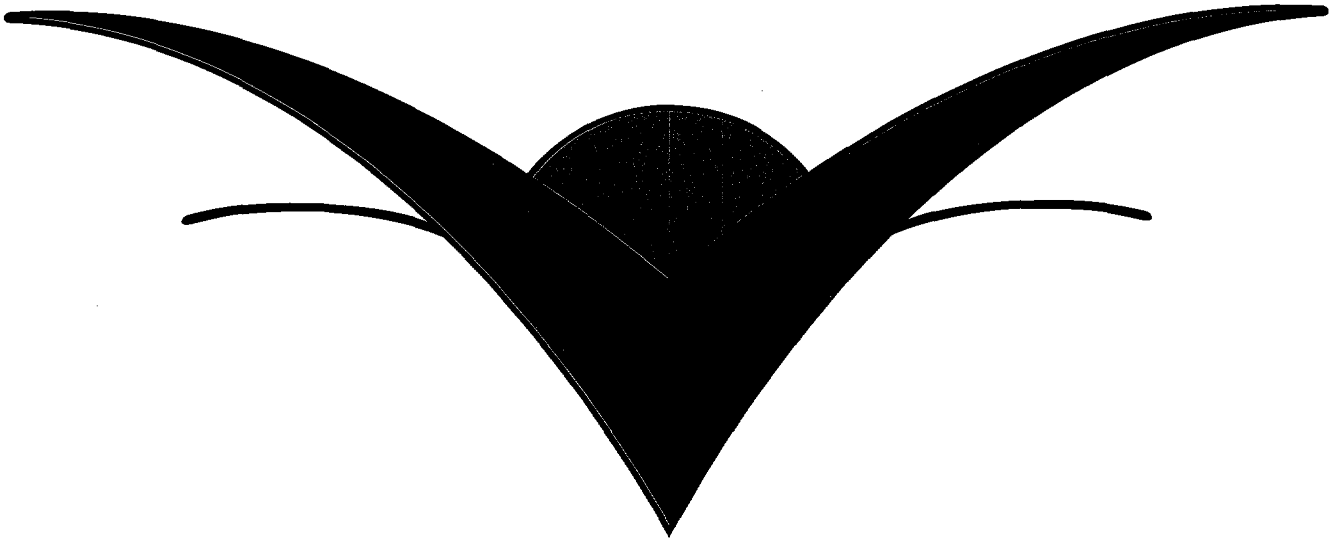
KFBs Biodrivmedelsprogram
Systemstudie

The Use of Methanol as a Fuel for Transportation



Karl-Erik Egebäck, Michael P. Walsh, Roger Westerholm

KFB
KOMMUNIKATIONS
FORSKNINGS

KFB-Meddelande 1997:15
Juni 1997

TITEL/TITLE: **The use of Methanol as a Fuel For Transportation**

FÖRFATTARE/AUTHOR: **Karl-Erik Egebäck, Luleå University of Technology, Roger Westerholm, Stockholm University and Michael P. Walsh, International Consultant, Arlington USA.**

SERIE/SERIES
KFB-Meddelande 1997:15
ISBN
ISSN **1401-1271**
PUBLICERINGSDATUM/DATE PUBLISHED
June 1997
UTGIVARE/PUBLISHER
KFB – Kommunikationsforsknings-beredningen, Stockholm
KFBs DNR **1995-0393**

ABSTRACT (Aim, Method, Results): The aim of the project was to collect and report international experiences concerning the use of methanol as an automotive fuel.

The method has been to study the literature which covers the subject and most of the information has been collected that way. The project started with a participation in a conference and a visit to people which have been involved in activities concerning the use of automotive alcohols. Car manufacturers, environmental authorities and users of alcohol fuels i.e. representatives of bus companies, were interviewed.

The different applications for the use of methanol as an automotive fuel has been described in the report as well as the production of methanol. Some results, mostly in form of emission data and other experiences derived from the use of alcohol fuels, have also been presented.

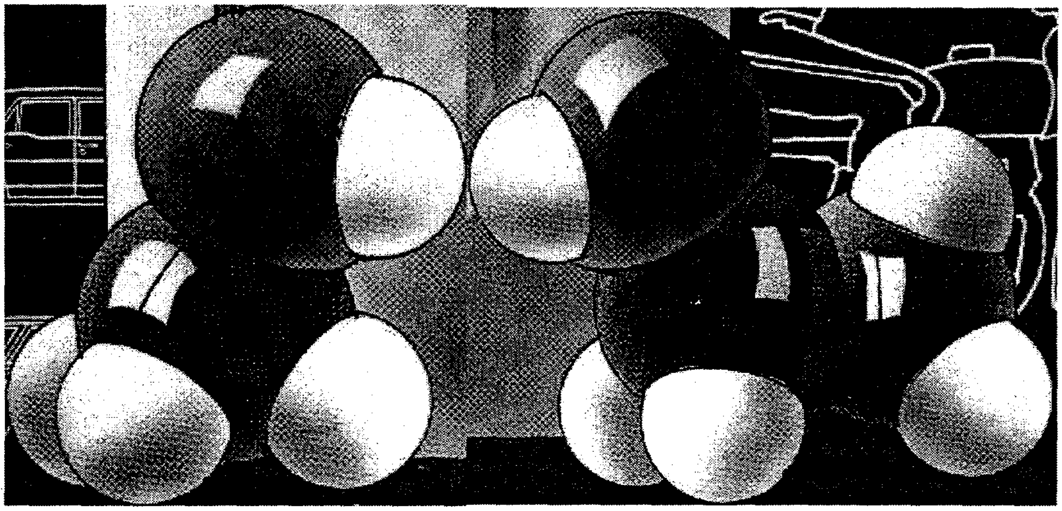
The use of ethanol and methanol has been compared and based on information from engine manufacturers and users of alcohol fueled vehicles there seems to be a preference for the use of ethanol. However, the question "Methanol or ethanol?" has not been answered as the decision which of the two is to be used seems to depend more on economic factors, such as cost of the production of the fuel etc., than on other factors.

KFB-rapporter försäljs *dels* genom Fritzes Offentliga Publikationer, 106 47 Stockholm, tel 08-690 90 90, *dels* genom KFB
Övriga KFB-publikationer beställs och erhålls direkt från KFB. Man kan dessutom abonnera på tidningen KFB-Kommuniké.

