segments; New York non-freeway, Los Angeles non-freeway, Los Angeles freeway, and New York freeway. Exhibit II-2 presents a graphic representation of the cycle. Engine speed and load are based on normalized values. A separate dynamometer schedule is used for heavy-duty gasoline engines because of differences in torque-speed characteristics compared to diesel. Engine manufacturers must qualify their heavy-duty engines on an engine dynamometer capable of following the EPA's speed-load schedule which includes periods of engine motoring represented by periods of negative power. These occurrences are meant to simulate deceleration when vehicle inertia is driving the engine. Although a test procedure to perform a transient emissions test on a heavy-duty vehicle exists using a chassis dynamometer, it is not recognized by the EPA for regulatory testing at the present time.

The U.S. transient test cycle supersedes the 13 mode test for regulatory compliance in the U.S. and Canada. The 13 mode test is a steady state test that reports engine emissions over a weighted average of 13 points. Steady state testing is still in use in Europe and Japan. Exhibit II-3 summarizes these test cycles. All three of these cycles are engine-based, although the Japanese 6 mode test procedure for heavy-duty diesels may be carried out on a chassis dynamometer for the purposes of emissions compliance.

The use of engine tests is based on the premise of the wide variability of applications for heavy-duty diesels. Unlike automobiles, trucks and buses are custom built with the purchaser specifying engine, transmission, axle ratio, tires, etc. The requirement to test heavy-duty vehicles would entail unnecessary bottlenecks and additional costs, particularly if the test facility is required to perform a transient chassis test.

Exhibit II-1. International Emissions Test Cycles

COUNTRY	LDV	LDT	HDG	HDD	EVAP
USA	CVS-75	CVS-75	EPA HDG Transient	EPA HDD Transient	SHED
Canada	CVS-75	CVS-75	as in USA	as in USA	SHED
Japan	10 MODE	10 MODE (3, 5)	6 MODE (5)	6 MODE (5)	TRAP
Europe	ECE 15.04			ECE-49 (5)	
Austria	CVS-75			ECE-49 (5)	
Sweden	CVS-72 (2)				
Switzerland	CVS-75	CVS-75	ECE-49 (4, 5)	ECE-49 (4, 5)	
Australia	CVS-75	CVS-75			SHED
Israel, Saudi Arabia, Singapore, Taiwan	ECE-15.03 (6)				SHED (7)

Notes: LDV = Light-duty vehicle or passenger car
LDT = Light-duty truck
HDG = Heavy-duty gasoline
HDD = Heavy-duty diesel
EVAP = Evaporative emissions test

(1) Data as of 1990
(2) Gasoline only
(3) Diesels use 6 mode test
(4) Applies to vehicles with 3500 < GVWR < 28000 kg
(5) Engine dynamometer procedure
(6) Gasoline vehicles with GVWR < 3500 kg
(7) Gasoline vehicles in Saudi Arabia
(8) Europe comprises common market nations of Belgium, Denmark, France, Federal Republic of Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain and United Kingdom

Exhibit II-2. Heavy-Duty Diesel Transient Test Cycle

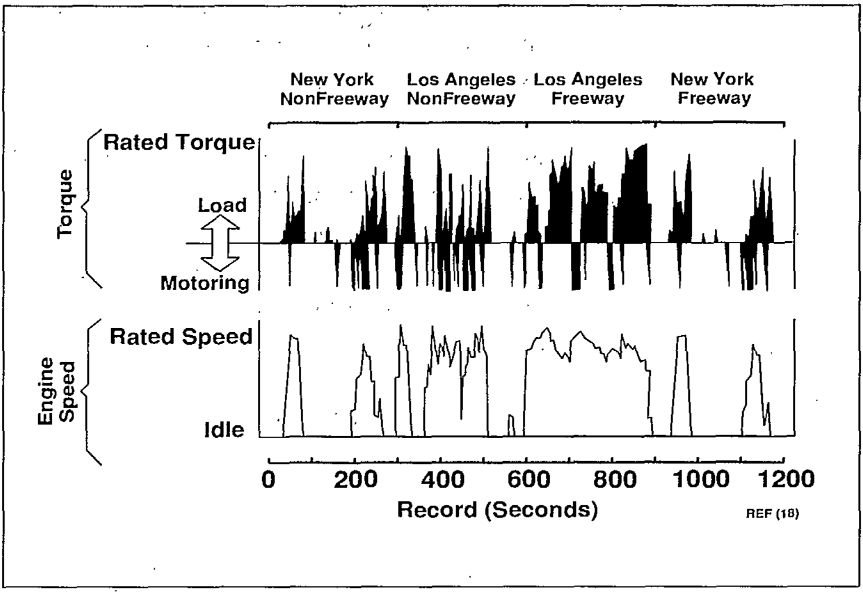


Exhibit II-3. Heavy-Duty Diesel Steady-State Test Cycles

	13-MODE: U.S. (1)			ECE 49			6-MODE: JAPAN		
MODE	SPEED	LOAD (%)	WEIGHT	SPEED	LOAD (%)	WEIGHT	SPEED	LOAD (%)	WEIGHT
1	Low idle	0	0.2/3	Low idle	0	0.25/3	Idle	0	0.355
2	Int.	2	0.08	Int.	10	0.08	40% Rated	100	0.071
3	Int.	25	0.08	Int.	25	0.08	50% Rated	25	0.059
4	Int.	50	0.08	Int.	50	0.08	60% Rated	100	0.107
5	Int.	75	0.08	Int.	75	0.25	80% Rated	25	0.286
6	Int.	100	0.08	Int.	100	0.25	80% Rated	75	0.286
7	Low Idle	0	0.2/3	Low Idle	0	0.25/3			
8	Rated	100	0.08	Rated	100	0.10			
9	Rated	75	0.08	Rated	75	0.02			
10	Rated	50	0.08	Rated	50	0.02			
11	Rated	25	0.08	Rated	25	0.02			
12	Rated	2	0.08	Rated	10	0.02			
13	Low Idle	0	0.2/3	Low Idle	0	0.25/3			

When comparing cycles, it can be argued that the transient test cycle is made up of many steady state points, but there are discrete differences. Theoretically, one can develop a steady state map of emissions from an engine and use it to predict the results that would be obtained over the transient cycle. However, when attempting to correlate emissions data from steady state to a transient cycle, one must consider the effect of factors from two groups; engine build and test cycle. For example, a component such as a turbocharger, which has a transient response, will affect the emissions profile of an engine when tested over a transient cycle that features frequent power and speed changes.

In terms of emissions collection and measurement, it is anticipated that legislation will evolve with greater uniformity in the method of sample collection and measurement technology (2).

The remaining area where a major difference in emissions regulations can exist concerns the legislated emissions limits. Exhibit II-4 presents some emissions limits presently in effect for heavy-duty diesel engines. A line by line comparison of overall effectiveness is not possible unless one knows the test cycle, sample collection and measurement technique. A method of comparing the net effect of emissions legislation from one country or region to the other is by generating a model of the net effect of the legislation on reducing emissions from a baseline case.

Although there are many possible approaches to controlling and subsequently reducing exhaust emission levels, the previous discussion is by no means an endorsement of any particular method. While the approach in the U.S. is generally regarded as the most stringent, increased awareness in exhaust emissions worldwide has been leading to the gradual adoption of some form of emissions regulations by many countries and the tightening of existing emissions levels in others. Increased European awareness of emissions has led to the adoption of tightened emissions levels with the intent being that the effect of exhaust emissions on the European environment will be equivalent to that produced by U.S. standards (9).

Exhibit II-4. Heavy-Duty Diesel Exhaust Emissions Limits - International

Country	Units	HC	CO	NOx	Particulates
U.S. (5)	g/kW.h	1.7	20.8	8.0	0.8
Canada (6)	g/kW.h	1.7	20.8	8.0	0.8
Japan (2)	ppm	670	980	520	
Europe (3)	g/kW.h	2.4	11.2	14.4	
Austria (3)	g/kW.h	2.8	11.2	14.4	
Switzerland	g/kW.h	2.1	8.4	14.4	

Ref: (4, 7, 8)

Notes:
(1) As of 1990
(2) For DI engines with GVWR > 2500 kg, effective April 1991 for imported models
(3) For GVWR > 3500 kg
(4) For GVWR > 28000 kg
(5) U.S. data converted from published figures in g/BHP. h
(6) Canadian data converted from published figures in g/MJ units

III THE USE OF METHANOL FUEL

A. APPLICABLE EMISSIONS LEGISLATION

Currently enacted exhaust emissions legislation has been directed at engines using gasoline and diesel fuel. Some countries have extended their regulations to encompass natural gas- and/or propane-powered vehicles. Of current concern to heavy-duty engine manufacturers who wish to sell in the U.S. are the 1991 urban bus and 1994 NOx and particulate standards which are presented in Exhibit III-1. The reduced particulate levels over the transient test cycle may pose the most difficult hurdle to pass. The new rules are targeted at urban transit buses starting in 1991, since they constitute a publicly identifiable source of pollution. As a result, heavy-duty diesel engine manufacturers such as Detroit Diesel Corporation, Caterpillar Inc., Cummins, MAN, Daimler Benz and others have begun to look at methanol as an alternative fuel capable of meeting future emissions regulations. While an alternative fuel has typically been thought of as being a petroleum substitute, methanol holds promise as a future fuel in the U.S. market because of its low particulate emissions.

Exhibit III-1. Heavy-Duty Diesel Engine Exhaust Emissions Limits - U.S.A.

Year	Units	HC	CO	NOx	Particulates
1991 - 93	g/kW.h	1.7	20.78	6.70	0.34 0.13 (1)
1994 +	g/kW.h	1.7	20.78	6.70	0.13 (2)

Notes:
(1) Applicable to urban bus engines
(2) All engines
(3) California permits engine manufacturers to certify to a non-methane hydrocarbon (NMHC) standard of 1.6 g/kW.h

All figures converted from units of g/BHP.h

In response to demands from engine manufacturers to establish "ground-rules" covering methanol engines, both the U.S. and the State of California have broadened their existing emissions regulations to include methanol-fuelled engines. The regulations treat methanol-fuelled engines in a manner similar to diesel- and gasoline-fuelled engines (5). This approach is consistent with the "level playing field" approach which does not discriminate against any particular fuel.

Although the methanol emissions regulations were implemented beginning with 1990 model year vehicles, the U.S. EPA has extended the compliance date to 1991.

The revised U.S. methanol emissions regulations retain the basic test cycle, method of sample collection and measurement of regulated emissions levels. The standards now include details as to the method of aldehyde and unburned fuel sample collection, measurement and quantification when certifying a methanol engine. In order to incorporate methanol engines into the existing gasoline and diesel engine categories of the present regulations, the methanol engine is subject to the following criteria check: If the methanol engine is run on the Otto cycle, then it is subject to the same regulations as a gasoline (spark ignition) engine. Conversely, if the engine is run on the diesel cycle (compression ignition), the engine would face the same regulations as a diesel. The standard calls for a weighted sum of hydrocarbons, aldehydes and unburned fuel to be measured against the existing hydrocarbon standards. In this manner, the ozone producing potential of methanol vehicles is limited to an amount no more than current vehicles. In other words, methanol engines are treated no differently than diesel or gasoline engines in terms of hydrocarbons. Total hydrocarbons would be reported as organic mass hydrocarbon equivalent (OMHCE) calculated according to the formulae given in Exhibit III-2.

Rules recently adopted by the Air Resources Board in California encompass U.S. Federal Rules, but also promulgate a separate aldehyde emissions standard, since increased use of methanol as a motor fuel is expected to lead to an increase in aldehyde emissions, and therefore ozone production. Exhibit III-3 summarizes proposed formaldehyde limits applicable to heavy-duty engines sold in California. The California Air Resources Board also believes that there are toxicological effects associated with aldehyde emissions (11).

Exhibit III-2. Organic Mass Hydrocarbon Equivalent Formulae

$$OMHCE = HC + \frac{13.8756}{32.042}(CH_3OH) + \frac{13.8756}{30.0262}(HCHO)$$

where HC = mass of hydrocarbons

CH_3OH = mass of methanol (unburned fuel)

HCHO = mass of formaldehyde

13.876 represents the molecular weight of current vehicle HCs

32.042 represents the molecular weight of methanol

30.0262 represents the molecular weight of formaldehyde

Total evaporative emission =

$$\left(M_{HC} + \frac{14.3594E6}{32.042} {}^{*}M_{CH3OH} \right) + \left(M_{HC} + \frac{14.2284E6}{32.042} {}^{*}M_{CH3OH} \right)$$

where: M_{HC} = hydrocarbon mass change in grams

M_{CH3OH} = methanol mass change in micrograms

14.3594 = represents the molecular weight of HC (diurnal test)

14.2284 = represents the molecular weight of HC (hot soak)

Exhibit III-3. Proposed Formaldehyde Standards for Heavy-Duty Methanol-Fuelled Engines - California

MODEL YEAR	FORMALDEHYDE LIMIT g/kW.h
1993 - 95	0.13
1996	0.07

Ref (56)

Notes: (1) Formaldehyde limits converted from units of g/HP.h

(2) Applies to both Otto and diesel engines

B. ACTIVITIES OF MAJOR ENGINE MANUFACTURERS

Cummins Engine Co.

Cummins Engine Co. has investigated the additive enhancement method of methanol engine operation, using its L10 medium-weight truck and bus engine. ORTECH International was engaged to perform power output, endurance and emissions levels tests on the experimental engines, including investigation of the effects of varying the levels of ignition improver additive. The additive used was Imperial Chemical Industries (ICI) "Avocet", at a concentration of 5%.

Two trucks using L10 methanol engines operated in service for the City of Vancouver fleet as part of Project MILE. The vehicles were used for industrial garbage collection, and were fitted with compactor bodies and a power take off driven hydraulic pump to operate the garbage loading and compacting equipment. The first truck started working in March 1988 using an engine rated at 270 bhp @ 2,100 rpm. The second was put into service in February 1989 with an engine producing 240 bhp, which was intended primarily as a potential rating for the transit bus market. The trial period was concluded in August 1990, at which time the two trucks had covered a combined distance of 51 000 km. The trucks demonstrated good equivalent energy consumption figures, virtually equalling diesel performance in this respect.

Cummins has also installed another 240 bhp L10 engine in a dump truck owned by the City of Los Angeles. The vehicle, which began operations in May 1989, runs on the same 5% "Avocet"/methanol mix as used in Canada.

Ongoing development of the methanol engine has focussed particularly on fuel injection timing and characteristics, including the use of variable injection timing. The engine tests using different "Avocet" concentrations revealed certain emissions "trade-off" situations. Lowering the "Avocet" concentration increased hydrocarbon (HC) levels because of less complete combustion. Raising the concentration in order to give better combustion tended to increase the oxides of nitrogen (NOx) output. The high current cost of "Avocet" makes it desirable to minimize the concentration employed. Cummins has investigated catalytic treatment of emissions in order to allow more economical concentrations of the additive. It has also done some work on glow plug ignition, but has not elected to undertake associated fleet trials at this time.

Caterpillar Incorporated

Caterpillar has converted two of its diesel-engine models, 3306 and 3406, to run on methanol. These are 6-cylinder heavy-duty automotive engines, of 10.5 and 14.6 litres displacement respectively. Both types have been subjected to extensive testing programs examining reliability, durability and fuel economy. Two 3406 engines ran in total over 500 000 km during 1988 and 1989, in highway haulage trucks in British Columbia (Project MILE). Caterpillar methanol engines use modulated glow plugs for ignition, and 99.96% pure methanol for fuel, the balance of 0.04% being a corrosion inhibitor to protect the fuel system. The two engines from the MILE trial were removed and returned to Caterpillar for dismantling and inspection at the end of 1989. EPA transient emissions testing of one engine showed little deterioration in emissions output since new, with slightly improved HC levels owing to the engine being well "run-in" after 240 000 km. The engines showed no more wear than would be expected in a diesel of equivalent mileage, apart from the valve seats and heads which showed a useful life of around 150 000 km. Cylinder bore wear was much less than would be usual for a diesel engine.

Caterpillar is participating in another fleet test in Glendale, California, where a 3306 methanol engine is installed in a garbage collection truck as part of a program sponsored by the California Energy Commission. This vehicle began service operations in the autumn of 1989.

MAN

MAN buses, powered by a methanol version of the company's D2566 11.4 litre, 6-cylinder engine, have run in service trials in New Zealand, Germany and the U.S. The methanol engines have used spark plugs for ignition (12, 13, 14), and also "Avocet" fuel additive. MAN opted for the spark ignition system as standard about four years ago.

A MAN bus was one of the two original methanol-powered buses to operate in the U.S. with Golden Gate Transit Authority in San Francisco, and this particular vehicle has been in service for over five years, not always on a consistent basis (15, 16). Because it was not equipped with handicapped persons' access facilities, operational restrictions hindered its use and slowed mileage accumulation . Ten MAN buses were put into service by Seattle Metro

Transit in the state of Washington in late 1987. They have accumulated over 60 000 km each (16, 17). Short spark plug life has been a major problem, and the buses have tended to require more maintenance than similar diesel vehicles. Early in 1990, Seattle Metro Transit decided to progressively withdraw the methanol engines from service because of high repair costs. Five of the ten methanol-powered buses have already been converted back to diesel power.

Klockner-Humboldt-Deutz

Deutz has developed a methanol-fuelled version of its air-cooled F8L413F diesel engine which has been used in fleet trials, including a bus and three garbage trucks operating in the city of Cologne (18).

A similar Deutz methanol engine was used in underground mining tests organized by Ontario Research Foundation (now ORTECH International)(19). An oxidizing catalytic converter was used, and was found to give valuable improvement in exhaust quality compared to a diesel engine in a similar application. Subsequent engine development work aimed at improving general engine efficiency as well as emissions reductions allowed Deutz to move away from any need for exhaust after treatment (20). In common with most other manufacturers, Deutz mentions that the very low particulate levels allowed by the U.S. standard demand careful control of engine oil consumption.

Hino Motors Limited

Hino has produced a spark-assisted methanol version of a 9.88 litre, 6-cylinder, direct injection diesel engine (21). This engine is intended for installation in a city transit bus, and is equipped with both an oxidation catalytic converter and exhaust gas recalculation (EGR). The EGR circuit is intended to facilitate auto-ignition of the fuel by increasing the in-cylinder temperature under suitable load and speed conditions, and introduces the possibility of running the engine either by spark ignition or by EGR induced auto-ignition. Each mode has distinct effects on exhaust emissions characteristics, and current research is directed towards exploration of the relative merits of each. The engine has not yet been placed in an operating vehicle.