KFB Reports are sold *either* through Fritzes', S-106 47 Stockholm, Sweden, *or* through KFB (The Swedish Transport and Communications Research Board), Box 5706, S-114 87 Stockholm, Sweden
Other KFB publications are ordered directly from KFB

KFB-MED--97-15

THE USE OF METHANOL AS A FUEL FOR TRANSPORTATION



Karl-Erik Egebäck*, Michael P. Walsh# and Roger Westerholm¤

*Luleå University of Technology, Luleå, Sweden
#Arlington; Virginia, USA
¤ Stockholm University, Stockholm, Sweden

RB

FÖRORD

KFB´s biodrivmedelsprogram startade budgetåret 1991/92 och pågår till och med utgången av 1997. Avsikten är att programmet skall ge kunskapsunderlag till beslutsfattare på olika nivåer inför beslut om hur ett framtida miljöanpassat transportsystem baserat på förnybara drivmedel praktiskt skall kunna realiseras. En slutrapport som sammanfattar erfarenheterna av programmet och drar strategiska slutsatser kommer att redovisas 1997.

För att ge underlag till slutrapporten har KFB initierat en *systemstudie.* Till systemstudien har knutits en grupp personer med olika kompetensområden under ledning av professor *Thomas Sterner,* Nationalekonomiska institutionen vid Göteborgs universitet.

Avsikten är att systemstudien skall ge ekonomiska utvärderingar samt bedömningar av potentialen för produktion och användning av olika drivmedel. Den skall vidare analysera de flesta aspekter på storskaligt införande av biobaserade drivmedel. Viktiga frågor att analysera gäller t ex effekter på miljön globalt, regionalt och lokalt, samhälls- och företagsekonomiska effekter, mark- och naturresursaspekter, prisbildning för bioråvaror, effekter på industristruktur och infrastruktureffekter.

Systemstudien skall också belysa olika strategier för introduktion av biodrivmedel givet olika förutsättningar, analysera konkurrens om användning av biobränsle för andra ändamål än drivmedel, göra jämförelser med andra drivmedel med hänsyn till ekonomi, miljö- och hälsoeffekter, m.m.

Systemstudien genomförs i form av ett antal delstudier som gruppen identifierat som viktiga hörnstenar för att kunna bedöma möjligheterna för en introduktion av biodrivmedel. Resultaten av dessa delstudier diskuteras löpande inom gruppen som värderar, drar slutsatser och sätter in delstudierna i ett större sammanhang.

Denna rapport behandlar bio-metanol som drivmedel i fordon. Rapporten pekar på och sammanfattar den utveckling som skett inom området, både utomlands och i Sverige.

Urban Karlström
Generaldirektör, KFB

DISCLAIMER

ABSTRACT

Ethanol and Methanol are two realistic alternative automotive fuels. Each of them can be produced from biomass by the use of at least two different methods. When comparing the two fuels, each seems to have advantages and disadvantages. Ethanol is less toxic than Methanol but it is estimated to more expensive at least when using the methods for production which are used today. Methanol is likely to produce higher yields and when used in a fuel cell lower emissions. Field tests have shown that the cost associated with the use of a new fuel is one of the key factors to take into consideration.

In Sweden an extensive program was established in order to evaluate the use of methanol as a fuel for motor vehicles. The program, which chiefly comprised light duty vehicles, started in the middle of the 1970s and was finished in 1990. This program also included E5 and E 23. Before that, a project was started aiming at an evaluation of the use of ethanol and in 1991 the Swedish Transport and Communications Research Board was commissioned by the Swedish Government to devise a program to stimulate the development of technologies for alternative fuels. The program is concentrated on the use of biofuels such as bioethanol and biogas and it was assumed that data and experiences from investigations carried out in other countries could be collected and used together with data and experiences generated during the above mentioned methanol project for an evaluation of the use of methanol.

The evaluation of the use of methanol is presented in this report, and conclusion is that both methanol and ethanol are attractive fuels with the long term potential to substitute for large quantities of petroleum based fuels. At the same time it can reduce urban air pollution, especially NO_X and particulate from diesel vehicles, and if biomass methanol or ethanol is used can the transportation contribution to the greenhouse effect be lowered dramatically.

1. INTRODUCTION AND OVERVIEW

The term alternative fuels may be interpreted differently in different countries. In California, alternative fuel means "a motor fuel consisting of methanol, ethanol (including methanol and/or ethanol in combination with gasoline as approved by the California Air Resources Board as an alternative fuel), liquefied petroleum gas (LPG), compressed natural gas (CNG), liquefied natural gas (LNG), or electricity" (AQMD, 1994)..

Methanol is not a new fuel for motor vehicles. It has not been used to the same extent as ethanol, especially if the use in Brazil is taken into account, but there seems to have been more research projects carried out when using methanol. Methanol is also commonly used for the production of ethers to be blended with gasoline. Methyl Tertiary Butyl Ether (MTBE) which is produced from about 40% of methanol and 60% of a C_4-olefin is used in both commercial and reformulated gasoline. As the octane number of MTBE is high, one of the purposes of using it as an additive is to improve the octane quality of gasoline. Another purpose is to reduce the emission of especially carbon monoxide and in this way improve the quality of gasoline. In the USA there is a requirement to use gasoline with a blend of oxygenates in areas with highly CO polluted areas.

Another alternative use of methanol is to blend it directly into gasoline, which was first attempted in the early 1970's during the oil crisis of 1973. Since the first trials took place, different alternatives for the use of methanol have been investigated and are in current use. Alcohols and ethers are oxygenates and are used as additives in gasoline in order to improve the octane number of the fuel and as a means of improving the emission behavior of the vehicle.

During the 1970's and early 1980's, there was a great deal of interest around the world in the use of biofuels as a means of reducing dependence on imported oil, especially oil from the OPEC countries. Clearly the most advanced of these programs was that which took place in Brazil where ethanol derived from the local sugar crop became a major component of gasoline and many vehicles were designed and built to run on 100% ethanol. As oil prices declined throughout the 1980's and as the supply of oil stabilized, the interest in biofuels for energy security reasons has declined. However, at the same time, the concern with global warming began to increase. This has culminated most recently in the finding by the IPCC Working Group 1 that "the balance of evidence suggests that there is a discernible human influence on global climate" and the evidence that 1995 has been documented to be the warmest on record globally. Biofuels with their potential to dramatically lower CO_2 emissions are now gaining increased attention around the world. To cite just two examples, the OECD recently released a study which concluded that ethanol and methanol produced from cellulose feedstocks would not only lower urban air pollution but would also result in much less CO_2 emissions. Further a soon to be released study in the United States has concluded that by 2010, approximately 1/3 of the fuel used in light duty vehicles could be alternative fuels, a substantial fraction of which could be produced from biomass.

The purpose of this report is to review the current status of alcohol fuels especially methanol from biomass, with particular focus on the forces which are encouraging interest in these fuels.

2. ALTERNATIVE USES OF METHANOL IN VEHICLES AND ENGINES

2.1 Use of methanol in Otto cycle engines

Methanol can be used in different ways in gasoline fueled vehicles or Otto engines. The methanol fuels discussed in this chapter include: low-level blends corresponding to maximum 3.5 w% % in the fuel, higher-level blends >3,5 w% % (oxygen) and high level blends of 85% methanol in gasoline (hydrocarbons) or neat methanol. Technically there is no problem to blend alcohols in gasoline.

At the time when exhaust gas catalysts were beginning to be introduced there was a need for lead-free gasoline, because catalysts do not tolerate lead. One way to keep the octane rate of the fuel at an acceptable level without lead was to add methanol to the fuel. This also had a favorable impact on the emission of CO. Therefore the use of not only methanol but also other oxygenates was encouraged and this is true even today. Oxygenates are used in reformulated gasoline in order to improve its quality.

One drawback with methanol as a blending component in gasoline is that it has been shown that the vapor pressure increases (see Figure 1). In Sweden, as in many other countries, there are no special specifications for a gasoline to which an oxygenate has been added. In addition the Reid vapor pressure is rather high according to the specification, 750 kPa (max) for summer gasoline and 950 kPa (max) for winter gasoline. The reason allowing such a high vapor pressure is that the car manufacturers argue that cold start problems may occur if the vapor pressure is reduced.

As there is a risk that evaporative emissions will increase if methanol is added to the gasoline, the gasoline should be adjusted so that the standards are met even when an oxygenate, such as methanol or ethanol, has been used. Even with such a requirement there may be difficulties as it is not certain whether these two alcohols can be added to gasoline at the refinery. Both methanol and ethanol are hygroscopic and therefore they usually are splash blended just before the distribution of the blended gasoline to the fuel filling station.

Standards in Sweden according to SS-EN 228.

Sweden: (SIS-STG, 1991a; SIS-STG, 1991B; SNV, 1993)

According to present Swedish standards (SS-EN 228) for lead-free gasoline and (SS 15 54 21) for leaded gasoline, an oxygenate content in gasoline is tolerated which corresponds to 2 w% oxygen. From the Table below it can be seen which oxygenate content correspond to a specific content of oxygen.

According to a proposal of environmental classification of gasoline, which the Swedish Environmental Protection Board has prepared and presented to the Government (SNV, 1993), the oxygenate content in gasoline should be limited to correspond to 2 wt % oxygen.

Taking into consideration the fact that Sweden is a member of EU the following EU directives with their corresponding limits for oxygenates in gasoline (2.5 wt % max) will even apply in Sweden. At the present there is an investigation in progress concerning the environmental classification of gasoline.

2.1.1 Low-level blends corresponding to maximum 3.5 w% oxygen in the fuel

The reasons for restricting the use of low-level blends of alcohols in gasoline is that the amount added could have an unacceptable influence on the cold start behavior and driveability of the vehicle. For older vehicles in service and especially these equipped with a carburetor such problems could occur. Newer types of vehicles equipped with a fuel injection system and especially these having a closed loop fuel system have been proven to tolerate a higher rate of alcohol in the fuel.

EEC Council Directive according to Allion, 1991.

EEC: (EEC, 1985)

According the a Council Directive from December 1985 the following applies:

- In agreement with Article 1 all member States must allow organic oxygenates as in the Table below

- Member States can allow contents which are greater than the limits in Column A; however the regulations are valid when concerning the marking of pumps, to be found in Article 3, and which apply to contents of organic oxygenates greater than the limits given in Column B in the Table below

Oxygenate	Col A (vol %)	Col B (vol %)
Methanol, a suitable stabilizer must be added[1]	3	3
Ethanol, a suitable stabilizer may be added[2]	5	5
Isopropanol	5	10
Tetra butyl alcohol, TBA	7	7
Isobutanol	7	10
Ethers which contain five or more atoms per molecule	10	15
Other organic oxygenates, defined in the relevant instructions	7	10
Blends with some organic oxygenate[3]	2.5 wt % which does not exceed the above stated individual limits	2.5 wt % which does not exceed the above stated individual limits

According to the regulations within the EU (Europe, see above) and the regulations in the USA there are different judgments about the acceptable amounts of oxygenates in the fuel. In Sweden it is not allowed to add more oxygenates than an amount which would result in 2.0

---

[1] In agreement with National specifications, or where such do not exist, with industrial specifications.

[2] In agreement with National specifications, or where such do not exist, with industrial specifications.

[3] Acetone is allowed up to 0.8 vol. % when it is included due to its being a by-product of certain manufactured oxygenates.

w% oxygen while in much of Europe the content can be 2.5 w% and in certain cases up to 3.7 w% (Egebäck, 1994). If the content of oxygenates in gasoline exceed 3.7 w% the content must be labeled on the pump at the filling station. However, as a member of EU Sweden has accepted the regulations applied by EU. Therefore in the long run the allowable content of oxygenates may be changed in Sweden.

In the USA the basic requirement is that reformulated gasoline must contain at least an amount of oxygenate which is equal to 2 w% oxygen. OxyFuel with an oxygenate equal to 2.7 w% oxygen is specified for "CO attainment areas" (areas with a high level of CO in the air) (Egebäck, 1994). The different oxygenates approved by the US EPA are summarized below.

Standards and limits in the USA.