Volvo

Volvo has had an alcohol-fuelled variant of its TD100 engine under steady development for over 10 years. It employs pilot diesel injection as the ignition method and has achieved up to 80% alcohol fuel substitution in normal driving. The most prominent fleet trial using Volvo engines took place in Sweden, where two trucks operated at a pulp mill in the town of Ornskoldsvik. The trucks ran on ethanol with diesel pilot and worked for over four years, covering collectively over 100 000 km, with satisfactory levels of reliability and performance (22, 23, 24). Later work by Volvo has included substitution of the diesel pilot charge with an alcohol/ignition enhancer additive mix, thereby eliminating the use of diesel completely.

Navistar International

Navistar has built a methanol version of its 6-cylinder DT-466 diesel engine. This engine is normally used in medium-range trucks at power ratings from 165 to 245 bhp, and has a displacement of 7.64 litres. For methanol operation, the engine used hot surface (glow plug) ignition assistance, with direct injection of the fuel. Test work showed regulated exhaust emissions considerably lower than the original diesel engine, and close to reaching the 1994 EPA standards. Power and efficiency were also closely comparable to the equivalent diesel engine. Navistar achieved these results with M85 fuel, and expected that more development would give further reductions in exhaust emissions (25). The engine has recently been undergoing durability trials in preparation for installation in a dump truck to be operated by the city of South Lake Tahoe in California. In-service trials are expected to begin in early 1991.

SAAB Scania

From 1985 to 1988, Scania operated four buses using an ethanol composite fuel as part of the Swedish joint industry/government "E95" project (24). The buses were used in regular transit operations in Gothenburg and Ornskoldsvik, and together, covered over 350 000 km before the end of the trials. Reliability and availability throughout the three years of testing remained at very satisfactory levels. The fuel contained 8% of ethyl hexyl nitrate as an ignition improver. The engines were a version of the Scania DS11 11-litre 6-cylinder diesel unit, using an 18 to 1 compression ratio and generating 184 kW at 2 200 rpm.

Scania subsequently developed a new generation of ethanol-fuelled engines based on the experience gained during the "E95" program. The new engines were still based on the well-proven DS11 design, but fuelled by ethanol containing between 1% and 2% of ICI "Avocet" ignition improver. Compression ratio was raised to 24:1, which gives excellent ignition stability and engine performance over the entire speed range at such low additive concentrations. Exhaust emissions levels were reported to comply with the 1994 U.S. EPA standards.

During 1989-1990, the city of Stockholm placed 30 buses powered by the new engines into service. Scania is closely monitoring their performance and continues to refine the engine design.

The fuel ethanol used in the Swedish projects is produced from forestry biomass. Ethanol is preferred over methanol since it is non-toxic, and is accepted in the workplace without need for amendments to existing health and safety regulations.

Mitsubishi Motors Corporation

Mitsubishi carried out extensive research and development work on a single cylinder test engine prior to producing a methanol version of its 6-cylinder, 11.15 litre, heavy-duty bus engine (26). Spark plug and glow plug ignition systems were tested. Emissions tests of the 6-cylinder unit showed high HC and CO levels in the Japanese 5 mode cycle, mostly emanating from low-load operations. However, installation of an oxidation converter gave dramatic reductions in both of these pollutants. The engine has not yet been operated in a working vehicle.

Nissan Diesel Motor Company

Nissan's heavy-duty methanol engine development work has been directed to a version of its 11.67 litre, 6-cylinder engine, using 100% methanol fired by twin spark plugs. The engine has undergone 500-hour durability trials and Nissan has published a report detailing the results. High valve and seat wear, and spark plug durability are mentioned as significant problems. The engine has not yet been configured for installation in a vehicle (27).

Komatsu Ltd.

Komatsu accumulated considerable experience with a methanol-fuelled version of a medium range truck diesel engine which was first tested in a bus over five years ago. It extended development to a smaller engine, of 3.26 litre capacity, which is used in light trucks and some types of construction machinery (28). This engine is being used in a large scale fleet trial administered by the Japanese Ministry of Transport, involving the co-operation of major research centres, trucking associations, and local governments. Sixty vehicles in all are involved, 23 using Otto cycle spark ignition engines, and 37 using the Komatsu diesels, all burning methanol fuel (29).

The Komatsu engine uses spark plugs to assist ignition of the fuel. Komatsu, whilst acknowledging advantages in regard to efficiency and durability of other ignition methods, has opted to use spark plugs at present because of their relative simplicity of installation and stable ignition characteristics. The first of the fleet of light trucks began operation in December 1986. Subsequently test vehicles have run in the cities of Tokyo, Osaka, Kanagawa, and Aichi. They have been used for regular delivery work by local trucking companies, under the terms of special leasing agreements. The object of the trial is to demonstrate a way of reducing Japan's total dependence upon imported oil, and to simultaneously attack its air pollution problem. The methanol trucks have shown a considerable improvement in exhaust emissions compared to a similar fleet of diesels.

Valmet

The Technical Research Centre of Finland and the Technical University of Helsinki jointly undertook a project to convert a turbocharged Valmet 611 diesel engine to operate on methanol. The engine was essentially altered to a carburated spark-ignition unit, including lowering of compression ratio, provision of twin downdraft carburetors, electric fuel pumps and a high-energy ignition system. An auxiliary cold starting system employing gasoline injection into the inlet manifold was also installed. The turbo-diesel 611 engine was originally rated at 120 KW at 2 400 rpm from 6.6 litres displacement. The methanol conversion produced 85% of the maximum power and 90% of the torque of the diesel.

The engine was installed in a Karhu-Sisu truck of 16 000 kg gross weight rating. Controlled on-road and chassis dynamometer testing was carried out and the results compared to similar tests made before the engine was converted in 1986-87. Performance of the truck was generally quite acceptable, and it was judged that most deficiencies in comparison to diesel could be addressed through an engine optimization program. The project was particularly designed to show that conversion of diesel to methanol power could be undertaken with limited funds and resources, and that the resultant vehicle could be maintained and operated by use of existing well understood techniques (30).

Detroit Diesel Corporation

DDC remains in the forefront of methanol heavy-duty engine development in the U.S., and is ready to market a 92 series two-stroke methanol bus engine in 1991 (31).

Detroit Diesel methanol engines have been used in fleet trials for several years, ever since the inauguration of the original "Methanol 1", the first U.S. methanol-powered transit bus, in California in 1984 (15, 16).

Original methanol exploratory work was carried out on a series 71 (71 cu. in. displacement per cylinder) engine, but the larger displacement 92 series was selected for intensive development as DDC's standard modern bus engine. Recently, growing U.S. interest in methanol power, particularly in New York State and California, has prompted the company to restart work on a 71 series in-line six engine, and to extend its program to a prototype 149 series unit. The large 149 engines are to be used in generating sets and develop approximately 100 bhp per cylinder.

The Detroit Diesel engine is a uniflow scavenged two-stroke with a blown air induction system. Ignition in the methanol engines is effected by a scavenge air control system, which retains some proportion of the burnt exhaust gases in the cylinder, thereby maintaining cylinder temperature at a level high enough to promote auto-ignition. Glow plugs have been necessary for reliable ignition under starting and light load conditions. However, the latest high compression (23:1) methanol engines require glow plug assistance only for cold starts and initial warm-up. The fuel used was 100% pure methanol until recently, when DDC began using an additive developed by the Lubrizol Company in order to solve persistent problems with injector tip blockage. Additive concentration level is substantially less than 1%.

Most fleet trials using DDC engines have involved buses, and the number has grown steadily until there are over 50 buses with 6V-92TA series methanol engines at work in Canada and the U.S. During 1988, 1989 and 1990, the rapidly expanding DDC methanol engine pre-production program has placed buses on the road in Phoenix, Denver, New York and Los Angeles. The largest concentration of methanol buses (30 units) is operated by the Southern California Rapid Transit District in Los Angeles. This fleet also has 12 more DDC engines using additive ignition enhancer in a parallel evaluation program. DDC methanol engines also moved into trucking during 1990. Five methanol trucks using both 71 series and 92 series engines were placed in service in California during late 1989 and the first half of 1990, working in a variety of urban and municipal applications. Detroit Diesel also delivered two horizontal 71 series methanol engines to Italy in the summer of 1990, for use in the Milan bus fleet test managed by Ecofuel.

Detroit Diesel has a contract to supply methanol 92 series engines for the large scale "Safe School Bus Clean Fuel Efficiency Demonstration" which is starting up in California. Fifty buses are scheduled to go into service during 1990-91. A number have already been delivered to participating school boards. It is expected that further large numbers of methanol buses will be taken into the program after 1991.

The Canadian Project "MILE" has operated DDC methanol buses since late 1986; two are located in Winnipeg, Manitoba, and two in Medicine Hat, Alberta. The city of Medicine Hat added three new methanol buses to its fleet in January 1990, followed by three more in September 1990, as part of a plan to convert all buses to methanol power. At present, the city has eight buses, or 50% of its fleet, powered by DDC methanol engines, and runs the greater part of its regularly scheduled services on methanol power.

Detroit Diesel Corporation circulates a regular monthly report of its methanol test activities to a wide audience of government, research, and industry groups. The company is also supplying ethanol-powered engines identical in design to the methanol units for bus fleet trials in the cities of Peoria, Illinois and Regina, Saskatchewan. By early 1991, thirteen buses are scheduled to be in service in Peoria and two in Regina.

Isuzu Motor Ltd.

Isuzu Motor worked with the Kitami Institute of Technology to examine the effects of injector spray pattern, spark timing and induction air conditions on starting and warm-up of a spark-ignited methanol engine. The engine employed controlled exhaust gas recirculation (EGR) to vary the oxygen content of the intake air. The objective was to achieve reliable starting over a wide ambient temperature range, and to lower exhaust emissions during the warm-up phase.

The engine was a modified version of an 11 litre truck engine using spark plugs and 100% methanol fuel. Three basic types of fuel nozzle were employed, using 5, 6 and 8 holes. The 8-hole nozzle gave equally distributed sprays around the entire combustion chamber, while the 5- and 6-hole nozzles concentrated all sprays within a 150° to 180° arc. The nozzles were set at varying alignments to the spark plug, always with one spray directed straight towards it. Spark timing was optimized at 15° BTDC. The concentrated injection spray patterns gave distinctly better startability than the 8 equally spaced sprays, allowing starting within 10 seconds cranking time at -15° C. They also reduced CO output during warm-up by some 30% in comparison to the 8 spray configuration. EGR was not a definite aid to starting, and rendered it impossible at levels above 45% intake air content, but throttled EGR was effective in reducing fuel consumption during warm-up, because of the recirculation of unburned methanol in the exhaust gas. None of the work carried out succeeded in reducing the exhaust odour during warm-up to a level considered acceptable by the researchers.

Toyota Motor Corporation

Methanol engine work at Toyota has centered around a version of the 2.2-litre 4-cylinder diesel engine, which employs a novel form of dual fuelling, named "Single Nozzle Dual Fuel" (SNDF) (51). The system introduces both methanol and diesel into one single injector nozzle per cylinder, and effectively blends, injects, and ignites the fuel charge in one continuous operation. The proportions of the two fuels are varied according to engine load conditions, with methanol content ranging from 30% at idle, through 60% at low loads, up to 94% at maximum load. The principle combines ideas from the double injector dual fuel system used by Volvo, and the in-line fuel emulsifying experiments carried out by Ontario Research Foundation (now ORTECH International) some years ago. Toyota's research with this engine has explored the nature of the dual fuel spray pattern, which is carefully controlled such that the diesel fuel emerges as a "net" surrounding the main body of methanol emerging from each orifice, and thus is fully exposed to the heat of compression and available oxygen in order to initiate combustion. The test engine has demonstrated energy based BSFC figures equal to the baseline diesel engine, similar CO and HC emissions, and NO_X levels around half the diesel figures. No exhaust catalyst was required to obtain these results. Other advantages include the expected absence of exhaust smoke and soot, and low combustion noise because of the controlled combustion rate. The variable methanol content with load gave smooth running throughout the operating speed range, particularly when idling. Subsequent stages of the research plan include evaluation of engine starting ability, and assessment of long-term reliability and durability of the unique injection system.

Japan Automobile Research Institute (JARI)

JARI has carried out extensive research and development work on diesel type methanol engines (58). Two types of engines have been used, a 3.5-litre dual-fuel unit and a 5.8-litre spark-assisted ignition design. The first engine was fitted in a small bus, and the second, which developed 136 bhp at 3 200 rpm, was fitted in a medium-size bus (32 passengers). This bus is undergoing a long-term testing and development program at the JARI research centre and automobile proving grounds in Tsukuba. The work has been in progress for more than five years, and includes investigation of all aspects of methanol vehicle design, construction, operation and reliability.

C. USE OF CATALYTIC CONVERTERS

Most Japanese makers appear to have accepted the desirability of using catalytic exhaust emissions control from an early stage of their methanol heavy-duty engine development programs. Other companies which have carried out relevant research include MAN, Detroit Diesel Corporation, and Cummins Engine Company. The sizeable fleet of light-duty methanol trucks operating in Japan, which have Komatsu engines and converters in chassis supplied by Toyota and Nissan, represents one of the largest concentrations of catalyst-equipped methanol vehicles. Deutz and Daimler-Benz did some methanol catalyst work in the past, but opted later to devote research efforts to fundamental engine design refinement.

The leading catalyst manufacturers have likewise all engaged in some degree of alcohol engine research, generally through involvement with one or more vehicle manufacturers. For instance, Engelhard, Degussa and Engine Control Systems have all supplied catalytic matrices to MAN, Corning and Johnson-Matthey have supplied components for Detroit Diesel developmental units, and Nelson Muffler have undertaken catalyst packaging design. Nearly all of these companies have also conducted internal research projects, but are unwilling to divulge any details due to proprietary rights considerations. Engelhard of Japan supplied the matrix for the catalytic activity testing carried out by Fujita, Ito et al., at Hokkaido University.

Brief updates on the positions of major diesel engine manufacturers regarding use of catalytic converters on their methanol engines are given in this section.

Cummins Engine Company

Cummins Engine Company has pursued the additive enhancement method of methanol engine operation. It has contracted much of the associated testing program to ORTECH International, which has investigated power output, endurance and emissions levels of the methanol engines. ORTECH has also investigated the effects of varying the concentration of ignition improver additive (ICI "Avocet").

There are obvious cost savings to be had from reducing the concentration of the relatively expensive additive, but testing has shown that some emissions products, particularly hydrocarbons (including unburned methanol fuel), may increase as additive concentration is decreased. Cummins began investigation of catalytic exhaust control as part of the method of attaining 1991 and 1994 emissions standards with additive concentration levels in the 1% to 2% range. All work to date has been conducted "in-house" with the co-operation of at least one major catalyst supplier. Information on progress is proprietary at this stage and not available for outside dissemination.

MAN

MAN buses have routinely been fitted with catalytic converters since 1984, and early reports stated that they were "very effective in reducing HC and specifically aldehyde emissions". The ratio of before and after hydrocarbons across the catalyst was reported to be as high as 27 to 1. (15). The oxidation type catalyst also controlled CO emissions and the buses were said to be capable of easily achieving 1991 EPA emissions standards (12). MAN also reported that the catalyst system provided some reduction of particulate emissions.

Earlier MAN methanol buses, with naturally aspirated engines, used dual converters, each one independently serving three cylinders. To achieve adequate heating of the substrate the converters were mounted very close to the engine. This arrangement proved satisfactory from an emissions viewpoint but highly vulnerable to destructive burnout in the event of the engine passing through any unburned fuel due to a misfire. Two common causes of misfires were spark plug failure and fuel starvation. These problems were greatly reduced by ongoing engine development, and parallel test work on the converters showed that it was not necessary to mount them so close to the engine to achieve adequate substrate heating.

A second design therefore evolved using a single larger converter mounted between 0.5 m and 1.0 m away from the engine, and handling the exhaust from all six cylinders. The more remote location resulted in a temperature loss no greater than 15°C, and the effect of ignition failure or misfire in any cylinder was reduced because only one sixth of the total gas stream contained unburned fuel instead of one third. This design became the standard for naturally aspirated engines. For the turbocharged buses operating at Seattle Metro Transit, MAN reverted to a dual converter design. This was in response to the greater gas flow rates through the turbocharged engine. The system retained the principle of the single converter layout inasmuch as the exhaust gas for all cylinders passes through the single turbocharger, and only then is it divided into two parallel streams. This was unlike the original version where each group of three cylinders fed straight into its own separate converter. Although vulnerability to converter burn-out is now much reduced, the possibility has not been totally eliminated and an emergency by-pass is provided. Burn-out temperatures have been estimated to reach 1200^{O}C, high enough to cause rapid destruction of the converter.

Engine Control Systems Ltd., of Aurora, Ontario, developed a system that can detect potentially destructive conditions and within eight seconds divert the exhaust gas stream around the vulnerable catalyst bed. MAN catalytic converters are packaged by the Zuena-Staerker Company of Augsburg, and have used matrices supplied by a number of the leading manufacturers.

Methanol-powered buses complete with catalytic converters were, for a time, commercially available from MAN. Seattle Metro Transit took delivery of 10 such units in early 1987, and placed them in regular operation. Since that time, MAN has chosen not to expand its methanol program to any extent.

Detroit Diesel Corporation

DDC engines are widely used in city transit fleets in North America, and the company has therefore always been extremely conscious of the impending 1991 EPA emissions standards for transit buses. DDC has conducted the most comprehensive program of methanol heavy-duty engine development and testing undertaken to date, and now has a methanol version of its well-known 92 series two-stroke engine ready for marketing in 1991 (31). The program includes catalytic converter work, in co-operation with a number of prominent muffler and catalyst substrate manufacturers. The aim is to evolve a design combining the necessary flow capacity, compactness and durability for fitting in the restricted space available for a transit bus exhaust system.