(US EPA, 1992; US, 1991; UOP, 1990)

The basic requirements concerning oxygenates is that reformulated gasoline must contain at least 2.0 wt % oxygen, though paying attention to the following:

- "OxyFuel" with 2.7 wt % oxygen has been specified for CO nonattainment areas (areas with too large an emission of CO).
- Reformulated gasoline, which has been certified according to a simpler model, may while being used in vehicles not give an increase in the NO_X emissions. Furthermore:
    - it shall not contain more than 2.1 wt % oxygen or
    - it shall be able to contain up to 2.7 wt % oxygen if the only oxygenate is MTBE

The simple model for certification of reformulated gasoline applies, according to information received, for the period Jan 1995 to March 1997 and does not include all the fuel parameters which affect emissions but only the following specifications:

- Benzene: 1.0 vol % maximum
- Oxygen: 2.0 wt % min.
- RVP summertime: 7.2 psi (49.6 kPa) for the Class B areas and 8.1 psi (55.8 kPa) for the Class C areas. The Class B areas refers to warmer regions such as Arizona, California and Colorado and the Class C areas to less warm regions such as Connecticut, Delaware and Illinois.

The complex model for certification of reformulated gasoline is, as can be seen, more comprehensive than the simple model and it is intended that it shall apply from March 1997.

Alcohol - gasoline blends which are approved by EPA in the US (Bechthold, 1986)

Type of alcohol	Blend contents
Ethanol	10 vol %
"Gasoline grade" tertiary butyl alcohol (GTBA)	3.5 wt % oxygen in the blended fuel. Ca 16 vol %
"Oxinol": (methanol GTBA blend not exceeding 1:1 per volume)	3.5 wt % oxygen in the blended fuel. Ca 9.5 vol %
"Syncolene": ethanol denatured with methyl isobutyl ketone	10 vol %
"Du Pont Waiver Fuel Blend": up to 5 vol % methanol in gasoline with cosolvent in a proportion of 2:1 (ethanol preferably) plus Du Pont corrosion or similar inhibitor	3.5 wt % oxygen in the blended fuel
Other aliphatic alcohols e.g. propanols, butanols, etc.	2 wt % oxygen in the blended fuel

Volumes of oxygenates needed for an oxygen content of 2,73 w% O_2.

Name	Formula	Volume Percent
MTBE - Methyl tertiary butyl ether	$CH_3OC(CH_3)_3$	15.0 (11.0)*
TAME - Tertiary amyl methyl ether	$CH_3OC(CH_3)_2CH_2CH_3$	16.0 (14.0)
ETBE - Ethyl tertiary butyl ether	$CH_3CH_2OC(CH_3)_3$	17.4 (14.0)
TAEE - Tertiary amyl ethyl ether	$CH_3CH_2OC(CH_3)_2CH_2CH_3$	19.2 (14.5)
EtOH- Ethyl alcohol	CH_3CH_20H	7.5 (8.75)
GTBA - Tertiary butyl alcohol (gasoline grade)	$(CH_3)_3COH$	11.8 (9.3)
IPA- Isopropyl alcohol	$CH_3CH(OH)CH_3$	9.6 (7.1)
MeOH - Methanol	CH_30H	5.0 (4.0)

*2W% oxygen

2.1.2 Higher-level blends corresponding to >3.5 w% oxygen in the fuel up to 85 vol% methanol in gasoline

Technically a higher content of alcohols can be added into the gasoline than the amount equal to these specified by the regulations. Experiences referred to in sections 4, 5 and 6 of this report have shown that up to 15 vol% can be added to gasoline without causing unacceptable driveability of the vehicle. These experiences were mainly generated when running carburetor equipped cars in field tests. Later experiences (Aspen, 1995) have indicated that the cars of today with adaptive fuel metering systems may accept even higher contents of alcohols (see also section 4 of this report).

In Figure 1 it can be seen that methanol has the greatest influence on the Reid Vapor Pressure (RVP) of all the oxygenates presented. It is also obvious that for all alcohols the influence on the vapor pressure is greatest at low blends and that the influence of TBA and MTBE is very small (Furey, 1985).

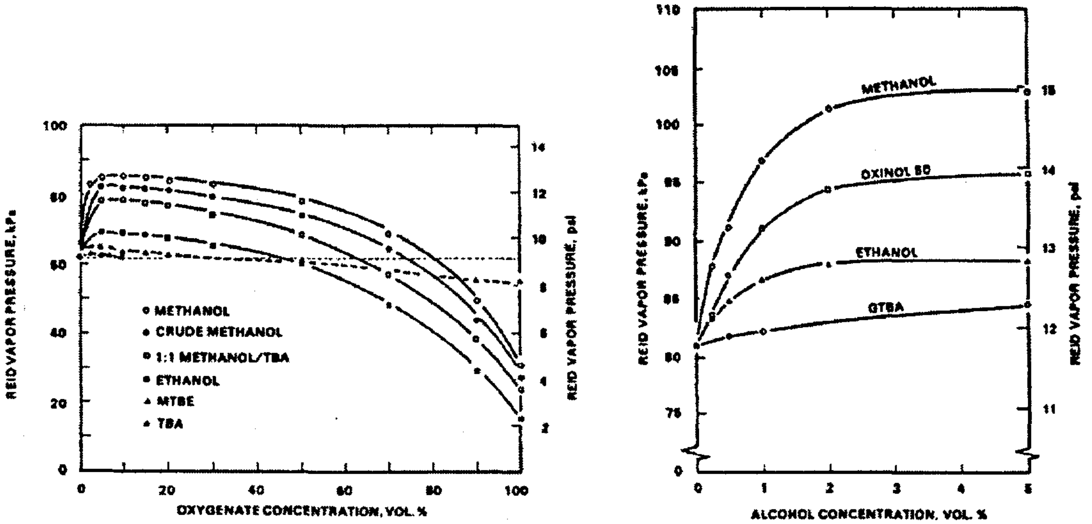


Figure 1. Changes in the vapor pressure of gasoline after blending in various oxygenates. (Furey, 1985).

2.1.3 High level blends of 85 vol% methanol in gasoline or neat methanol (@95 vol% excl. additives)

Commonly higher blends of alcohol in gasoline are used and up to 85 vol% for flexible fueled vehicles (FFV's). As this fuel contains 15 vol%. gasoline or other hydrocarbons there seems not to be any serious cold start problems especially as the vehicles are adapted to the fuel. The risk for an increased evaporative emission will be eliminated by the high rate of alcohol as can be seen in Figure 1.