Initial laboratory work used dual 4.3-litre volume "bead bed" converters mounted vertically above the test 6V-92TA (turbocharged, aftercooled) engine. Two catalysts were evaluated, a standard production platinum-palladium oxidation type supplied by AC division of General Motors, and a palladium-silver formulation developed by GM Research Laboratories, which was particularly effective for oxidation of methanol. U.S. 13-mode and transient tests were run with and without the catalytic converters. Exhaust samples were taken at inlet and outlet of the converters to allow assessment of conversion rates. Tests without converters fitted were run with the engine rated at 200 kw at 2100 rpm. Tests with converters used a reduced rating of 154 kw at 2100 rpm because of the additional exhaust backpressure.

The platinum-palladium catalyst was reported to give good conversion rates for unburned methanol fuel and CO, but was found to increase the output of formaldehyde. The palladium-silver catalyst gave less efficient conversion of unburned methanol fuel and CO, but a high efficiency of formaldehyde conversion. Neither catalyst significantly affected NO_X output. These trends were consistent in both 13-mode and transient test procedures, although actual efficiency figures varied. The paper by McCabe, Mitchell et al., (32) discusses the findings in detail and also comments on the reasons for the trends.

DDC then engaged in fleet trials using a "bead-bed" design of converter combined with a muffler unit, dimensionally the same as a standard RTS series bus muffler. In March/April 1988, six methanol-powered buses began operations for Triboro Transit in New York City. Four of these buses were fitted with catalytic converters, one platinum, one silver, and two combination silver/platinum. The remaining two buses were not fitted with converters and are employed as "control" vehicles, against which to measure the emissions reductions produced by the test converter units.

In-chassis emissions comparison tests are carried out by the New York City Environmental Protection Department test laboratories. The test cycles used are specific to New York, and were devised to reflect typical bus operating conditions in New York City traffic. Results do not directly co-ordinate with FTP 13-mode or transient tests. The New York City Department of Environmental Protection has reported on two rounds of tests (33), and presents comparisons between diesel buses, methanol buses without catalysts and methanol buses with catalysts. General trends identified include very low particulate levels from the catalyst-equipped buses, high formaldehyde levels from all methanol buses, high HC levels from all methanol buses (unburned methanol fuel), but much lower NO_x levels from the methanol buses. All the foregoing comparisons are made against typical diesel performance. CO is also generally much higher for the methanol vehicles. Dramatic differences in emissions output according to catalyst formulation have been observed. CO and HC are reduced more effectively by platinum, while aldehydes are best controlled by silver. No clear effects on NO_x have been noted.

Comparisons between the first round of tests in May 1988, and the second round, on average seven months and 20 000 miles later, indicated noticeable increases in CO and HC output from all the methanol buses. It was suggested that this may have been due to deterioration of both combustion and catalyst efficiency, and corresponding increases in the vehicle fuel consumption rates were noted. Detroit Diesel recently announced its 1991 bus engine range. Methanol- and ethanol-fuelled engines are offered, which will comply with the 1991 EPA bus emissions rules. Catalytic converters will be available to customers wishing to achieve even lower emissions levels.

Hino Motors Limited

Hino produced a spark-assisted methanol version of a 9.88-litre, 6-cylinder, direct injection diesel engine (21). This engine was equipped with both an oxidation catalytic converter and exhaust gas recirculation. The EGR circuit was intended to facilitate auto-ignition of the fuel by increasing the in-cylinder temperature under suitable load and speed conditions. The use of EGR introduced the possibility of running the engine by spark ignition or EGR induced auto-ignition. Each mode showed distinct effects on exhaust emissions characteristics, and research was directed towards exploration of their relative merits.

Hino used a monolithic matrix platinum-palladium converter supplied by Tokyo Roki Limited. Development problems experienced included burnout, cracking and generally short service life. Hino suggested that converter control of emissions would probably be necessary for future methanol engines. It has not yet installed an engine and converter in a working vehicle.

Komatsu

Komatsu has supplied a number of methanol compression ignition engines to a test program supervised by the Japanese Ministry of Transport, in which over 30 small trucks were leased to local delivery companies in Tokyo, Osaka and Kanagawa. The trucks were all fitted with catalytic converters, and are engaged in long-term durability trials which continue at the time of writing. The catalysts are reported to be effective in reducing hydrocarbon and carbon monoxide, and in controlling aldehyde levels at part load, when incomplete in-cylinder combustion is experienced (28).

The catalyst used is palladium on a honeycomb structure. Komatsu has reported that service life is unpredictable, and may often be less than 20 000 km. Emissions levels are well within the Japanese 6-mode standard regulations, even though the catalysts suffer from aging. Komatsu expects to make further gains in aldehyde reduction at part load conditions through ongoing engine design work.

Mitsubishi Motors Corporation

Mitsubishi carried out extensive research and development work on a single cylinder test engine prior to producing a methanol version of its 6-cylinder, 11.15-litre, heavy-duty bus engine (26). Spark plug and glow plug ignition systems have been tried. Emissions tests of the 6-cylinder unit showed high HC and CO levels in the Japanese 6 mode cycle, mostly emanating from low-load operations. However, installation of an oxidation converter gave dramatic reductions in both of these pollutants, and it is likely that Mitsubishi will employ converters on any production vehicles using this engine.

Nissan Diesel Motor Company

Nissan's heavy-duty methanol engine development work is directed to a version of their 11.67-litre, 6-cylinder engine, using 100% methanol fired by twin spark plugs. In common with most Japanese experimenters with both spark ignition and compression ignition methanol engines, Nissan opted to install an oxidizing catalytic converter on the engine early in the development program. When 500-hour endurance tests were run the platinum honeycomb catalyst selected was one of the items examined for deterioration. The primary characteristics studied were its ability to oxidize CO and unburned methanol. Nissan's report on the development program (27) mentions a 60^{o}C increase in converter reaction temperature after a 500-hour endurance test.

Several governmental and independent organizations have performed catalytic converter research with alcohol engines. Most of the work has been undertaken in conjunction with engine or vehicle manufacturers, or both, and sometimes involved fleet-trials of actual operating vehicles. Many of these programs are therefore mentioned in other sections of this paper. Examples include the Japanese MOT involvement in the extensive testing of light trucks with Komatsu engines, and the partial sponsorship of the Triboro Transit methanol buses in New York by the U.S. EPA and the New York State Energy Research and Development Authority. Two other programs making more laboratory oriented contributions to the sum total of research are the ongoing work at Hokkaido University and a new project about to begin at Southwest Research Institute in Texas, which is sponsored by the California Air Resources Board.

Hokkaido University

Fujita, Ito and Sakamoto have published further reports of their ongoing investigations into the performance of catalytic converters. By creating an artificial exhaust gas stream composed of typical combustion products, they are able to demonstrate converter activity under a wide variety of simulated engine operating conditions. Results may be applied to spark ignition or compression ignition engines (34, 35).

The bead-type test catalyst employed used 0.5% wt. platinum on aluminum oxide, manufactured by Engelhard of Japan. In the presence of oxygen and nitrogen only unburned methanol oxidizes readily over a wide temperature range. Introduction of typical exhaust gas components, in particular NO, reduces the catalyst's ability to fully oxidize unburned methanol and results in a concentration of formaldehyde. Actual rates and ratios of methanol oxidation and formaldehyde generation were affected by the rate of change of NO concentration and changes in catalyst temperature. The authors suggest that consistent catalyst performance in service may be aided by preheating provisions for cold starts, and some means of suppressing fluctuations of temperature during hot operation. A catalyst must be capable of adequate oxidation in the presence of NO to be useful in vehicle applications.

California Air Resources Board

The California Air Resources Board is encouraging research into catalytic converters for methanol-fuelled vehicles. It is currently concerned principally with automobiles, and is sponsoring a program at Southwest Research Institute (SWRI) of San Antonio. All the major U.S. catalyst manufacturers, including Allied Signal, Engelhard and Johnson Matthey, have been invited to submit recommendations and sample catalyst matrices for testing. The test matrices are supplied to standard external dimensions to fit interchangeably inside packaging built by SWRI.

Four engine-vehicle configurations are being used in the program. These are a Toyota Camry using M85 fuel, flexible fuel vehicles from Ford and Chevrolet, and an M100 fuelled car. It is likely that the M100 vehicle will have to be specially configured, since no U.S. manufacturer is currently producing M100 cars.

The emissions sampling program is geared to identifying the most effective catalysts, progressively narrowing the selection down to two or three for intensive testing. Eventually, one optimum configuration will be subjected to a long-term field evaluation program.

D. EMISSIONS TEST RESULTS

Given the relatively wide variation, from a global perspective, of exhaust emissions test procedures, there exists a desire by manufacturers to standardize exhaust emissions regulations. The benefits of such an arrangement could be:

- For the manufacturer - reduced development, production and compliance testing costs.

- For the consumer - cost savings passed on by the manufacturer.

- Globally - benefits gained by emissions regulations in some countries or regions will not be negated by the unregulated (or underregulated) emissions output in neighboring countries.

The difficulty in achieving a global consensus is characterized by the conflicting goals of governments and the differences in test cycles employed in the regulatory test procedures.

The U.S., European and Japanese test cycles were initially developed for their own specific applications. While there has been a trend by countries towards U.S. style transient tests, particularly in the developed world, the majority of countries in the world are still utilizing European style steady state tests. This is because tests such as the ECE 49 standard, a derivative of the U.S. 13 mode test cycle, have been sanctioned by the United Nations. Furthermore, the fact that it is a steady state test, means much lower capital costs for test cell development. However the reasoning behind utilizing any test cycle is that any improvement (reduction) in emissions recorded in one test cycle should similarly be reflected if the engine is tested against another cycle, although possibly to a different degree.

Researchers and engine manufacturers share a common desire to evaluate the emissions performance of methanol in engines. As was depicted in Exhibit II-1, because of the different test cycles employed, there is a natural desire to predict the performance of an engine on one test cycle given its emissions output recorded during an evaluation on another test cycle.

Engine manufacturers have attempted to correlate emissions from a steady state cycle to those that would be obtained over the transient cycle for diesel fuelled engines. Facilities capable of carrying out a steady state test are more readily available. In the case of non U.S. based engine manufacturers, local facilities may not be equipped to carry out the U.S. style transient cycle which is required if they desire to sell in the U.S. or Canada. The use of steady state data or even complete engine maps will provide a means for a manufacturer to predict engine emissions performance. Typically, when implementing a new engine build or during the engine development phase, a manufacturer may try different combinations of components on the engine. Steady state testing is then performed to collect operating characteristics of the engine, including emissions data. An understanding about how these components affect NO_X, HC, CO and particulates can help guide the manufacturer towards an optimum engine build. Although such data is not a substitute to an actual running of the transient test cycle for engine certification in the U.S. or Canada, it would provide a method of collecting preliminary emissions data at a much reduced cost.

Engine build components such as a turbocharger, cam lobe profile, charge air cooling, electronic injection controls, etc., affect engine response. Engine response tends to be dynamic. In the case of a turbocharger, for example, there tends to be a transient between its operation and the engine's operation when moving between engine operating points. This is particularly apparent during acceleration phases in the diesel engine where the fuel flow is limited to prevent smoke or engine bog until the turbocharger catches up. Therefore, in reality an engine being run through a transient cycle is not quite stepping through a series of steady state points. For these reasons, some researchers feel that a transient type test will gain prominence in the near future.

An understanding of the test cycle that an engine is subjected to will help predict what type of emissions levels are to be expected on another test cycle. The average load applied to an engine during an emissions test and the engine operating temperature will have an effect on the total emissions recorded during the test cycle. In the case of engine load, the U.S. heavy-duty diesel engine transient test cycle has an average load over the cycle of approximately 22% versus approximately 33% for the now outmoded U.S. 13 mode. Furthermore, the emissions quantity will not necessarily increase or decrease at the same rate as does engine power, which will affect specific emissions output (weight of emissions constituent per engine load per time). Also exhaust emissions have been shown to be related to engine operating temperature. In the case of the heavy-duty diesel transient test cycle, the test begins with a cold engine start (25°C) whereas the 13 mode test (or steady state test programs) only begins once the engine has been fully warmed up and stabilized. Finally, the steady state tests, while recording data at each mode, typically only use the last minute or so of data recorded.

A great deal of research has been carried out in the past by engine manufacturers and other agencies to look at correlation trends between a steady state test and the transient emissions test. Most of this has been engine specific research to enable a manufacturer to predict where any engine of theirs will fall based on an extrapolation of 13 mode steady state results (36). Other research has been conducted to permit a general characterization of emissions trends when moving from steady state to the transient test cycle (37). Although trends have been developed for diesel engines, much of the thought used in their postulation is equally applicable to methanol engines. As methanol-fuelled heavy-duty diesel engines become more prevalent in field tests, an emissions data base is being developed that will permit a more accurate correlation between steady state and transient emissions test results.

Unlike their diesel counterparts, methanol heavy-duty diesel engines use alternative means to achieve combustion. The Caterpillar 3406 DITA and DDC 6V92TA, both used in the MILE program in Canada, utilize glow plugs to assist with fuel ignition. In addition, the DDC engine, being a two-stroke engine, utilizes a variably controlled amount of exhaust gas scavenging to help maintain charge air temperature. Other techniques used to assist in the combustion process include the use of fuel additives (Cummins L-10 which uses a cetane enhancer), pilot injection (Volvo TD-100-A), fumigation (Daimler Benz) and spark ignition (MAN). All the techniques described above will have an impact on emissions results and must be considered if one attempts to extrapolate between test cycles.

Data from a Project MILE Caterpillar methanol engine, a Volvo pilot injection methanol engine, glow plug assisted DDC and Deutz methanol engines, a MAN spark ignition methanol engine and ignition improved (Avocet) methanol Cummins L10 and DDC 8V-71 engines are presented in Exhibit III-4 along with typical data for similarly rated diesels. The Caterpillar, Cummins and ignition improved DDC methanol engines were tested as part of the MILE program. The Caterpillar engine was tested by Caterpillar, while the Cummins engine was tested at Ortech International and the DDC engine at Southwest Research Institute. The Cummins L10 and DDC 8V-71 were tested from the perspective of examining the effect of varying Avocet concentrations on emissions. The results for the other engines are derived from published data but represent similarly rated engines with respect to a manufacturer. While a strict back-to-back comparison cannot be made, Exhibit III-4 provides a good indication of emissions trends from two perspectives; change in fuel (diesel to methanol) and a change in test procedure (steady state to transient).

A strict back-to-back comparison of diesel and methanol HC results cannot be made since until recently, most researchers have measured methanol HCs based on the diesel standard, i.e. HFID (heated flame ionization detector). The HFID has been shown to be less sensitive to oxygenated hydrocarbons, the major HC component expected from a methanol engine (38). Engine manufacturers have only recently begun reporting HC levels using the OMHCE weighted formula.

Similar to diesel engines, a predictable effect of the transient test cycle on methanol engines is to increase HC values compared to values reported during the 13 mode cycle. This is to be expected due to the overall cooler operating temperatures experienced during the test cycle coupled with lower average operating loads. Contributing to the cooler operating temperatures is methanol's higher heat of vaporization. With low levels of Avocet, misfire was observed in both the Cummins and DDC engines, a measure of the difficulty of obtaining self-ignition (39, 59). In the case of the Cummins L10, the highest HC levels were recorded at idle and low load levels (39). At increased loads and speeds, enough heat is generated within the combustion chamber to initiate combustion. Therefore the quantity of ignition enhancer plays a significant role in predicting HC levels. At middle and higher operating points, varying concentrations of ignition improver do not have any significant effect on HC emissions. However, the exact quantity of ignition improver will be engine-type specific.

Exhibit III-4. Heavy-Duty Engine Emissions Test Results

ENGINE	TEST CYCLE	BSHC (3)	BSCO	BSNOx	BSP	BSAld
			(g/kW.h)			
			DIESEL ENGINES			
CATERPILLAR (1)	13-M	0.27	1.45	11.43	NA	0.04
3406 DITA	TRAN	0.30	2.43	7.68	0.34	0.05
VOLVO	13-M	1.05	3.18	11.88 (6)	0.70 (5)	
T-100A	TRAN	1.14	4.03	11.18	0.70	
DDC 6V92TA (7)	TRAN	0.76	2.14	6.53	0.33	
DEUTZ F8L-513/11	TRAN	1.25	NA	12.51	0.46	
DDC (10)	13-M	1.34	10.19	10.72	NA	
8V71NA	TRAN	2.41	5.63	10.72	1.07	
			METHANOL ENGINES			
CATERPILLAR (2)	13-M	3.81	8.75	4.13	NA	0.44
3406 DITA	TRAN	5.97 (4)	16.55	4.09	0.20	0.66
VOLVO	13-M	1.45	9.54	5.25	0.31 (5)	0.12 (5)
T-100A	TRAN	1.94	10.28	7.31	0.40	0.34
DDC 6V92TA (8)	TRAN	0.94	2.7	3.08	0.11	0.11
(with catalyst)	TRAN	0.13	0.27	3.08	0.04	0.05
DEUTZ F8L-513/11	TRAN	1.47	NA	5.21	0.16	NA
DDC w/7.5% Avocet	13-M	1.74	11.26	10.05	NA	NA
8V71NA (10)	TRAN	2.28 (4)	3.75	10.86	0.84	0.23
MAN M2566LUH (9)	13-M	0.17	0.19	5.24	0.07	NA
CUMMINS L10, 3% Avocet		3.75	2.01	6.41	NA	0.17 (11)
5% Avocet	13-M	2.10	2.04	7.29	NA	0.17 (11)
7.5% Avocet		1.69	1.94	7.40	NA	0.15 (11)

NOTES:
(1) Engine rated at 350 HP, 1800 RPM, with electronic fuel control
(2) Engine rated at 350 HP, 2100 RPM with mechanical fuel control
(3) Reported on diesel basis (via HFID) unless otherwise noted
(4) Reported via EPA methodology for total HCs
(5) Represents 7 mode data
(6) Correction factor for intake humidity not applied
(7) 1990 engine build using #1 diesel fuel
(8) Proposed production unit
(9) Equipped with a catalyst
(10) Engine rated at 198 kW with diesel fuel, 227 kW on methanol-Avocet blend
(11) Represents BS Formaldehyde
Ref. (12, 20, 39, 40, 41, 42, 59)

Based on the range of methanol-Avocet concentrations tested, a 5 percent Avocet blend was determined to be the optimum level in the Cummins and 7.5 percent in the DDC. Unfortunately, no Cummins L10 transient methanol or diesel data is available to perform a back-to-back comparison.