According to regulations in Sweden methanol but not ethanol can be distributed as an automotive fuel without denaturation. In order to improve the cold startability, a hydrocarbon like isopentane commonly is added to the methanol fuel. Some other additives may also be used and therefore "neat" methanol for internal combustion engines does not contain 100 % methanol but up to 95 vol% + 5% hydrocarbons. When using M100 in a DISC-engine stability was achieved down to -29 °C.

This specified fuel can be used in dedicated vehicles, i.e. vehicles which are fully adapted for the use of an alcohol such as methanol. If an alcohol-gasoline blending system to be used at the fuel filling station can not be developed, it is suggested that this type fuel may be used only for special fleets of vehicles.

2.2 Use of ethers as blending components in gasoline

Production of methyl tertiary butyl ether (MTBE), the well known oxygenate, started in the USA 1979 in and Europe in 1973 (CDTECH, 1993). After the start of production, legislation in the USA concerning improvements of gasoline has dramatically increased the demand for MTBE. In 1991 the worldwide production capacity of MTBE was 257,650 barrels/day (40,963 m^3/day) and is estimated to reach 611,470 barrels/day (97,216 m^3/day) by the year 2000 (Fuel, 1991).

Ethers in gasoline play a role in replacing some part of the aromatics and olefins. Depending on the refinery process a reduction of the content of aromatics in the fuel may lead to lower octane numbers. One type of olefin, C_5-olefin, is photochemically reactive and these olefins are also high in vapor pressure, which may cause the gasoline to have a negative effect on the environment and therefore the content of olefins should be reduced. On the other hand olefins are generally high in octane numbers, a positive function of this component. One way of overcoming the above negative effect is to use the olefins for the production of ethers and then replace the olefins with an ether. Changing olefins with ethers will raise the octane number of the gasoline.

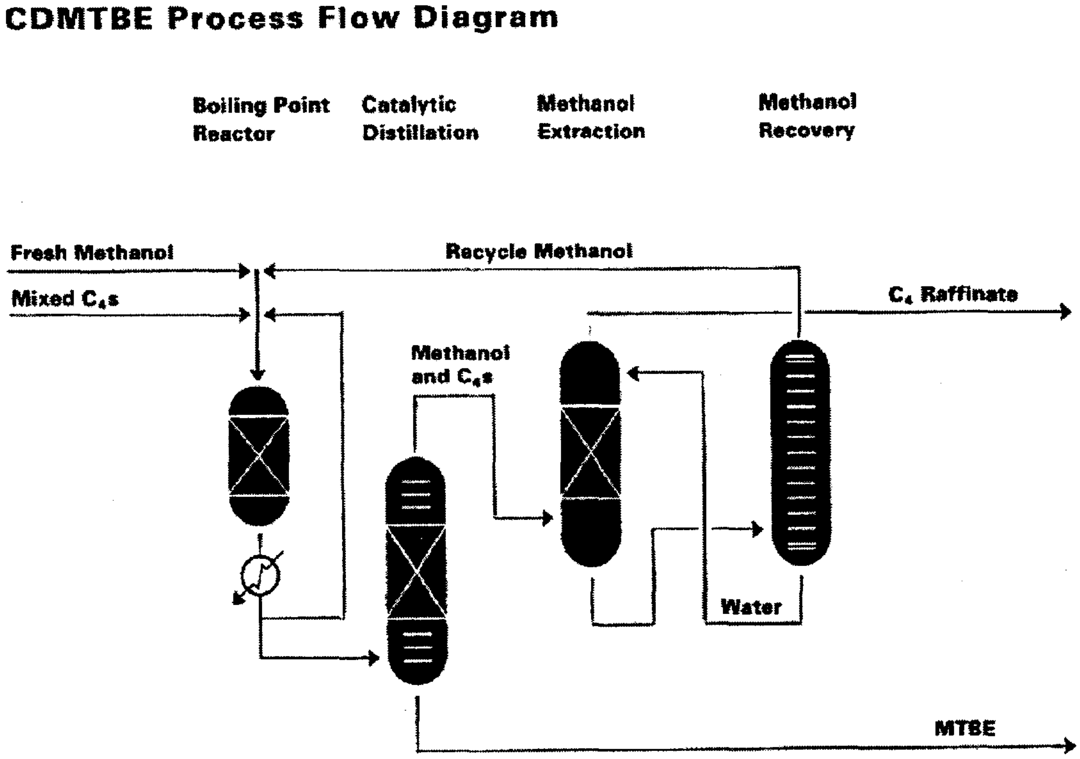


Figure2. Flow scheme for production of MTBE.

Aromatics in gasoline may play a role in the formation of ozone and may also cause less efficient combustion in the engine, which may lead to the formation of carcinogenic compounds such as Polycyclic Aromatic Hydrocarbons (PAH). Benzene, a well known aromatic component in gasoline, is known to be a carcinogen. There is therefore a clear need to reduce the content of aromatics in gasoline.

When manufacturing ethers as methyl tertiary butyl ether (MTBE) or tertiary amyl methyl ether (TAME) from methanol, C_4- or C_5-olefins are used as components - C_4-olefins for MTBE and C_5-olefins for TAME - and when manufacturing ETBE and tertiary amyl ethyl ether (TAEE) from ethanol, the same type of manufacturing process is used. For production of ETBE, c_4-olefins are used, and for TAME c_5-olefins. The content of methanol in MTBE is 33.9 w% which is less than the ethanol content in ETBE, which is 42.5 w%. The refinery process can be seen schematically in Figure 2.

2.3 Use of methanol in fuel cells

The "direct methanol fuel cell" is powered by a water-methanol (3%) mixture and air and may be used in both automobiles, in stationary plants for generation of electricity and for domestic heating. Several laboratories and others will be involved in the development work led by the Jet Propulsion Laboratory (JPL), California Institute of Technology, Pasadena (Public Information Office). According to one information source (Lewis, 1995) this is the ultimate invention for solving environmental and potential health effects from vehicles in densely populated areas, i.e. transforming methanol to electricity which can be used for transportation purposes. The fuel, a 'solid-state energy storage device', is called "direct methanol fuel cell" as it uses noble metal catalysts and carbon electrodes as the reaction sites on both sides of a solid polymer membrane. According to those involved in the research about fuel cells, the great advantages of the direct methanol fuel cell compared with the conventional fuel cell is that it does not "require a complex humidifier", (Public Information Office, 1995).

2.4 Compression Ignition Vehicles and Engines

There are many differences in important fuel parameters between diesel and alcohols which must be considered when using alcohols in compression ignition engines. Both ethanol and other alcohols have a lower heating value than diesel fuel and also lower flash point. As alcohols have a high octane number the cetane number is very low, which can be seen in Table 1.

Table 1: Some properties of diesel fuel and alcohols (STU, 1986).

Property	**Diesel**	**Ethanol**	**Methanol**
Boiling range, °C	180-360	~ 78	~ 65
Flash point, °C	> 60	12	11
Auto-ignition temp, °C	200-220	420	460
Low heating value (LHV), MJ/l	35.5	21.1	15.8
Viscosity at 20°C cSt	2-3.5	1.5	0.75
Cetane number	40-45	<8	<3

2.4.1 Use of neat methanol in compression ignition engines

Realistic alternatives to diesel fueled engines are engines fueled with LPG, natural gas and alcohols such as methanol or ethanol. Development and investigations have shown that there is a great potential for the reduction of exhaust emissions from heavy duty vehicles fueled with alcohol. However, in order to reach an emission level in the vicinity of the level which has been obtained for a light duty vehicle fueled with alcohol, it seems that an Otto engine with a three way catalyst system is required. Because such an engine is not as fuel efficient as a diesel engine the car manufacturers have directed their resources to the adaptation and development of diesel engines when using an alcohol as a fuel.

Auto-ignition in a compression ignition engine requires a fuel which easily ignites when the fuel is injected into the compressed air in the engine. Diesel fuel is such that it ignites when it is injected in compressed air in the combustion chamber and is specified to have a high cetane number i.e. has a good auto-ignitability. On the other hand alcohols, methanol and ethanol have a low cetane number, which means that they are difficult to auto-ignite in an engine. Therefore, alcohol-fueled engines must be designed so as to improve the ignition and one method used is to increase the compression rate and in addition use some mean of ignition improver as a spark plug or glow plug. In addition to measures taken in the engine, the fuel itself can be treated in order to improve its ignitability for which there are several ways available.

One of the methods used in order to improve the auto-ignition is to add an ignition improver to the fuel. There are many different ignition improvers which could be used. Unfortunately some of them are expensive. One rather efficient ignition improver, which has been used for ethanol fueled bus engines was *ethyl hexyl nitrate* (EHN). Unfortunately there were some problems with this ignition improver including the health risk in handling it. Later on, a *nitrate ester* was used but the manufacturing of this ignition improver was shut down. Therefore the only ignition improver in use in Sweden today is an *poly ethylene glycol* (PEG).

2.4.2 Use of alcohol blends in diesel engines

The use of methanol or ethanol as blending components in diesel oil has been investigated and reported by Oak Ridge National Laboratory (Bechtold, 1986). As emulsions of alcohols and diesel oil can be of two types, stable and unstable, it is important that a proper emulsifier is chosen and a efficient method for making the emulsion is used. Usually stable emulsions, which are micro-emulsions, do not separate under normal ambient conditions. Using non stable emulsions may be dangerous because of the risk of damaging the engine. One of the researchers added water in order to make it insoluble and a surfactant to make the emulsion stable and by using sufficient quantities of a certain surfactant the emulsions could be characterized by typical properties of micro-emulsions as the following:

- "They formed spontaneously requiring only minor stirring".
- "They were transparent indicating the dispersion sizes were less than ¼ wavelength of light".
- "They had "infinite" stability, i.e., they were thermodynamically stable, and there was no separation even after several months".

Referring to the above mentioned investigation it was shown that certain fuel parameters, such as the cetane number and the flash point, were rather dramatically changed when blending methanol and ethanol respectively with a stabilizer (emulsifier) in the diesel fuel as is shown in Table 2. The properties in the emulsion determined were specific gravity, viscosity, cetane number and lower heating value.

Blending ethanol in diesel fuel is currently being investigated in Sweden by a project sponsored by the Swedish Transport and Communications Research Board (KFB, 1996). The driving force for this project was the positive experiences gained by a similar project in Australia.

Table 2: Physical Fuel Properties of Ethanol and Methanol in Diesel Fuel Micro-emulsions (Bechtold, 1986).

Fuel Identification*	Base (W%)	Stabilizer (W%)	Alcohol (°API)	Gravity (cSt)	Viscosity (°F)	Flash Point	Cetane Number	Lower HeatingValue Btu/lb**
DF2	100%	0	0	35.3	2.45	160	44	18 263
15X EtOH-95/ 7.5 HEXL	77.5% DF2	7.5% HEXL	15% ETOH-95	36.5	2.05	68	35	16 906
10% MEOH-98/10% HEXL	80% DF2	10% HEXL	10% MEOH-98	36.1	2.03	61	36	16 961

*Key: DF2 = No. 2 Diesel fuel; ETOH-95 = 190-proof ethanol; HEXL = hexanol;
MEOH-98 = 98 w% methanol/2% water; cSt = centistoke
**1 Btu/lb = 2326 kJ/kg

3. PRODUCTION OF METHANOL

Methanol is an important industrial chemical which is used as a solvent and as raw material for the production of industrial chemical products such as formaldehyde, methylene chloride, dimethyl ether and other organic compounds. Methanol was initially discovered by the well known English chemist/physicist Robert Boyle (1627-1691) in 1661 during experiments with degasification of wood. He also isolated and discovered acetone in the same experiment.