NO_X emissions from methanol engines, compared to diesel engines, tend to be lower because of the very high heat of vaporization of methanol as compared to diesel. Research on NO_X levels from diesel engines, when run through a transient or steady state (13 mode) test cycle, has tended to show that NO_X levels would remain fairly stable between either test cycles (36, 37). This effect has been attributed to the lower average loads experienced during the transient cycle, which although tending to raise specific NO_X levels, are countered by the overall cooler operating conditions the engine experiences at lower average loads. In the case of the methanol engine, however, the use of ignition assists, such as glow plugs, spark ignition, pilot injection or an ignition improver are designed to initiate the combustion process, particularly at lower loads. The use of ignition assists can offset reductions in NO_X. The results from the ignition improved Cummins L10 engine illustrate this phenomenon. Relative to diesel, increasing quantities of Avocet decreased the ignition delay resulting in early combustion compared to a diesel with identical injection timing (59). At higher loads, greater fuel quantities will cause NO_X levels to rise faster than the power. Increasing quantities of ignition improver were not needed at these operating points (indicated also by the HC results) and probably only caused the combustion reaction to progress more rapidly, thus further elevating in-cylinder temperatures and NO_X levels. However, it is unknown how much the Avocet ingredients themselves contribute to NO_X levels.

Carbon monoxide emissions can be attributed to the air-fuel ratio, with CO emissions tending to decrease with leaning of the air fuel ratio. However, the rate of reduction is not linear and will be influenced by the particular engine. The stoichiometric air-fuel ratio for a methanol engine is approximately 6.5:1 versus approximately 15:1 for diesel fuel. When comparing results obtained over different test cycles, a transient test cycle is better suited to capturing what is going on in the engine, particularly in the case of a turbocharged engine. Unlike their diesel-fuelled counterparts, methanol engines are not sensitive to fuel produced particulate emissions, therefore the engine does not necessarily require a fuel (or smoke) limiter.

During transient conditions, the extra fuel supplied in a methanol engine will tend to increase CO levels as compared to steady state.

Particulate emissions from methanol engines have been demonstrated to be much lower than those from their diesel fuel counterparts. With improvements in diesel engine design, the fraction of particulates attributed to diesel fuel will diminish especially as fuel sulphur content is reduced. Particulate production has been shown to be proportional to fuel sulphur (55). Effective lube oil control within the combustion chamber will become critical if greater particulate reductions are to be achieved. Methanol-fuelled engines offer the advantage of significantly reducing fuel-based exhaust particulate emissions. Future methanol engine designs must also incorporate improvements directed at minimizing lube oil consumption.

The DDC engine results offer a snap shot of the current status of methanol and diesel engine development. DDC is the primary supplier of transit bus engines to the North American market. The diesel engine results, for a 1990 model year diesel engine, will not meet the 1991 U.S. or California urban bus emissions rules due to high particulates. Their methanol engine development program will satisfy the 1991 urban bus standards. DDC has announced its intention to sell a methanol-powered engine starting in model year 1991 (83).

IV ADVANCED DIESEL TECHNOLOGY

A. INTRODUCTION

This section describes and discusses advances and trends in diesel technology brought about by the need to meet U.S. EPA 1991 and 1994 emissions standards. When these rules were first proposed there was a considerable upheaval in the diesel industry, including predictions of the demise of the diesel-fuelled engine in the automotive world. The announcement had implications outside of the U.S., since many European and Japanese manufacturers export engines to the large U.S. market. Additionally, the world has come to view the U.S. as a trend setter in emissions laws, and its actions in this regard tend to be copied in other countries. One result was a surge of interest in alternative fuels, in particular methanol and ethanol, and later natural gas.

A second result was a call for changes in the composition of typical automotive diesel fuel oil, especially regarding the level of sulphur content. For some time, there was a controversy between engine manufacturers and oil companies. The manufacturers claimed that it was impossible to meet the standards without better quality fuel, while the oil companies claimed that better fuel would be too expensive, and it was up to the manufacturers to design engines to run on the current specification fuel.

Eventually a level of agreement was reached between all parties. Low sulphur fuel is to be made available, and the engine manufacturers have lately begun revealing the results of intensive research into diesel emissions reduction measures. The low particulate level stipulated by the 1994 regulations was intended to speed the development of exhaust gas filters or "particulate traps". Particulate trap research and testing has been undertaken in many other countries as well as the U.S., and there is ample evidence that this method of emissions control is practical and effective.

The evolving new generation of "clean" diesel engines may meet the 1994 emissions reduction targets without the use of exhaust particulate filter traps.

However, if this is not possible in practice, having regard to the need for a degree of tolerance to accommodate production line variations, then particulate traps will be available to make up any deficiencies. Fleet users and the diesel industry in general would much prefer to continue using diesel oil if at all possible. There is now a strong belief that the diesel engine will continue as the predominant heavy-duty vehicle engine for the near to medium term future.

B. SUMMARY

The emissions reduction technology employed may conveniently be divided into three major groups:

- modifications to the actual engine;
- after-treatment of the exhaust gases;
- reformulation of diesel fuel oil.

Engine modifications include higher pressure injection for improved fuel mixing, variable boost turbocharging and charge cooling, and control of lubricating oil ingress into the combustion chamber. Electronic governing and engine control provide superior ability to co-ordinate operating parameters in comparison to mechanical systems, and will become standardized in future automotive diesel engines. Most features which will be used to meet the 1994 EPA standards already exist on the most recent engine designs, and the future path will be one of increasing refinement of component performance and electronic control strategies.

Exhaust gas after-treatment devices have been tested in many countries, and adopted for large scale use by a number of fleets. Filter elements or "traps" are used to remove carbon particulates. Removal of particulates and use of low-sulphur fuel make it possible to use catalysts to reduce other exhaust pollutants such as CO and HC. Particulate traps are capable of self-cleaning or regeneration, through a process of burning out the accumulated carbon deposits. Usually the burning is initiated and assisted by an auxiliary heat source such as a diesel-fuelled flame or an electric element.

A major attraction of exhaust after-treatment devices lies in their potential to cut emissions from the existing vehicle and engine stock. The technology has accumulated an extensive history of use in several fleet trials, which have culminated in orders for large numbers of particulate traps for existing vehicle fleets, e.g. 400 buses in New York City.

Several European manufacturers, such as Deutz and Volvo, have developed and test marketed particulate trap systems. American manufacturers are studying traps, and DDC has supported trials on its bus engines and acknowledged and published some results (40). This work has been successful enough to allow DDC to advertise the commercial availability of a trap system for its bus engine range in late 1991.

Traps are widely used on diesel engines in underground mines, and will be used on road vehicles in the future. The active regeneration system, either by diesel burner or electrical heater element, is most likely to predominate. It is universally applicable and not dependent upon engine duty cycle to ensure complete regeneration. Trap durability is not fully proven over distances of significance to heavy vehicle operators, but tests continue to build experience daily. There appear to be no fundamental reasons why traps should not give the required long-term reliability.

The future use of traps and catalysts will be greatly influenced by the actions of the EPA and other legislative bodies. Many engine and vehicle manufacturers hope to avoid using traps in 1994 by achieving the requisite emissions levels through engine modifications alone. However, in the meantime there may arise a demand for compulsory trap fitting to existing vehicles. There will also be an imposition of even lower emissions standards for new vehicles some time after 1994. EPA deliberately imposed the 1991 and 1994 rules as a technology forcing tactic, aware that manufacturers may have been compelled to use particulate traps. The diesel industry may in fact succeed in reaching the 1994 standards without traps and catalysts, but then the authorities are unlikely to ignore the possibilities of even more emissions reductions by imposing their use in later years.

Diesel fuel reformulation is primarily concerned with lowering the sulphur content to a maximum of 0.05%. Low sulphur diesel will be available in the U.S. and Canada by 1994, pending final passage of legislation in both countries. Lowering the aromatic content of diesel is also advantageous in some respects, but the aggregate cost to achieve a reduction to the 10% level which has been suggested would be very high. The refinery modification required is much more extensive and costly than for desulphurization alone.

Vehicle modifications, including particulate traps, will be largely transparent to operators. Trap systems operate automatically, and internal engine changes will not affect driveability, power, or reliability. Vehicle configurations and load capacities will not be altered. Modern particulate traps can be directly substituted for a conventional muffler.

The U.S. EPA proposed the 1991 and 1994 diesel emissions standards in order to force development of cleaner heavy vehicle engines. Some organizations, particularly in California, have used the situation to press for a move away from diesel to alternative fuels such as methanol. EPA is not attempting to advance any particular technology, but it is obliged to couple the demand for low emissions engines to a call for low sulphur (0.05%), minimum 40 cetane number, diesel fuel. If the better fuel is not made available then diesel engines will effectively be prohibited from use.

The cost increase for low sulphur fuel in the U.S. and Canada is estimated at 10% to 20%, or 2 cents to 4 cents per litre, depending somewhat on region. Manufacturers are not prepared to forecast costs of the new engines, using only terms such as "competitive" and "comparable to current". It has been estimated that the capital cost for an engine will increase by 10% to 15% or $2 000 to $3 000 on a $25 000 engine. This is exclusive of any exhaust after-treatment devices. Current prices of particulate trap systems are in the $10 000 range, but a leading U.S. manufacturer has suggested that quantity production could lower this to around $4 000 by 1994.

C. ENGINE DESIGN

Electronic Microprocessor Control Systems

Electronic control of diesel engines is becoming increasingly widespread, and will eventually supplant mechanical control, just as electronically controlled fuel injection systems have replaced carburetors on automobile gasoline engines. The transition will probably occur during a similar timeframe, approximately 10 years, so that by the year 2000, the majority of light- and heavy-duty automotive diesel engines in operation will have electronic control systems.

One example is the Detroit Diesel Electronic Control system (DDEC), first offered as an option in 1985. The second version (DDEC2) introduced in 1988 was smaller and simpler, and yet capable of processing much more engine information with far greater speed and accuracy. It is now fitted as standard on the transit bus version of the Detroit Diesel 92 series two-stroke engine. Detroit Diesel's new four-stroke engine, the "Series 60", was designed from the outset to use this system and is not available with mechanical governing. This engine is available in two-cylinder displacement sizes, with a range of power outputs from 250 bhp to 425 bhp. The new Caterpillar "3176" is a slightly smaller engine for mid-size trucks, with a power range of 200 bhp to 300 bhp. It is fitted as standard with the Caterpillar "Programmable Electric Engine Control" (PEEC) system. Both of these engines can meet 1991 EPA truck emission standards without exhaust after-treatment. Electronic control is the coordinating element which allows maximum exploitation of other engine modifications and exhaust after-treatment devices.

High Pressure Injection

Increasing fuel injection pressures gives more complete atomization of the fuel and deeper penetration of the spray pattern into the surrounding air, both of which promote more complete combustion. It also allows a higher fuel flow rate, which gives the designer freedom to inject a given quantity of fuel in a shorter time, or to vary injection timing over a wider range.

All manufacturers are turning to higher pressure systems. The "Series 60" DDC engine employs pressures up to 23 000 psi. The new range of Cummins engines will increase maximum injection pressures from the current 14 000 psi level to 21 000 psi. One effect of the higher pressures is a trend to the use of unit injectors. This type of injection system avoids potential problems with pressure wave propagation in the long high-pressure feed lines necessary in a separate pump and nozzle system, due to the expansion of the line itself and fluid compressibility effects. This phenomenon can make it more difficult to time injection events precisely. Caterpillar began using unit injectors for the first time in a truck engine in the 3176 design, and is continuing the practice in a new range of smaller engines aimed at the light and medium end of the truck pumps, has introduced a range of electronic unit injectors for use in what it describes as the next generation of diesel engines.

Robert Bosch Gmbh has undertaken much research on both types of systems. It has demonstrated that higher injection pressures and electronic control may also be used with success in a separate pump and nozzle system. Ricardo Consulting Engineering Ltd. also carried out research into high pressure injection using a Bosch separate pump and nozzle system on a Volvo 12-litre truck engine (60, 61). The high pressure system was shown to be an important contributing factor in controlling the trade-off effect between NO_X and particulate output. Ricardo also examined the effect of a range of other emission control features including turbocharging, air swirl, charge cooling and oil control. EPA truck emission targets for 1991 were achieved using 0.05% sulphur fuel. Ricardo estimates that 1994 targets could be achieved with further development of these engine modifications. Exhaust after-treatment could be used to provide necessary margins for production tolerances in a mass production situation.

In conventional injection systems, pressure is proportional to engine speed and load, so that peak levels are not possible at low speeds. Navistar International has used a hydraulic pressure multiplier system to provide up to 18 000 psi over the upper 60% of the engine speed range in a version of its 466 cu.in. six-cylinder diesel. This engine uses a combination of advanced modifications to achieve 1994 emissions standards. Engine-out particulate levels are low enough to allow use of a catalytic converter to cut HC and CO emissions without an intervening particulate trap. Navistar is currently demonstrating a truck equipped with this engine to interested organizations in the U.S. and Canada (62).

Lubrication Oil Control

The 1991 and 1994 EPA restrictions on particulate matter output are so low that lubricating oil entering the combustion chamber becomes a major concern. Particulate matter generated this way can be between 25% and 70% of total depending on engine load and speed (63, 64).

Heavy-duty diesels have oil consumption rates around 0.2% of rated power fuel flow (65). Ricardo Consulting Engineers has estimated that oil consumption must be cut by a factor of 4 for achievement of 1991 truck particulate standards. Cummins Engine Co. is planning to progressively reduce engine oil consumption from a current average of 3 000 km per litre to 6 000 km per litre by 1991, and 12 000 km per litre by 1994. Manufacturers are addressing this problem through tighter tolerances on pistons, rings and bores, together with detail changes to ring design. Oil consumption may also be reduced by lowering the rated speed of an engine.

Navistar claims significant emissions reductions by positioning the top ring much closer to the top of the piston than normal diesel practice, and eliminating piston ring movement by intensive study of ring spacing and configuration. The high ring position reduces the angular crevice volume of gas around the piston crown, which cannot easily be mixed into the main combustion process, and so can contribute to incomplete combustion. The improved lower ring pack reduces oil transfer. Navistar also employs high efficiency valve stem seals on both inlet and exhaust valves. The improved ring pack has been shown to provide a 30% particulate emissions reduction in comparison to the normal design, and the valve stem seals give a 15% reduction in comparison to an engine without seals.

Direct Injection

There is no evidence of any move towards reintroduction of indirect injection into heavy diesels. All designers and manufacturers appear to agree with Ricardo Consulting Engineers, which states that the direct injection design is capable of accommodating the 1991 EPA legislative requirements when used with the latest turbocharging and charge cooling arrangements, and a four-valve cylinder head.

Turbocharging and Charge Cooling

Heavy truck and bus engines to meet 1991 and 1994 standards will be turbocharged with an air to air aftercooler. Air to air charge cooling has taken over from water cooling because of its ability to reach lower intake air temperatures, thereby providing increased charge density. In addition, peak combustion temperature can be held to a lower level if the incoming air charge is as cool as possible, and this has an important influence on NO_X formation. Turbocharger matching can be enhanced by use of electronic control and feedback loops, using variable geometry vanes to modulate air flow when required. The technology requires sophisticated control arrangements and high precision manufacture, but the results obtained are promising, giving reductions in HC, smoke and particulate emissions, with no increase in NO_X levels (66).

Exhaust Gas Recirculation

The Japanese Traffic Safety Institute has sponsored work on an 11.6-litre truck engine, in which the potential of exhaust gas recirculation (EGR) to provide over 50% NO_X reduction was demonstrated (67). A reduction of 30% in the excess oxygen available in the inlet air stream virtually eliminated NO_X generation. However, it was also shown that more than 15% oxygen reduction produced a rapidly rising CO output. The recirculation system and control strategy used held HC and CO increases to very low levels, with a corresponding negligible effect on fuel consumption. The Institute advocates further research in the field, particularly regarding the question of long-term wear effects on cylinder bores.

Glow Plugs

Navistar International has proposed the use of glow plugs at part load conditions to reduce NO_X formation by shortening the ignition delay period. Reductions in HC emissions are also anticipated. It has not yet carried out significant testing of the concept, and anticipates problems with glow plug life and electrical power demand. There appears to be no particular barrier to the development of a suitable glow plug. Existing types have shown poor reliability when used in alcohol-fuelled engines, but this is because they were not designed for continuous service in the open combustion chamber of a direct-injection engine.

D. EXHAUST AFTER-TREATMENT

Particulate Traps

A vehicle particulate trap resembles an exhaust muffler and consists of four fundamental elements: a carbon filter, a heating device for regeneration, a housing to route the exhaust gas and carry the filter and heater, and a control system to initiate and control regeneration. The filter element also provides an adequate sound dampening effect, so that the trap may actually be used as a direct substitute for a vehicle muffler.

A basic particulate trap is only capable of filtering carbon particles and has no effect on gaseous emissions (CO and NO_X). The filter element cannot remove particles below a certain size, or all soluble hydrocarbons. However, over 90% of particulate matter can be removed, and by achieving this, traps offer the opportunity to apply catalytic control to other emissions. Filter elements are normally made from ceramic compounds to withstand the high temperature involved. Mineral wool and ceramic foam may be used, but all current designs in practical use have moulded matrices, exactly as used in automotive catalytic converters except that alternate passages are plugged to create a labyrinth filter (68). Corning and NGK supply nearly all of the matrix filter elements. Researchers are studying the question of durability and structural integrity of the filter elements when subjected to thousands of high-temperature regeneration cycles. It appears that no insuperable problems exist in this regard (69, 70, 71).

Carbon burn-off or regeneration is achieved by the use of an auxiliary burner device to initiate combustion. The most common option is a diesel-fired flame burner. Electric heating elements are also widely favoured. The Donaldson Company, a leader in U.S. trap production, offers a choice of either method (72). An alternative is to use exhaust heat only to initiate regeneration ("passive" regeneration). The incoming exhaust gas stream is throttled through a restrictor valve to produce a blow-torch effect on the filter element. Ignition becomes self-sustaining and a flame front moves through the filter, supported by excess air admitted through a metering valve when necessary. The effectiveness of passive regeneration is limited in some respects, particularly when the engine is cold or power demands are low. Catalytic assistance may be used to promote carbon combustion at lower temperatures, either in the form of a fuel additive or as a coating on the filter element.