A principal reaction mechanism for industrial production of methanol is the exothermic reaction of carbon monoxide with hydrogen gas forming methanol as shown in reaction I. If the synthesis gas also contains carbon dioxide, methanol is produced in accordance to reaction II, which is however less efficient compared to reaction I, due to more hydrogen gas being consumed. Furthermore, water is also formed which makes the exothermic reaction less energy efficient compared to reaction I. Heavier alcohols also produced from carbon monoxide are present in the synthesis gas as shown in reaction III. By controlling the H_2/CO-rate the formation of methanol in accordance to reaction I may be increased. Furthermore, the use of catalysts in the chemical processes increases the methanol yield.

$$CO + 2H_2 \Rightarrow MeOH + energy \qquad (I)$$

$$CO_2 + 3H_2 \Rightarrow MeOH + H_2O + energy \qquad (II)$$

$$2CO + 4H_2 \Rightarrow EtOH + H_2O + energy \qquad (III)$$

Production of synthetic gas, mainly carbon monoxide and hydrogen, aimed for methanol production can be based on several feedstocks ranging from heavy residual oils to biogas. Depending on the feedstock (hard coal, brown coal etc.) the synthetic gas needs to be purified and treated to increase the yield of methanol. There are several techniques developed for the production of synthesis gas depending on the feedstock (IEA, 1986). A scenario for the production of methanol in large quantities and cheaply is to build movable methanol plants on boats, which could be transported to the oil field and use excess natural gas as the feedstock (Lewis, 1995).

The chemical content of biogas is variable and it depends on the raw biomaterial used for generation of the biogas. Table 3 shows the chemical contents of biogas emanating from different sources in comparison with natural gas which is considered to be relatively clean and simple. It is evident that the process of production and purification of the synthetic gas is more complex when using biogas as the feedstock. The chemical industrial process for forming methanol from either natural or biogas produces exhausts containing emissions of nitrogen oxides and carbon dioxide etc. However, comparing natural gas and biogas as feedstocks, the latter feed-stock has the potential to reduce the net flow of carbon dioxide to the atmosphere as discussed in the introduction to this section.

Table 3: Chemical contents of biogas and natural gas, and some additional data (Brolin et al., 1994).

Compound, (volume % of dry gas)	land fill gas	digested sludge gas	anaerobic sludge gas	natural gas
Methane	45 (40-55)*	68 (55-76)	80 (50-90)	91.1
Carbon dioxide	35 (30-40)	32 (25-45)	20 (10-50)	0.5
Nitrogen	16 (2-25)	0.2	traces	0.6
Oxygen	4 (0-5)	traces	traces	traces
Hydrogen	traces	traces	traces	traces
Hydrogen sulfide	<10ppm	<10ppm	<10ppm	traces
Non methane hydrocarbons	<10ppm	<10ppm	<10ppm	7.8
Water, (volume %)	4-7	4-7	4-7	**
Additional data				
Density, (kg/m$^{3)}$	1.27	1.12	0.97	0.81
Heat content, (kWh/Nm^3)	4.6	6.8	8.0	10.8

*Numbers in brackets refer to the estimated content variation interval.
** No data is presented in the report referred to.

When using methanol as an engine fuel there are several important properties that needs to be considered regarding the quality of the methanol used. These properties are water content, energy content and low corrosiveness. It means that depending on the feedstock, Table 3, the purification processing of crude methanol will be different due to relatively more of other compounds being formed. Relatively large water contents are obtained in the methanol when natural gas is used as the feedstock compared to coal. A common method of purifying raw methanol is distillation. Methanol has an advantage in the distillation process, compared to ethanol, since methanol does not form an azeotropic mixture with water.

At present the most commonly used methods for the production of methanol are feedstocks which are not based on renewable organic material. However, in countries which have access to wood, alcohols such as bio-methanol and bio-ethanol can be produced and used in automobiles. Comparing methanol with ethanol production from wood the former have a yield of 47 wt % and the latter 17 wt % (Elam et al., 1994). The reason for methanol giving a higher yield is that ethanol production involves a fermentation step of sugar into ethanol where the bio-chemistry is converting carbohydrates. The fermentation process also produces carbon dioxide. The carbon dioxide is vented to the atmosphere which reduces the yield of carbon emanating from the wood into alcohol. A theoretical consideration to improve the yield of alcohols would be to store the carbon dioxide produced in the fermentation process and produce methanol in accordance with reaction II as previously referred to. This will result in the simultaneous production of bio-ethanol and bio-methanol. To sum up it is expected that the production volume of alcohols from organic material will increase in the future. A potential spin-off may be methanol production from carbondioxide emitted in the fermentation processing of beer/wine emanating from larger brewery and wine plants.

The production cost of bio-methanol has been under discussion in Sweden for a long time without arriving to a fixed cost. The uncertainties depends on many factors the availability of biomass such as the size and type of the prodution plant, the possibility of utilizing the production of heated water from the plant as a source for heating houses etc.

Significant emissions of oxides of nitrogen (NO_X) as well as toxics, greenhouse gases and other contaminents, are produced from the on-site flaring of copious quantities of methane from current landfills. (Wuebben and Bonny, 1995). A demonstration plant has been established which will turn this waste to good use and produce 50 metric tons per day of methanol. Since it is expected that clean fuels such as methanol will play an increasingly important role in improving air quality over the next two decades it would seem vital, among other things, to take advantage of this significant option for landfill gas abatement and produce methanol in this way. Major applications of this landfill-gas-to-methanol technology are possible though vision, commitment and shared risk-taking will be essential .

The Californian Fuel Methanol Cost Study (Chevron, 1989) reports conventional technologies and three new technologies which would reduce both investment costs and operating costs in a valuable way. The conventional technology involves first converting natural gas into a synthesis gas, which consists of hydrogen, carbon oxides, steam, etc. and secondly converting the synthesis gas into methanol. The new technologies include the Lurgi combined reforming process, which differs from conventional technology by adding an auto-thermal reformer after the steam-methane reformer, the synthesis gas produced having less inert material and a better balance between the methanol reactants. In the Catalytic partial oxidation process from Davy McKee the steam-methane reformer is replaced by a reactor that contains a catalyst producing, like the combined reformer, a better gas. The fluidized-bed methanol synthesis process from Mitsubishi Gas Chemical uses a different synthesis stage with a fine catalyst that is suspended as a dense cloud within the reactor, allowing more efficient heat removal and higher conversion than the other processes. Each of these technologies uses oxygen from an air separation plant, which reduces the size of some of the key equipment and permits larger train sizes. There is a moderate reduction in costs with each of the new technologies.