Burner systems ("active" regeneration) are used by Webasto, Detroit Diesel/ORTECH, Deutz, FEV and IVECO. The passive method is in use in Athens, in a fleet of buses equipped with traps developed by Thessaloniki University (74). Mitsubishi (75) and Nippon Shokubai (76) are also conducting tests with passive systems. The Athens buses use approximately 100 ppm of cerium naphthanate in the diesel fuel as a catalyst to lower regeneration temperature. It is claimed that this additive produces no harmful effects or emissions, and that its cost is minimal. Active systems require power, either as additional diesel fuel burned, or as heavy current electricity, leading to some increase in average fuel consumption. Fleet trials report fuel consumption penalties ranging from 1% to 8%.

Volvo has introduced a system for buses and city vehicles in which the filter element is big enough to last through one day of service without serious exhaust back-pressure increase (77). Regeneration is by means of a 220V heater element and an air pump. At the completion of the day's operations, the driver plugs the bus into the main electricity supply and the system automatically regenerates. This system offers advantages through the absence of an automatic on-board control system with its associated cost and maintenance complications, and the ability to regenerate filters under more controlled and slower burn rate conditions. Volvo has equipped about 100 trucks and 30 buses in Sweden with these traps during the past year, but the high cost of 30 000 to 70 000 Swedish Crowns ($6 000 to $13 500 Cdn) deters many potential purchasers. Individual filter-equipped vehicles have recorded over 170 000 kms without major problems. The filter element has a catalytic coating which reduces CO and HC emissions at high exhaust temperatures. The 220V element can be used to pre-heat the filter before starting to cut emissions levels during cold starting and warm-up.

Particulate traps have often been used in pairs. Exhaust gas flow passes through one trap until it is saturated. Flow is then diverted to the second trap while the first is regenerated. The Detroit Diesel/ORTECH system under test in New York is an example (73). Experience has shown that two traps may be unnecessary. More use is being made of single trap systems, sometimes with a bypass provision in case of failure to regenerate and consequent excessive plugging of the filter. The Deutz system is a good example (82). Deutz initially used a bypass muffler to protect against trap plugging, but identified a number of disadvantages, including control valve reliability and overall system size. These led the company to abandon the bypass and improve the reliability of the basic trap and burner. The result was a compact and simple single trap system which has been under test since 1988. The tests have been successful and the German Ministry of the Environment plans to equip 1 500 buses in a large scale field test program.

Trap Control Systems

The particulate trap control system must initiate the regeneration process and ensure that it is continued until the filter is clean enough for the next cycle of use. Detail functions may include switching traps in a dual system, starting and modulating a diesel fuel or electric heater, or throttling exhaust gases in a passive regeneration system.

Most systems use exhaust back pressure as the primary signal for regeneration. Engine overheating and damage can result if the filter is allowed to overload. Filter temperature and exhaust temperature signals are used to modulate carbon burning, maintaining the trap hot enough for complete combustion but cool enough for safety and reliability. Uncontrolled engine or filter temperature rise will shut down the engine and/or the burner. An engine speed signal is required because different back pressures are acceptable at different engine speeds. It is desirable to operate at the highest allowable back pressure levels because filter efficiency increases with back pressure.

Regeneration may be on a timed schedule if the engine duty cycle is predictable. The Volvo daily regeneration system is perhaps the extreme example of this philosophy. General Motors (78) and FEV (79) have used algorithms of fuel flow and engine speed to compute engine loading and hence particulate generation rate, which is then used to predict regeneration requirements.

Exhaust Catalysts

Catalytic treatment of diesel exhaust is being explored for two purposes. The first is to allow regeneration of a particulate trap filter at lower temperatures, so reducing the chance of thermal damage. The second is to oxidize CO and HC emissions. The catalyst may be introduced as a coating on the filter, or an additive in the fuel. Mitsubishi Motors Corporation used a platinum catalyst-coated filter for tests in a truck powered by a 6.5-litre engine (75). The passive mode of regeneration was effective with adequate exhaust heating, but Mitsubishi concluded that a truck or bus in normal service would not generate enough heat to ensure consistent total regeneration. This would result in an incremental plugging of the filter and a corresponding deterioration of vehicle performance.

The city of Athens has 120 buses equipped with trap systems designed by the Aristotle University of Thessaloniki. Fifty to 100 ppm of cerium naphthanate ($Ce\ 0_2$) is added to the diesel fuel to allow regeneration at temperatures between 500°C and 600°C. Another 100 buses are to be equipped with the same type of system (74).

Catalysts to reduce CO and HC emissions are also used in a bus operated by the New York City Transit Authority, equipped with a dual-trap system developed by ORTECH International. Two 11.25 X 12 in. Corning filters are used, coated with a catalyst formulated by Engelhard Corporation. Diesel burners are used for regeneration, which takes place in alternating traps. The overall particulate reduction efficiency is stated to be 80%, and the catalyst coating results in 60% CO reduction and 50% HC reduction. Low sulphur (less than 0.05%) diesel fuel is used (73).

E. DIESEL FUEL REFORMULATION

Diesel reformulation concerns sulphur content, aromatics content and cetane number. Sulphur and aromatics contents must be reduced in order to cut emissions. Cetane number, the index of auto-ignition quality, must be maintained at or above a certain level in order to allow reliable ignition, which in turn affects emissions output.

Sulphur Content

Sulphur cannot be made harmless by improved combustion or catalytic action, and must be removed at source. It contributes to the particulate emissions count of an engine, and also effectively prevents use of a catalyst to clean up other emissions. Use of a catalyst with normal diesel fuel can lead to an increase in particulate emissions due to catalytic oxidation of sulphur compounds. In time, the sulphur also poisons the catalyst and reduces the efficiency of CO and HC conversion. The EPA promoted legislation which was passed last summer, mandating low sulphur diesel for road vehicles in the U.S. by 1994. Canada expects to enforce a similar law.

It is now more or less generally accepted that the 0.05% sulphur, 40 cetane fuel will become standard, and engine manufacturers all predict future performances based on this premise.

Aromatic Hydrocarbons Content

Aromatic hydrocarbons in diesel oil affect cetane number (80), emissions of CO and HC and, to a lesser extent, NO_X (81). Typical current diesel fuels contain 25% to 35% of aromatics. South Coast Air Quality Management District (SCAQMD) requires a maximum of 10% aromatics content in diesel sold in the Los Angeles area. There are suggestions that this standard should be enforced across the U.S. The refinery process required to reduce aromatics to this level calls for very high pressures and temperatures, and consequently extremely costly equipment. EPA has not yet elected to restrict aromatics content in the U.S. It is questionable whether aromatics reduction would be justifiable on a cost/benefit basis. The specification of a minimum cetane number effectively prevents increase of aromatics content above current levels.

Cetane Number

Cetane number ratings of diesel fuels in the U.S. and Canada have fallen steadily over the last ten years, due to a lessening of demand for heavy fuel oils, an increase in demand for diesel fuels, and an overall decrease in the quality of crude oil supply. There is general agreement that modern engines cannot tolerate cetane ratings of less than 40 without noticeable effects on combustion. The 40 level can be maintained without much difficulty by suitable adjustment of refinery processes.

Diesel Fuel Supply Implications

Supplies of diesel fuels will not be affected if specification changes are phased in with sufficient lead time to allow necessary refinery plant adjustments. Modern refining technology allows considerable flexibility in the processing of crude stock. However, a sudden demand for low aromatic diesel would cause difficulty because use of a significant percentage of middle distillate stock would be ruled out. Depending upon the refinery, diesel production capacity could be cut by 10% to 25%. Installation of a suitable plant to redress this capacity imbalance would take 3 to 5 years, and the cost would be very high.

An increase in desulphurization capacity will be required to circulate sufficient quantities of low-sulphur fuel, and it is probable that a number of smaller refineries which are unable to afford the associated costs will be forced to close. The oil industry is most concerned about the lowering of aromatic content. The high pressure hydro-treatment facilities necessary for production of low aromatic diesel can also be used for low sulphur fuel. The reverse is not true. A particularly wasteful and disruptive situation would occur if a decision to legislate low aromatic fuel were taken after heavy investments had been made in new desulphurization capacity, which would instantly be rendered obsolete.

V THE IMPACT OF FUEL SUBSTITUTION

A. BACKGROUND

To meet new emissions standards, several technologies have been proposed. These include diesel engines with particulate traps, and alternative fuels such as methanol and natural gas. Recent emphasis by engine manufacturers centers on producing an engine that qualifies from an emissions perspective, achieves the durability of current diesel technology (measured as mean distance between failures), and is comparable to current diesel engines with respect to operating cost (with the exception of fuel costs).

To examine the net impact of these different technologies, a model was built with the aim of comparing on-road emissions contributions in terms of emissions output per distance (gm/km). The model examines a fleet of replacement urban transit buses in a Canadian city. Four options are available to the fleet:

- replace with a current technology diesel engine, i.e. status quo;
- replace with a current technology diesel plus particulate trap;
- replace with a methanol engine;
- replace with a natural gas engine.

The model and ensuing discussion center around the net impact on emissions for each option. Some of the logistical and operational problems associated with the different options are identified and summarized. The analysis does not examine the contentious issue of when different technologies will be available for commercialization. Rather it is a straightforward examination based on currently available data and a number of assumptions. Urban transit buses were examined because of imminent U.S. regulations and since their operation is within a defined zone. Under these conditions, urban transit buses are more likely to be offered with alternative fuel engines.

Exhibit V-1 summarizes the engines examined in this analysis. Specific engines were selected to establish an emissions profile and to compare different technologies. For a specific engine to be selected, a number of criteria had to be satisfied, including:

- engine presently, or at some point in the recent past, had to have been under consideration as an urban transit bus engine;

- basic engine emissions and fuel consumption data are available in the public domain;

- the engine carries a heavy-duty rating.

Exhibit V-1. Potential Transit Bus Engines

Fuel Type	Engine	Notes
Diesel	DDC 6V71N	baseline Canadian transit bus engine
	DDC 6V92TA	emissions certified Canadian engine (Dec. 1988) to replace the 6V71N
	DDC 6V92TA	with particulate trap
Methanol	DDC 6V92TA	Proposed "production" unit
Natural Gas	Cummins L10	Generation I Technology, e.g. Toronto Transit

Assumptions include:

Diesel Engines: The predominant engine used in Canadian transit buses is the DDC 6V71N engine. With new Canadian emissions rules in place as of December 1, 1988, the DDC replacement engine is the model 6V92TA.

Particulate Trap: It is assumed that a viable particulate trap is commercially available for the 6V92TA engine. Furthermore, the particulate trap medium would be treated with a catalyst to achieve reductions in gaseous emissions too. In addition, the durability of the trap is at least 464 700 km (290 000 miles), the U.S. certification standard. Traps would be employed on a DDC 6V92TA engine with low sulphur fuel.

Methanol Engines: The proposed "production" catalyst-equipped engine is profiled. This is the methanol engine that DDC intends to market in 1991. This engine version offers the lowest possible emissions from a methanol engine. DDC is the pre-eminent supplier of transit bus engines in North America. DDC methanol engines have been undergoing field trials in various demonstration programs throughout North America. The proposed "production" version is the latest version of DDC's methanol engine. The version features refinements including idling on 3 cylinders, an increased compression ratio, an improved turbo match, a new exhaust cam profile and a catalyst aimed at even greater reductions in regulated exhaust emissions and improved fuel efficiency. Eventually, DDC will offer two approaches with catalysts: at one extreme, the catalyst will be optimized towards CO emissions reductions, while at the other extreme, the catalyst will be optimized towards HC reductions. Thus prospective engine purchasers can select an engine build optimized to their particular environment. The methanol engine presented in this analysis is assumed to be commercialized.

Natural Gas Engine: A natural gas version of the Cummins L10 engine is featured. The Cummins L10 was selected since there have been efforts in recent years to develop a natural gas version of the L10 model and secondly, Cummins has been making significant inroads into the North American transit bus market. The natural gas L10 engine presented herein represents generation I technology, so named because this engine is employing first generation modifications that allow it to operate on compressed natural gas. The modifications include an Impco type gas mixer and spark ignition, similar to the set-up on Iveco engines once used by Hamilton Street Railway. Cummins L10 natural gas engines have entered service with the Toronto Transit Commission and Hamilton Street Railway. Already, a more advanced natural gas fuel system is under development; the new system, entitled generation II will feature electronic controls and direct cylinder injection of the gas. This system is still in the developmental stages and has yet to be field-tested. The engine is assumed to be equipped with a catalyst and offered commercially. Similar to DDC, Cummins has announced its intention to market a natural-gas-powered L10 engine in the U.S., starting in 1991.

B. REGULATED EMISSIONS

Engine dynamometer emissions data were assembled from published reports. To predict the emissions impact of each engine, on a weight per distance basis [gm/km], the EPA emissions factor (EF) procedure was utilized (37). The emissions factor is computed as follows:

$$EF = \frac{\text{Fuel density}}{SFC * VFC} \qquad \frac{\{kW.h\}}{\{km\}}$$

where: SFC = specific fuel consumption {g/kW.h}
VFC = vehicle fuel consumption {km/l}
Fuel density {g/l}

On-road emissions are then predicted as:

Emissions = EF * (engine dynamometer emissions)

An emissions factor considers on-road fuel consumption and thus permits engine dynamometer data to be scaled to account for the driving habits of a particular fleet. Since back-to-back chassis dynamometer emissions results are unavailable for all scenarios, the use of EFs allows more equal treatment of all options. Emissions results are presented on a weight per distance basis to equalize the power rating differences between the engines (e.g. 6V71N @ 140 kw, and 6V92TA @ 207 kw) and to present data in a format that has a more immediate and recognizable impact. While the results presented are not an absolute indication of emissions, they will give an indication of relative differences between power plants. One weakness with such a comparison is the effect of changing an engine rating. This will impact cycle loads over the transient procedure and in turn, overall brake specific emissions and on-road fuel consumption. Under this analysis it is assumed that the fleet will accept a particular engine. However, in reality, the current trend in Canadian transit bus engines is towards increasing power, up from the nominal 150 kw rating of the 6V71N.

On-road fuel consumption data is available on most Canadian fleets from published Canadian Urban Transit Association (CUTA) data. For the most part, this data derives from a fleet operation with 6V71N engines. As illustrated in Exhibit V-2, fuel consumption varies considerably between the various cities. For the purposes of this analysis, a base city was selected so that on-road fuel consumption data for the various alternatives could be scaled to represent fleet-wide average fuel consumption. In the example to follow, city of Vancouver data was selected for the diesel base case (6V71N engine). On-road methanol and diesel (6V92TA) fuel consumption data for Vancouver was then predicted by comparing the percentage difference in engine SFC of methanol and diesel 6V92TAs with engine SFC for the 6V71A. The percentage difference was used to scale up the on-road 6V71NA engine results. Natural gas engine vehicle fuel consumption results were predicted by adjusting in-use L10 fuel consumption figures obtained from Toronto Transit by the percentage difference between Vancouver and Toronto diesel fuel consumption figures. Exhibit V-3 summarizes the vehicle fuel consumption results used. A fuel consumption penalty of 6% was imposed on the particulate trap equipped engine.

Exhibit V-2. Canadian Transit Bus Fuel Consumption (1986)

City	Litres/100 km
Vancouver	50.99
Edmonton	55.95
Hamilton	59.32
Toronto	54.72
Montréal	63.44
Average	56.88

Note: Figures represent total diesel fuel consumed divided by total fleet kilometers

Exhibit V-3. Predicted Fuel Consumption By Engine Type (Vancouver)

Engine	Fuel Consumption
Diesel DDC 6V71N	51.0 L/100 km
6V92TA	47.8
6V92TA w/particulate trap	50.9
Methanol 6V92TA	107.5
Natural Gas	66.8 m^3/100 km

The emissions calculations only considered engine exhaust emissions. Neither crankcase or evaporative HC emissions were considered. Data for engine exhaust HCs represent total HCs. There has been much debate between stakeholders regarding the optimum method to present HC emissions results, especially from alternate fuel engines. Much of the debate is centered on accurately reporting the reactivity or net impact of emissions products. The U.S. EPA, as described in Chapter III, has taken an initiative with methanol-fuelled engines. The primary HC emissions component from natural gas engines is methane. Methane, while being photochemically inert, is a greenhouse gas.

The particulate trap was assumed to be 80% efficient in reducing particulate emissions. Recent developments in particulate trap designs also show that they are capable of reducing regulated exhaust gas species. Gaseous emissions of HC, CO and NOx are assumed to be reduced by 40%, 70% and 25% respectively (73). There was a net fuel consumption penalty of 6% (45, 46, 47). No provision was made for emissions during trap regeneration.

On-road emissions were predicted using the emissions factors and emissions profiles. The engine dynamometer test emissions results, and predicted on-road emissions profiles are presented in Exhibits V-4 to V-7, and Exhibits V-8 to V-11 respectively.

A switch to alternate fuels or the addition of a particulate trap and low sulphur diesel fuel can result in a significant reduction of baseline regulated emissions. In the example illustrated in this section, all 3 engines, i.e., the "production" methanol, natural gas and the particulate trap-equipped diesel engine will meet the 1991 U.S. emissions standards (Exhibits V-4 to V-7). The addition of a particulate trap and low sulphur fuel in a diesel engine results in an emissions profile comparable to the alternate fuel engines (Exhibits V-4 to V-11).

In the example depicted, the methanol engine produces the lowest overall emissions. Most of this benefit is derived through the use of a catalytic converter. The results in Exhibits V-4 to V-11 give an indication of the feasibility.of emissions reduction using an alternate fuel or a particulate trap-equipped engine. If alternate fuel engines are to gain acceptance, they must demonstrate an overall reduction in emissions and not merely trade off emissions reductions of one species for another. Furthermore, engine manufacturers will have to solidify the emissions reductions that alternate fuel engines achieve with long term engine durability and economical operating costs over the life of the engine/vehicle.

With strict emissions regulations looming in the U.S., manufacturers are working on developing a certifiable engine. At this writing, only DDC has publicly announced its intention to offer a methanol engine for model year 1991.

Exhibit V-4. Comparative Hydrocarbon (HC) Emissions

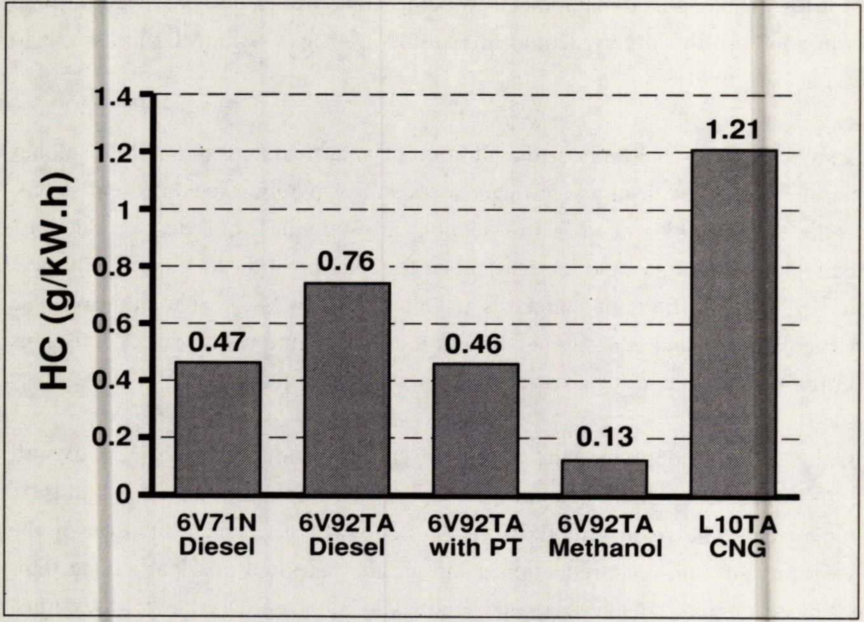


Exhibit V-5. Comparative Carbon Monoxide (CO) Emissions

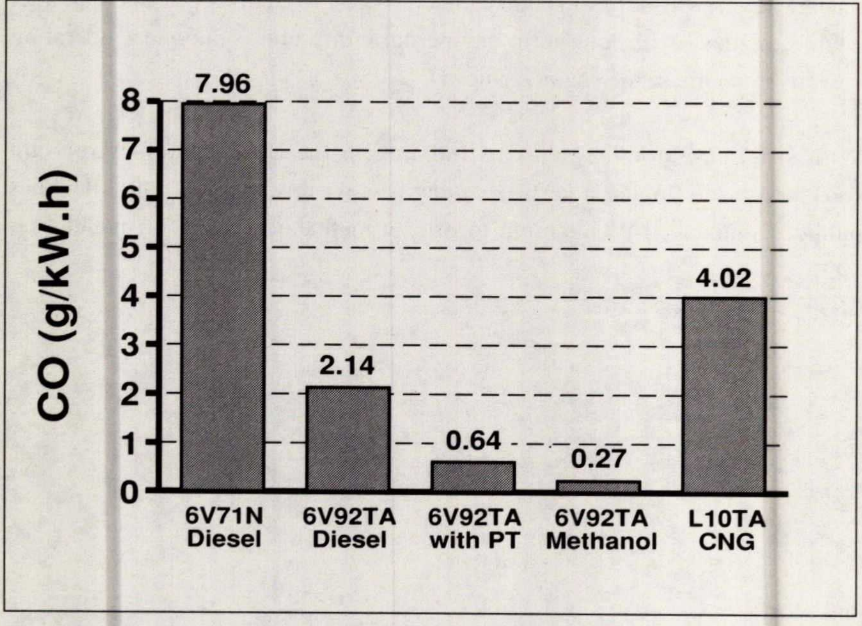


Exhibit V-6. Comparative Nitrogen Oxide (NO_x) Emissions

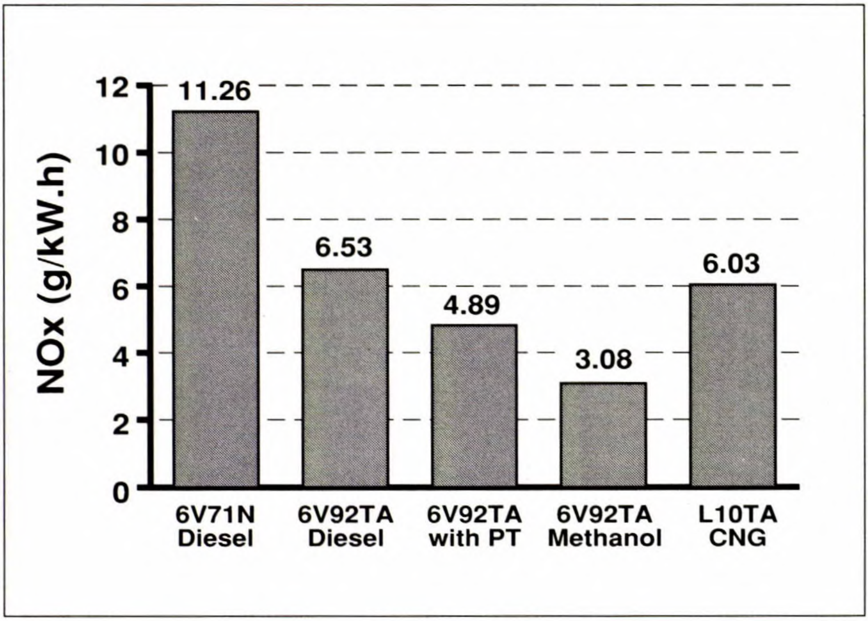


Exhibit V-7. Comparative Particulate Emissions

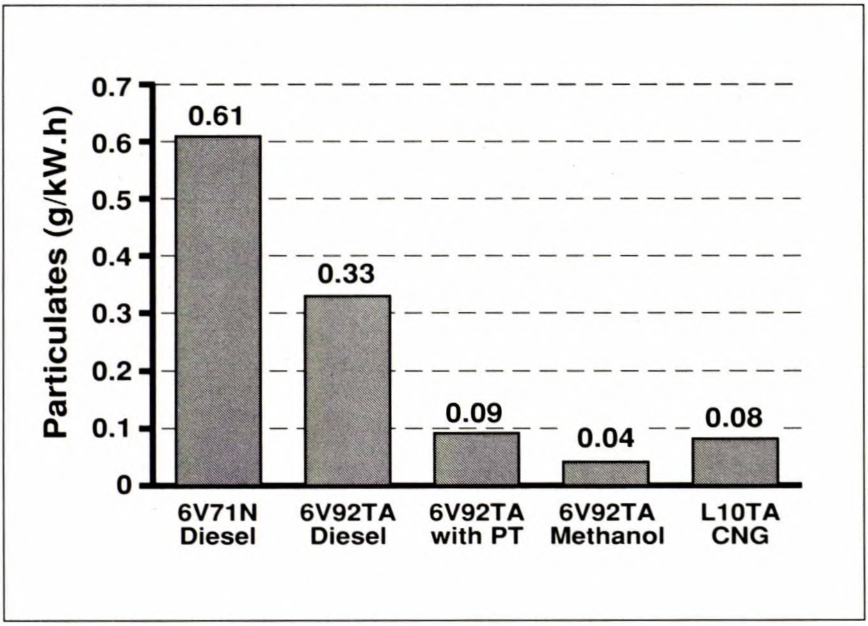


Exhibit V-8. Predicted Hydrocarbon (HC) Emissions

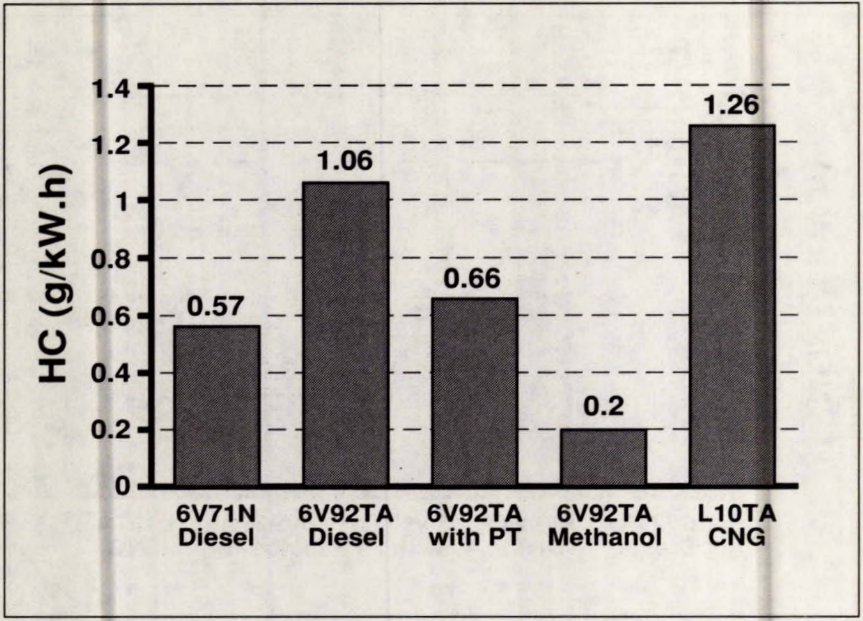


Exhibit V-9. Predicted Carbon Monoxide (CO) Emissions

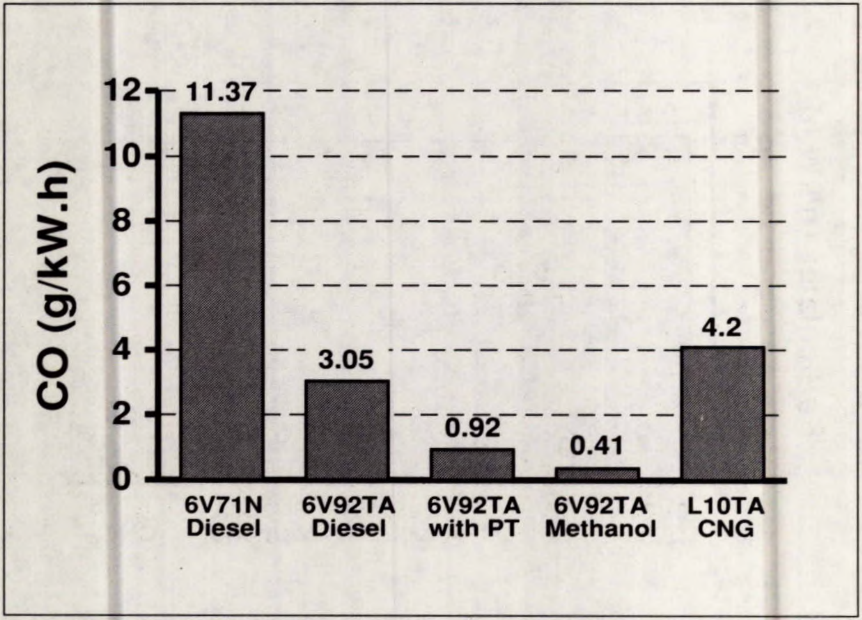


Exhibit V-10. Predicted Nitrogen Oxide (NO_x) Emissions

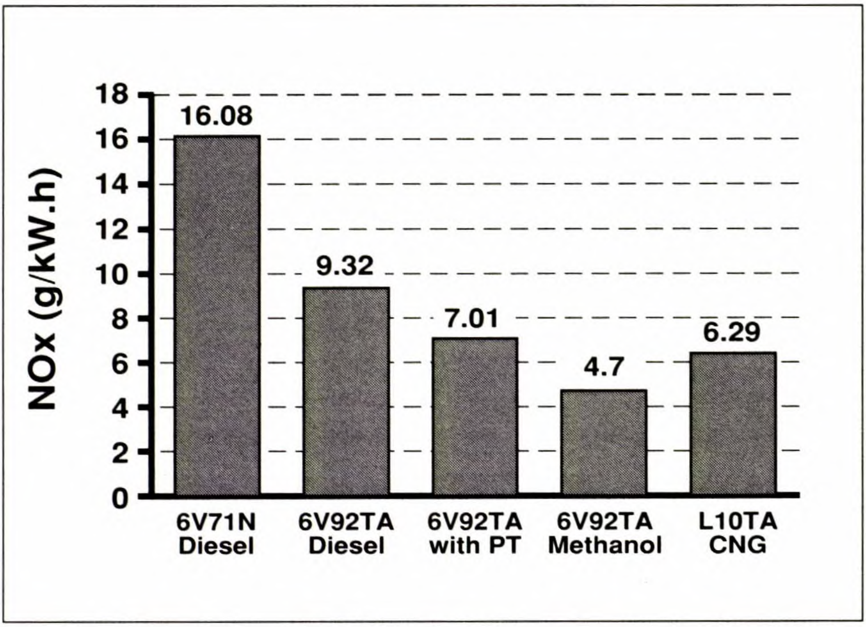
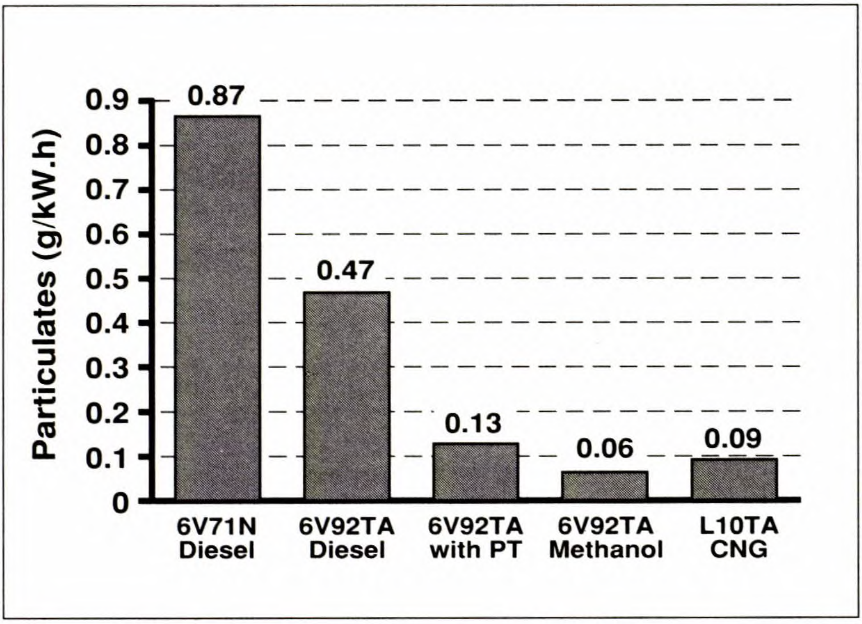


Exhibit V-11. Predicted Particulate Emissions



C. CARBON DIOXIDE PRODUCTION

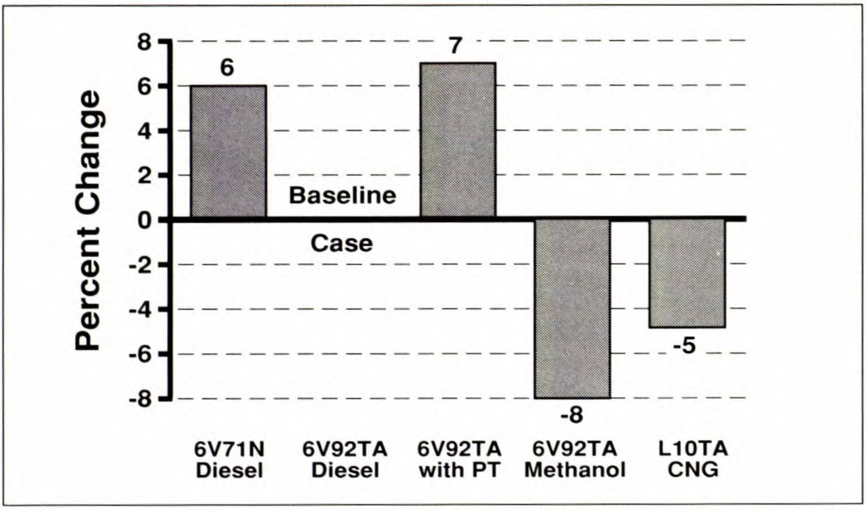
Over the past few years, there has been a great deal of concern expressed in the news media with regard to carbon dioxide and its effect on global warming. Carbon dioxide is the fourth most common gas in the atmosphere.

The primary sources of CO_2 are non anthropogenic. The proportion of man-made CO_2 emissions amounts to approximately 2% in global terms (52). Unlike the emittants previously discussed, which tend to be a local or regional problem, a change in ambient CO_2 concentrations has global ramifications. Increases in atmospheric CO_2 content will have a disruptive effect on the entire global biosphere.

Anthropogenic emissions of CO_2 are the result of combustion of carbon-containing substances. Carbon dioxide emissions from motor vehicles are unregulated. One potential mechanism to regulate CO_2 levels would be through the use of a maximum fuel consumption limit. This mechanism has been employed with light-duty vehicles. By and large, the market place is self-regulating, particularly in heavy-duty engine operations where owners are concerned about their operating costs. Reduced fuel consumption will translate into reduced operating costs.

CO_2 emissions are proportional to the carbon content of the fuel. Tailpipe CO_2 emissions of the five previously discussed engines were compared to the baseline diesel 6V92TA. The relative CO_2 emissions, presented in Exhibit V-12, were derived on the basis of a simplified balance of the carbon-containing constituents; i.e. fuel, as either $C_{11}H_{19}$ (diesel) (53), CH_3OH (methanol) or CH_4 (natural gas) less hydrocarbons produced (assumed as the fuel), carbon monoxide (CO) and particulate carbon. The results illustrate that CO_2 emissions are proportional to fuel consumption and carbon content of the fuel. In the case of diesel fuel, the particulate trap-equipped engine shows a 7% increase in CO_2, attributable to increased fuel consumption. The lower carbon content of methanol and natural gas, at one carbon atom per fuel molecule, shows that reduced carbon dioxide output is possible. Even without the simplification used here, CO and particulates are rather minor carbon-containing constituents in exhaust gas. Total CO_2 output is thus a function of fuel consumed and the conversion rate of carbon to other carbon-containing species.

Exhibit V-12. Predicted Change in Engine-out Carbon Dioxide (CO_2) Emissions



While CO_2 emissions have been associated with the greenhouse effect, it would be prudent to conduct a thorough audit of greenhouse gas production for any contemplated fuel. The audit would then include a summary of **all** important greenhouse gases produced, from fuel extraction and processing through distribution and eventually combustion in an engine. Some important greenhouse gases to consider in addition to CO_2 are methane (CH_4), chlorofluorocarbons (CFCs) and nitrous oxide (N_2O). Although CO_2 is the predominate vehicle exhaust gas, estimates of the greenhouse effect of CH_4, CFC 12 and N_2O on a per molecule basis, compared to CO_2, range from 5.8 to 42.3, 10 000 to 44 449 and 286 to 449 times respectively (53).

D. OTHER CONSIDERATIONS

The results discussed in this chapter present the potential emissions benefits that can be gained with an alternative fuel. Before a final decision on engine technology (either particulate trap, methanol or natural gas) can be taken for a fleet, a full examination of the cost associated with either alternative fuel will be required. Among the issues that will require examination are the current fleet infrastructure, vehicle range and payload capacity.

A major expense for either alternative fuel will be the modification or construction of fleet facilities. This will include fuel pumps and, because of safety concerns with methanol and natural gas compared to diesel, ventilation equipment, fire suppression equipment and electrical componentry rated for explosive and flammable areas. One recent study conducted for a U.S. transit facility, estimated the total costs to re-engineer their facility at $2.5M for methanol and $4.65M for natural gas (54). These costs represented a site specific estimate for a 150 bus garage. Costs will be site specific and influenced by municipal, provincial/state and federal regulations.

Fleet operation will be impacted by vehicle range and payload capacity. Methanol being a liquid fuel, can be easily handled by conventional fuel handling methods. The fuel tank volume will have to be doubled to accommodate vehicle range compared to diesel. Consideration will also have to be given to ensure material compatibility. Compressed natural gas requires pressurized storage vessels which can limit available cargo volume and pose a severe weight penalty on the vehicle. The issue of a weight penalty has been overlooked in much of the literature promoting natural gas. If vehicle operation is to proceed within maximum allowable axle loads, then weight penalties associated with alternative fuels, in particular natural gas, can only be overcome by augmenting the fleet size (or by developing buses with an additional axle) which imposes an additional cost.

VI CONCLUSIONS

1. There is great variation in the approaches used to regulate engine and vehicle exhaust emissions. Exhaust emissions regulations are a method of exercising sovereignty and therefore it is unlikely that a standardized regulatory approach will be used in the near future.

2. Exhaust emissions levels are measured either for regulatory purposes or for scientific knowledge. However, emissions testing is primarily directed at achieving regulated levels which limits opportunities for a free international scientific exchange of emissions data.

3. The establishment of a common exhaust emissions test would accelerate the scientific exchange of data and possibly permit improved engine technologies aimed at reducing exhaust emissions to be brought to the market sooner.

4. From an exhaust emissions perspective, methanol-fuelled heavy-duty engines offer promise to engine manufacturers seeking to meet future emissions standards (U.S. 1991 and 1994).

5. Only the U.S. Federal Government and the state of California have addressed methanol-powered engines within their regulatory framework.

6. The lack of an emissions standard for an "alternative" fuel creates an air of confusion. Manufacturers are reluctant to invest heavily in engine development until they are aware of the ground rules.

7. Prototype advanced diesel engines can meet 1994 emissions standards. Manufacturers are optimistic that production engines will be available by 1994.

8. Particulate traps may be used to cut particulate emissions by approximately 80% on any diesel engine, and will allow the use of catalytic treatment to reduce CO and HC emissions.

9. Engine manufacturers will have to establish long-term engine durability comparable to the diesel if alternate fuel engines or advanced technology diesel engines are to succeed in the market place.

10. Reductions in carbon dioxide emissions can be achieved either through a decrease in fuel consumption or a switch in fuel type.

11. Both methanol and natural gas offer reductions in carbon dioxide emissions compared to diesel fuel.

12. When evaluating the net environmental impact of different alternate fuels, a thorough energy and emissions audit is required. The audit would identify the net impact due to the use of an alternate fuel, including factors such as fuel extraction, processing, distribution and combustion.

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APPENDIX

STANDARDIZED EMISSIONS RESEARCH CYCLE

A. INTRODUCTION

Advancing towards a standardized emissions research cycle will bridge a major gap among engine researchers worldwide. While regulatory test procedures will remain in effect in most individual jurisdictions, a standardized international test cycle will permit researchers to freely exchange emissions results and permit rapid comparisons amongst different methanol engine technologies.

The following discussion will identify the basic concerns that must be addressed if researchers are to agree on a common research cycle, and make recommendations for their resolution. Once a framework for a test cycle has been established, the discussion will focus on a recommended test cycle and the reasons for its acceptance.

B. DESIGN CONSIDERATIONS

A common research cycle will consist of three major components:

- engine or chassis dynamometer procedure;
- type of test cycle (steady state or transient);
- method of sample collection and measurement.

From a developmental perspective, an engine-based procedure is the most logical choice since engine-based testing will enable the greatest latitude when selecting and modifying engines to be tested. Chassis dynamometer testing is not normally applied to the heavy duty category of engines because of the wide latitude in vehicle builds, the cost of facilities and the lack of available data that permits a correlation to engine dynamometer test results (1).

As emissions regulations become more stringent, engine performance will become more sensitive to changes in operating conditions. The results of moving from steady state conditions to transient test conditions have been summarized (3). While a steady state test may be relatively simple to perform, offer basic engine performance data and require less costly equipment, a transient test cycle offers the following distinct advantages (2, 3, 4):

- the ability to examine transients during acceleration and deceleration, in particular to examine the effect of increasing fuel supplied to the engine;

- a better representation of real world engine operation;

- the ability to consider the effect of engine warm-up.

However, a transient cycle is indicative of a specific type of engine operation and not all engine operations. Also the cost of emissions sampling equipment and a control system to conduct a transient test have been the major drawback to its acceptance, particularly in light of the U.S. EPA regulatory approach which includes conditions of engine motoring*.

Another equally important motivating reason to select a transient style test cycle, as opposed to a steady state cycle, is the effect that methanol fuel has on regulated gaseous emissions as compared to diesel. Total HC**, CO and particulate levels tend to be sensitive to air-fuel ratio and methanol-fuelled heavy-duty engines tend to produce increased levels of total HC and CO compared to the baseline diesel. Transient testing can help induce periods when the air-fuel ratio is too rich or lean and thus aid researchers by highlighting any potential deficiencies with a specific engine.

In addition to the need to address a test cycle, the research cycle must seek a consensus on emissions sampling, measurement and reporting techniques. At the present time, as reported in section II, there appears to be a fairly uniform convergence towards the measurement technique of regulated gaseous emissions. Since the ultimate goal of methanol engine research will be towards a greater dissemination of emissions data, standard measurement techniques for all the measured emissions must be adopted. The gaps that must be bridged are:

- sampling method;

- issue of particulates/smoke;

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* Engine motoring being defined as work being done on the engine, as in the case of coasting or braking.

** Total HC being the sum of non-oxygenated and oxygenated HC plus aldehydes.

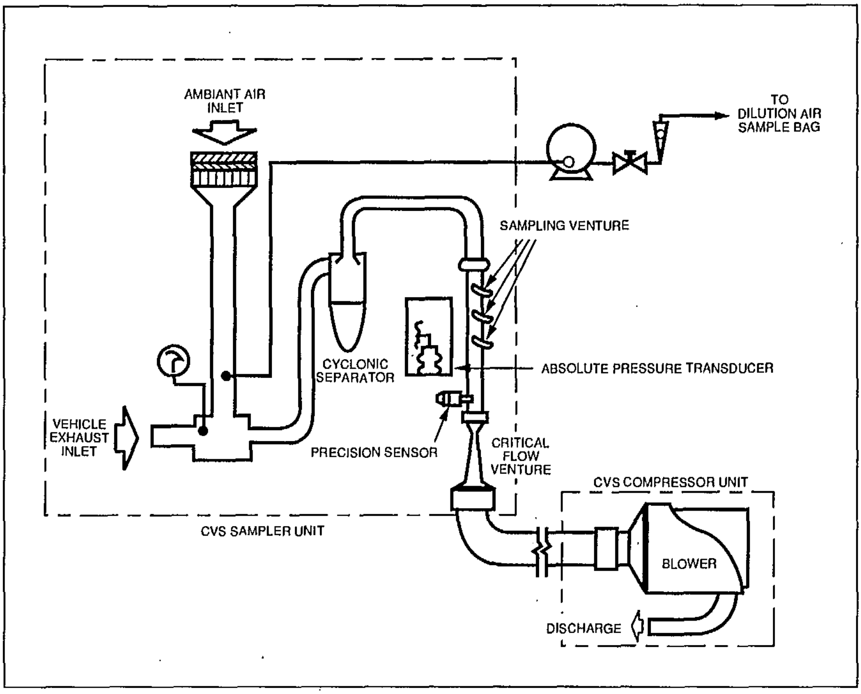
- measurement of HC levels;

- reporting of the final results.

The sampling of exhaust gas from an engine undergoing transient operation involves a more elaborate procedure than steady state sample collection. To sample the varying volume of exhaust gas being produced at any instant, over the course of a transient cycle, the constant volume sampling (CVS) technique has been developed. A CVS system, illustrated in Exhibit 1, mixes a continuously variable amount of ambient air with raw exhaust to produce a constant flow rate of diluted exhaust gas for sampling. The technology for CVS sampling is well developed and has been used in the U.S.A. for all engines and in Europe and Japan for automobiles and light-duty vehicles for years. Not all facilities may be equipped to handle the greater volume of exhaust gas generated by a heavy-duty engine. In the case of steady state emissions sampling, the exhaust sampling equipment does not have to be as sophisticated since one is sampling the exhaust at a set of well-defined discrete points.

Methanol produces very low particulate emissions compared to diesels. At the present time, particulate emissions are only regulated in Canada and the U.S.A. Europe and Japan have focussed on smoke and measured its opacity. The creation of a transient research cycle for methanol engines should not preclude adoption of particulate measurement. Smoke measurements are relatively simple to perform at steady state points or over a prescribed acceleration. However they fail to report the mass and make-up of the solid material contained within the exhaust. Particulates are made up of soot, soluble organic fraction (SOF) and oxides (6). Although methanol engines produce a significantly reduced quantity of particulates in the exhaust, particulate measurements will still permit researchers to record the mass content of filterable solids in the exhaust and to examine their composition.

Exhibit 1. A Constant Volume Sampling (CVS) System (5)



Particulate measurement is of critical concern to those who wish to sell in the U.S.A. because of the impending phase-in of future emissions regulations. With reduced particulate emissions, combustion chamber design and engine oil control will be featured more prominently in future designs as engine manufacturers strive to reduce particulate emissions even further (6).

Unlike their diesel counterparts, methanol heavy-duty engines produce oxygenated HCs in addition to the non-oxygenated species and aldehydes. It is extremely important that all three hydrocarbon levels be measured and identified. There has been concern expressed over the reactivity of certain HC species. The present technique employed to record HCs from a diesel engine, using an HFID, will not accurately record unburned fuel (oxygenated HC) or aldehyde levels in the exhaust (7). A technique such as 2,4 Dinitrophenylhydrazine (DNPH) coated cartridges has been used to successfully collect aldehyde samples (8). EPA proposed modifications to existing emissions standards and test procedures to incorporate the use of 2,4

DNPH cartridges to collect exhaust gas aldehydes. Similarly, distilled water impingers have been used to collect the unburned fuel (methanol) contained in the exhaust.

The method of reporting final test results is extremely important if researchers are to make back-to-back comparisons of test results. Presenting three HC values, HFID results for non-oxygenated hydrocarbons corrected for unburned fuel, oxygenated hydrocarbons, and aldehydes will permit researchers to make these comparisons and form their own opinions.

C. TEST CYCLE

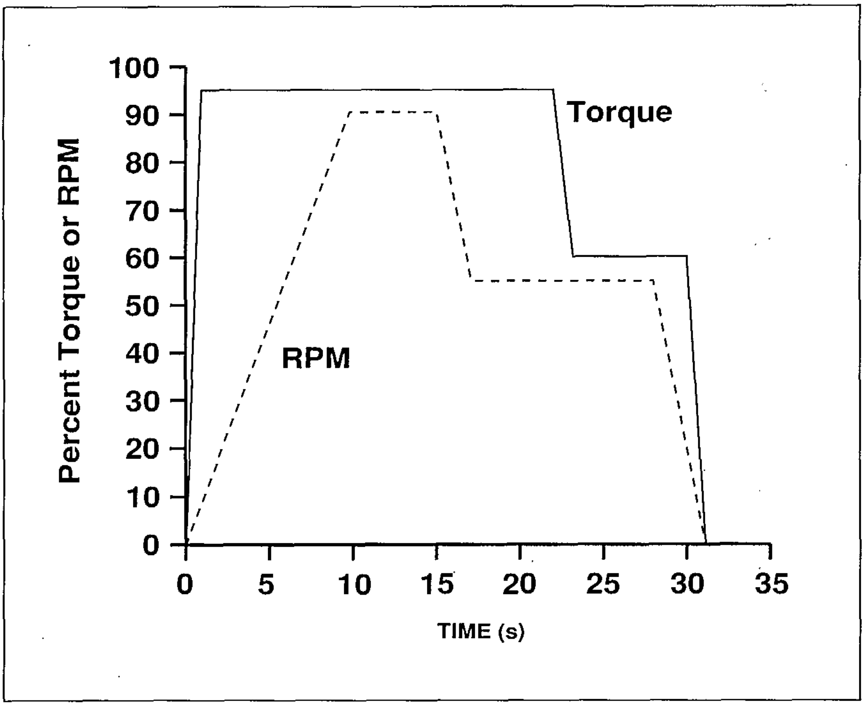
The preceding section dealt with many of the intricacies involved when developing an emissions test cycle. Therefore, any cycle that is to become universally accepted by those interested in methanol engines, must involve relatively common and accepted techniques, particularly given the propensity of most people to report results based on one of the regulatory techniques.

To bridge the perceived gap, in terms of test cycles, a research oriented emissions cycle, depicted in Exhibit 2, is proposed by SYPHER:MUELLER International Inc.

The cycle is geared towards engine testing, with its main features being:

- smooth accelerations/decelerations;
- rapid accelerations/decelerations;
- normalized engine RPM and torque loads;
- no motoring;
- bias towards urban operation.

Exhibit 2. Proposed SYPHER Methanol Engine Emissions Research Cycle
Single Segment



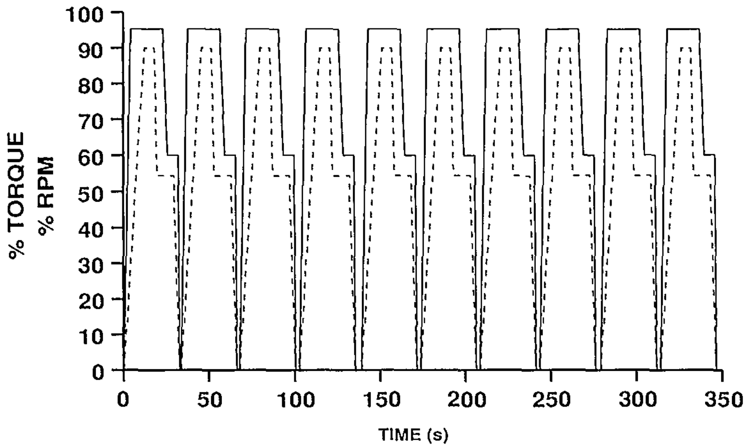
% RPM = (Actual RPM - Idle RPM)/(Rated RPM - Idle RPM) * 100
% Torque = Actual Torque/(Max Torque at Actual RPM) * 100

In the proposed cycle, torque and speed levels were determined based on an examination of current regulations, literature and conversations with various industry sources (2, 3, 9, 10, 4, 11). Thus the cycle shares some similarities with the central business district (CBD) chassis dynamometer cycle. The actual loading over the test cycle is presented in terms of a normalized engine speed, RPM, and torque, T. These conventions were adopted from widely practised procedures including U.S. federal test procedures.

The use of normalized torque and engine speed readings permits the greatest latitude of engine ratings to be fairly compared on a brake specific basis. A rigid selection of power and speed settings would enable a comparison of all engines to be made based on equal work performed over the cycle. However this would unfairly penalize some engines since some of the operating points dictated by the cycle may not be achievable or be too far off from the ideal operating point of the engine.

An entire emissions test would be conducted over ten repetitions of the cycle (Exhibit 3). Ten repetitions would enable users to gauge overall engine emissions under repeated acceleration. The test cycle would commence after the engine was started up and the idle speed allowed to stabilize. The engine could be left to idle for 30 to 60 seconds to simulate the driver allowing vehicle air pressure, for example, to be built up. Testing would then commence. A number of choices are available when deciding upon hot or cold engine tests. Ideally two tests could be used; the first run simulating a cold start and the second run a subsequent hot test after a fully warmed up engine had been allowed to sit for 10 minutes. A cold test represents the reality of having to start the vehicle. For practical purposes, the cold temperature would have to be at room temperature since low temperature start-ups may be beyond the operational range of some of the engines, unfeasible due to facility constraints or not representative of operating temperatures in some countries. Since the cycle is from a research perspective, both hot and cold start data, and not a weighted average, should be presented.

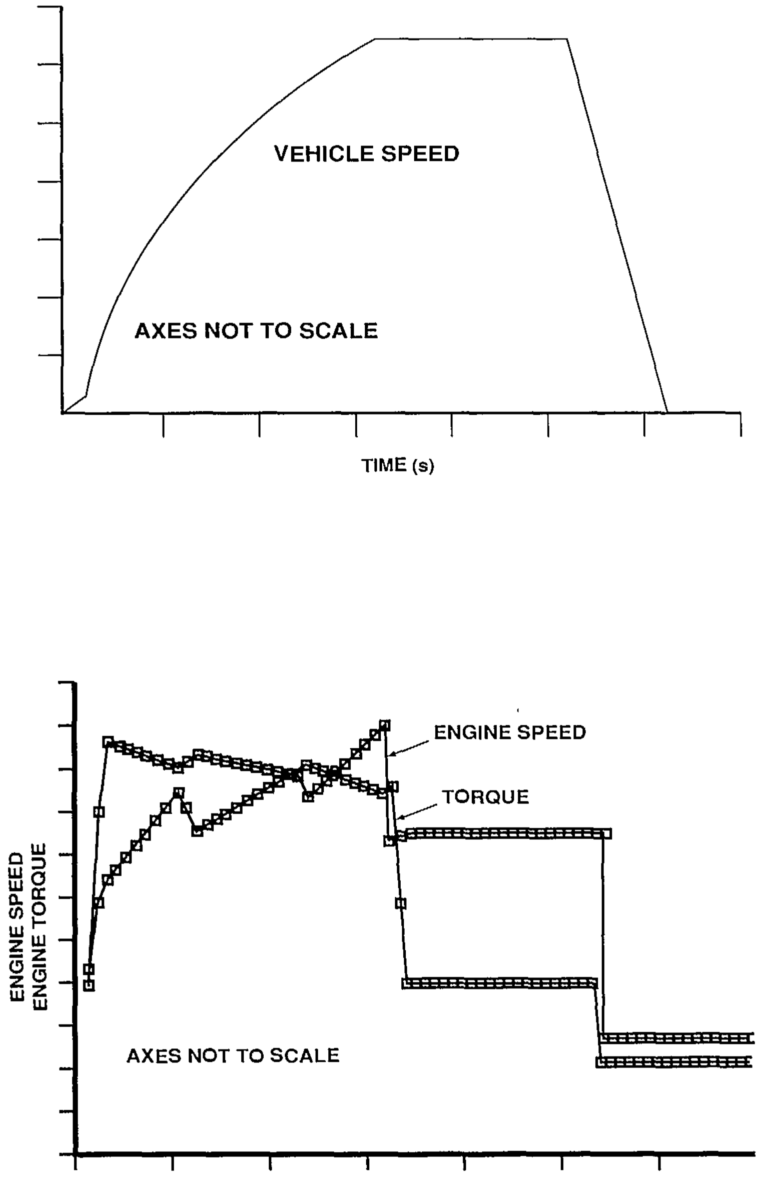
Exhibit 3. Proposed SYPHER Methanol Engine Emissions Research Cycle - Multi Segment



A transient cycle is meant to simulate a particular type of engine operation. For the SYPHER cycle, smooth loading/unloading ramps were chosen since these are easy to replicate. More importantly, a rather jagged RPM or load profile with many spikes tends to give the impression of a specific type of operation. The EPA transient cycle is a well-known example. These types of cycles contain rather sharp and sudden changes in engine speed and load representing the many nuances of actual operation. Similar examples exist for chassis dynamometer cycles which present vehicle speed versus time. These cycles were developed by instrumenting motor vehicles, recording operating data and converting their typical operation into either a vehicle speed cycle or a pattern of engine speed and load conditions to simulate actual vehicle operation. While such a cycle may be more representative of real life operation, the introduction of yet "another cycle" is likely to generate a negative response, especially from users who believe that the prescribed cycle is not representative of the operation their product experiences. Criticism of a cycle is likely to be greater if people are requested to use yet another cycle that appears to be describing a very specific type of operation. At one time, Caterpillar Inc., in the U.S.A., had vigorously contested the EPA cycle and developed their own transient cycle which they believe is more indicative of how an engine is actually operated under highway and urban driving patterns. Similarly, the Motor Vehicle Manufacturers Association (MVMA) successfully contested the EPA heavy-duty gasoline engine test cycle and has subsequently promulgated its own transient cycle that is used for engine certification in all states except for California.

Like many of the other transient cycles in widespread use, the proposed cycle would utilize a rapid application of engine load, simulating the inertia required to accelerate a vehicle from a stationary position and get it moving up to a cruising speed. In reality, one would expect that as engine speed picked up and the vehicle began to move, less torque would be required. Consequently, depending on the engine, transmission, axle ratio and traffic conditions, there would be a gear change and the engine speed would begin to reclimb, with a corresponding drop in torque. This pattern would be repeated until the driver achieved a cruising speed which, under ideal conditions, would be a constant road and engine speed and torque. This scenario is depicted in Exhibit 4. The profiles presented in Exhibit 4, although derived from a specific scenario, can be considered representative of the idealized scenario described above: acceleration - cruise - coast down/brake cycle.

Exhibit 4. Idealized Acceleration and Drive Phase (9)



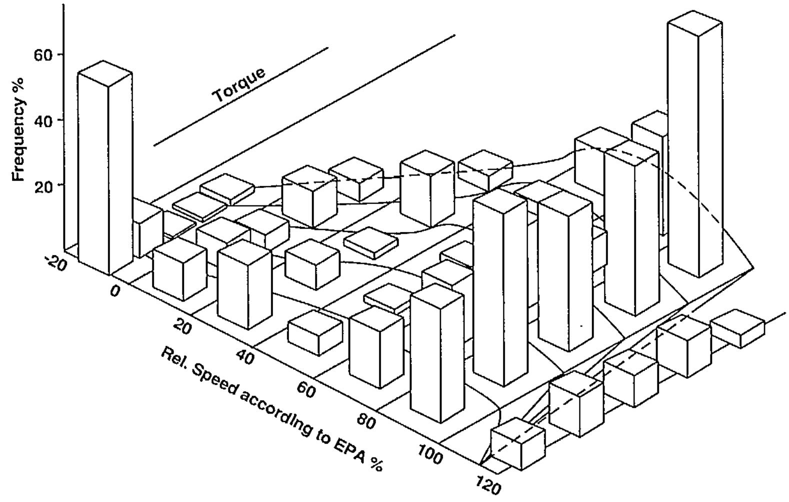
The foregoing figure and discussion thus far illustrate a classic problem confronting those who design engine test cycles. First, it is necessary to characterize vehicle operation, which may typically be done by vehicle speed versus time. Applying the profile to an engine demands knowledge of how the engine behaves over the chosen cycle or type of operation. Engine data may be collected directly, while one is compiling data to develop the cycle. Alternatively, the vehicle can be tested over the chosen cycle on a chassis dynamometer and parameters on engine operation collected. In either case, engine parameters are being collected while the engine is linked up to a vehicle. Vehicle configuration and driving habits will have some impact on how the engine is operated. Thus rather than attempt to make a statement about how methanol heavy-duty diesels will be driven, the proposed cycle seeks simply to force the engine to execute a series of transients that do bear some correlation to engine operation.

The start of the cycle is meant to simulate an acceleration from an idle or vehicle stopped condition. Once the vehicle has gained speed, engine speed falls off and never recovers, unlike a gear change. However, engine torque does fall. The assumption being that less energy is needed to keep the vehicle moving. At the conclusion of the run, the engine (vehicle) comes to a stop (idle). The emphasis of the cycle on relatively high torque operation at mid to full speed is based on the desire to force the engine into relatively fuel rich air:fuel ratios and possibly to induce higher emissions.

The prescribed steady state regulatory tests in Europe (R.49), Japan (6 mode) and the superseded U.S. test (13 mode) focussed on the intermediate speed peak torque area of engine operation. Even the U.S. HDD transient test biases engine operation in this region (Exhibit 5).

Motoring, a condition used to simulate vehicle braking, is avoided in the cycle. Few facilities, even those in the U.S.A., are equipped with engine dynamometers capable of performing engine motoring. Engine motoring during transient testing is a very controversial and divisive issue. Its inclusion in a methanol engine emissions research cycle could be misinterpreted by some parties. Due to this controversy, and equipment costs, motoring is not included in the SMI test cycle. It is also recommended that no further action on the issue of engine motoring be pursued until a more harmonious global consensus is achieved.

Exhibit 5. Relative Weighting of the U.S. EPA HDD Transient Emissions Test (3)



U.S. EPA HDD CYCLE
TORQUE & RPM HISTOGRAM

Ultimately any engine dynamometer test, no matter how simple, must be reflective of on-road vehicle operation if it is to gain acceptance. One aid to measure the authenticity of the cycle is actual on-road data. A collection of engine speed and torque versus frequency maps, shown in Exhibit 6 illustrate the relative time that various engines spend at different engine speed torque conditions. All the maps indicate that, with the exception of idle times, the vehicles tend to operate around the peak torque condition. Unfortunately the maps do not indicate the real-time trend, i.e., how the drivers actually drive. But they do show a propensity to operate at mid range engine speeds and near peak torque loads. This type of operation can also be attributed to the final vehicle configuration which, if done properly, will mate the correct transmission and axle to the engine given the desired vehicle operation. All the maps show that those vehicles were geared towards peak torque operation.

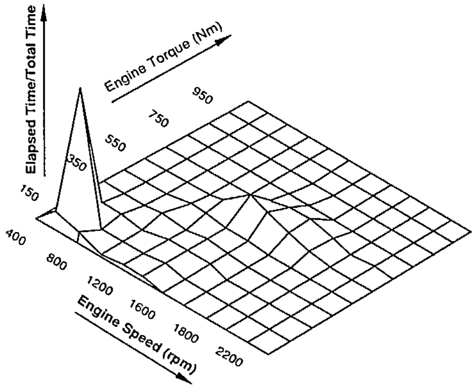
The data presented in Exhibit 6 are for diesel-fuelled engines, but illustrate an important consideration if methanol engines are to gain acceptance in the future. Methanol vehicle configurations (transmission and axle ratio) must account for the performance characteristics of the engine and the ultimate application of the vehicle. Canadian Project MILE data for a methanol truck and bus confirm the trend that drivers of methanol vehicles tend to seek mid to high engine speed and attempt to operate near peak torque.. Instead of engine load or torque being shown in Exhibit 7, fuel pump rack is presented. Rack position is an indicator of the fuel being supplied and hence power.

The repetitive nature of the test cycle: engine loading, idle and downloading were designed to create a bias towards operation in an urban environment. This approach was taken since urban operation will likely place the most severe range of transients on an engine, i.e. speed and load pick-ups. From an emissions perspective, the greatest concern with air quality is in urban regions. Engine manufacturers, worldwide, including Detroit Diesel, MAN, Daimler Benz and Volvo, have been focussing their methanol engine efforts towards power plants that are likely to see service in urban transit buses. This may be attributed to the desire to satisfy U.S. 1991 emissions regulations. Since this appears to be one market segment that engine manufacturers have been moving towards, a test cycle should reflect this type of operation. In the future, a more refined methanol engine research cycle could incorporate portions to simulate highway driving. Highway driving could be reflected by fewer stops, and lower torque outputs for long periods of time once the vehicle has achieved cruising speed.

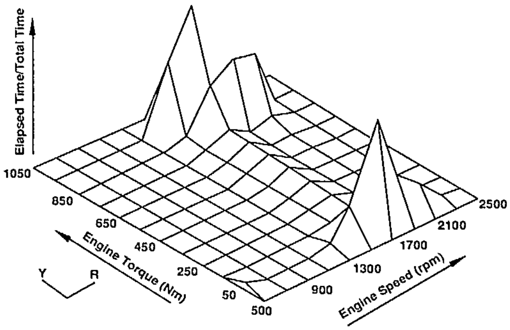
D. MEASUREMENT METHODS

The use of a standard test cycle will ensure that all engines are operated in a comparable manner, however exhaust sampling and measurement techniques must be standardized too, to ensure that the final test results are comparable. Section B reported that there was fairly uniform convergence on the measurement techniques for gaseous emissions. Users of the proposed cycle must agree upon an exhaust sampling technique, HC measurement and reporting, and particulate measurement.

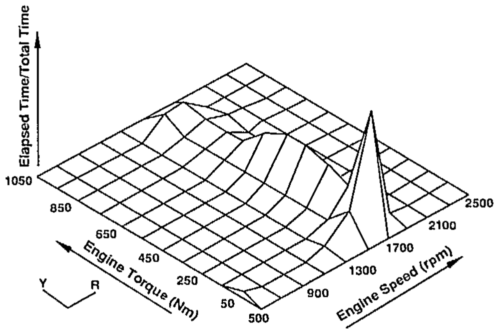
Exhibit 6. Engine Operating Profiles of European Vehicles (3)



(a) Urban Bus Circuit

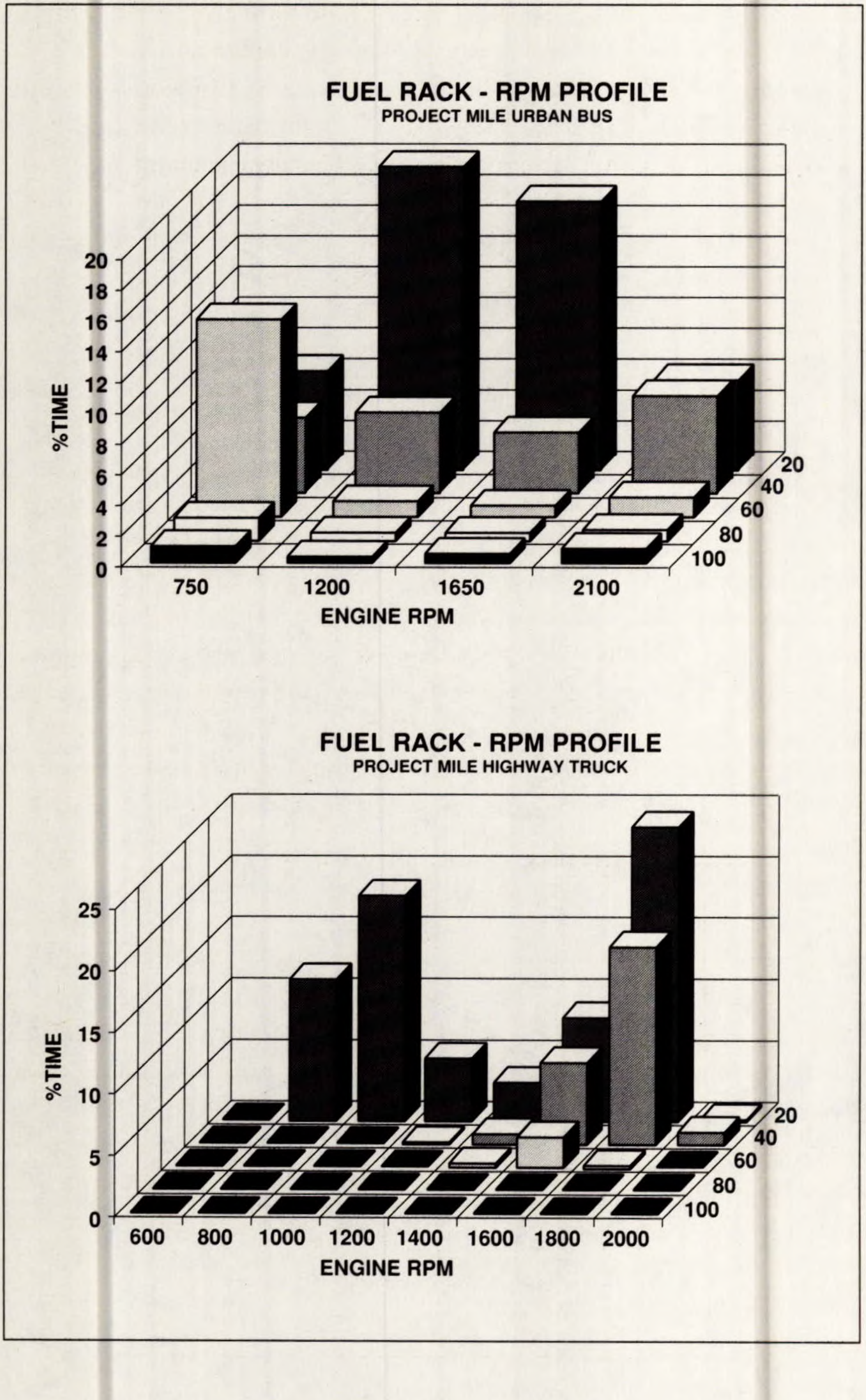


(b) Truck; Mixed Road Circuit (GVWR 38t)



(C) Truck; Highway Circuit (GVWR 18t)

Exhibit 7. Engine Operating Profiles of Canadian Methanol-Powered Vehicles (12)



Already the trend of researchers and manufacturers is to publish THC emissions data or present the individual levels (oxygenated, non-oxygenated and aldehydes). This practice is critical if people are to form a fair opinion on HC levels. The major drawback in determining the unburned fuel level and aldehyde level is that these figures typically require post-emissions test laboratory analysis with a high pressure liquid chromatograph (HPLC) and gas chromatograph (GC), both expensive pieces of laboratory equipment.

The sampling technique and the issue of particulate measurement are the two areas where a consensus must be sought. Section B indicated that the use of a transient cycle will necessitate a CVS sampler. Alternative techniques that would permit sampling of a variable flow gas stream have been described in the literature (13, 14, 15, 16). These systems have ranged from the use of a miniaturized CVS system, measurement of raw exhaust that is passed through a condensate trap and particulate trap, to successive samples of exhaust during each segment of the transient cycle through a manifold and solenoid actuated valve arrangement. All the above described set-ups bear one point in common; they were designed as experimental set-ups to support research work into emissions. A logical starting point for a sampling system for the proposed test cycle would be some form of CVS system. It may not be necessary to use a complete CVS system as described in U.S. regulations. However any device must produce repeatable results and ideally permit a correlation to results obtained with the techniques prescribed in the regulatory literature. The use of a CVS system will also permit continuous particulate sampling over the entire test cycle. For reasons discussed in section B, particulate sampling is still highly desirable.

As environmental issues become a more pressing concern, increasing pressures will be exerted on engine manufacturers to develop or refine new technologies. Methanol has been identified as one potential alternative fuel that offers promise to help alleviate air quality concerns. Before methanol can gain widespread acceptance, the technology of burning methanol in diesel-type engines and its effect on emissions must be further studied. The adoption of a common emissions research cycle provides a solid starting point. A common cycle will help coordinate any effort, accelerate the development process and reduce development costs for engine manufacturers. The test cycle is not meant to be a substitute for eventual regulatory compliance.

Manufacturers will still need to eventually achieve regulatory compliance. A common research test will permit a coordinated approach for the international community. In parallel with the research cycle, individual manufacturers may then desire to develop engine specific correlation parameters between the research cycle and a particular regulatory test.. In this manner, individual manufacturers may participate in a joint information exchange while still working towards a marketable product that meets emissions regulations criteria.

E. CONCLUSIONS

1. For a research based test cycle to be successful, it must be widely accepted and implemented.

2. Given that heavy-duty engines used in mobile applications are subject to dynamic loading and operation, a transient based research cycle will permit a realistic representation and hence prediction of a particular emissions profile.

3. Successful implementation of a common methanol engine test cycle must include agreement on sampling and measurement techniques for HC levels and a common format for reporting results.

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