4. THE METHANOL PROJECTS CARRIED OUT IN SWEDEN.

Alcohols as automotive fuels have been used in Sweden since the mid 70's for the purpose of research and investigations. At that time the research and investigations were directed towards the use of methanol and the driving force for that was the threat from an oil crises like that which occurred in 1973. To start with, most of the projects launched were aimed at the development of the use of methanol for light duty vehicles. During later projects both light duty and heavy duty vehicles were fueled with alcohols but then mostly ethanol was used for heavy duty vehicles. Interests in the use of alcohol fuels depends not only on a possible replacement of some share of imported motor fuels or crude oils with domestic fuel constituents, but also on possible environmental improvements such as reductions of the emissions. During the years 1975 to 1983 there was also a demand for a lead free fuel to make it possible to introduce the catalytic emission technique. To fulfill this demand for high blend fuel, i.e. 15 %, methanol become of great interest. After 1983 when the Swedish Parliament decided to introduce the 1988 US emission standards for light duty vehicles and lead free gasoline, the use of high alcohol blend fuels became of less interest (Egebäck and Westerholm, 1988). Below follows a brief presentation of results from methanol projects carried out in Sweden in comparison with conventional gasoline or diesel fueled vehicles.

4.1 Light duty vehicles

A field test performed in Sweden involved a fleet of 22 light duty vehicles involving 7 different car makes was coordinated by the Swedish Motor Fuel Technology Co. (SDAB) and financed by the Swedish National Board for Technical Development (STU). The vehicles investigated were equipped with carburetors except one which was equipped with a fuel injection system. The project lasted for more than two years in the time period mid eighties, Project M100, (STU 1987). The aims of the project were to acquire new knowledge from automobiles fueled with methanol under Swedish conditions i.e. giving the Swedish government data that could be used for evaluating field tests for decisions and to give participating oil companies and car manufacturers knowledge and experience of designing engines and lubricating oils. The project recommendations may partly be summarized as: Wider fleet trials, development work regarding reduction of warm-up time, start-up systems and engine design for low ambient temperatures, engine lubricating oil adaptations and developments. To reduce exhaust emissions substantially, it was stated that fuel injection engines with catalytic converters would emit less exhaust emissions. This conclusion was later confirmed by other projects in Sweden and elsewhere. It was stated in the project that even under the cold weather conditions of Sweden methanol fueled vehicle are acceptable; however, the methanol concept needs to be improved i.e. cold start applicability. Recently, an evaluation of evaporative emissions from methanol and ethanol gasoline fuel blends has been carried out which concludes that ethanol blends are advantageous compared to methanol blends (Egebäck, 1994).

Table 4: Exhaust emission levels, US 72 driving cycle (Egebäck and Bertilsson, 1983)

Compound (g/km)	Vehicle concept				
	a	**b**	**c**	**d**	**e**
CO	16	3.0	13	5.6	7.7
HC	1.6	0.36	1.7	0.66	1.4
NO_X	1.8	0.20	0.78	0.19	2.2
(ug/km)					
PAH (sum of 14)	150	34	6.2	3.4	66
b(a)p	4.1	1.5	<0.1	<0.1	1.1
Methyl nitrite	104	35	$5.7\text{x}10^3$	$6.3\text{x}10^2$	150
Ethyl nitrite	na*	nd**	nd	na	nd
(mg/km					
Methanol	125	9.0	$3.4\text{x}10^3$	$1.3\text{x}10^3$	3.2
Ethanol	4.3	6.4	na	na	nd
Ethene	80	20	14	1.8	77
Propene	28	6.7	5.6	nd	30
Benzene	110	35	nd	nd	100
Toluene	230	41	nd	nd	190
Ethyl benzene	155	24	nd	nd	150
Formaldehyde	35	1.3	110	19	30
Acetaldehyde	nd	nd	nd	nd	nd
Particle raw extract mutagenicity (k-rev/km) Strain					
TA 98 -S9[#]	29	3.4	1.0	0.5	10
TA 98+S9	15	1.0	1.5	0.7	11
TA 100-S9	25	2.1	0.8	<0.1	33
TA 100+S9	40	5.3	3.7	1.3	30

* not analyzed, ** not detected, [#] Without -, with + metabolic activation.

a. lead free 15% methanol. **b.** Lead free 15% methanol and a catalyst with feed back control. **c.** 95% methanol. **d.** 95 % methanol and a catalyst without feed back control. **e.** leaded gasoline.

Table 4 shows exhaust emissions factor results from vehicles year models 80/81. The vehicles may be seen as engine concepts at a relatively early stage of development i.e. the engines were not adapted for alcohols. Comparing the emissions and biological data emanating from 15% methanol and neat gasoline, i.e. vehicle concepts **a** versus **e,** there is no major advantage in using a 15% methanol gasoline blend compared to gasoline. Using neat methanol as fuel results in relative large emissions of non-combusted methanol and methyl nitrite was emitted. As shown in the Table the measured HC values (vehicle concepts **c** and **d**) are underestimated. Due to the large methanol emissions the HC value is approximately a factor of two too low which may be explained by the response factor of methanol using a flame ionization detector (FID). This shows that it is of importance to quantify methanol emissions in exhaust samples using a methodology avoiding on-line measurements and using a FID to estimate a potential under estimation of determined HC values. In general, emissions of formaldehyde (and probably acetaldehyde) are larger from methanol fuel concepts compared to gasoline. To summarize Table 4, it is obvious that a catalyst exhaust after-treatment system reduces measured exhaust components as well as biological activity. Furthermore, selection of fuel has a relative large impact on exhaust emissions emitted from the vehicles i.e. high level blends of methanol do not alone give any significant emission reductions.

Table 5: Exhaust emission factors from catalyst equipped vehicles, US 78 driving cycle (STU, 1987).

Compound	Fuel			
(g/km)	M90	M90	M95	M100
CO	0.99	3.2	6.3	20.7
HC	0.17	0.41	0.64	0.48
NO_X	0.57	0.46	0.40	0.11

In Table 5, the HC emissions (unburned fuel) are underestimated due to expected relatively large methanol emissions, cf. Table 4 and discussion above. As shown in the Table, using increased methanol contents in the fuel increases the emissions of carbon monoxide and decreases the emission of nitrogen oxides. Besides this, carbon monoxide formed in the combustion process in the engine cylinders and non-combusted methanol in the exhaust produce, in principal, carbon monoxide in the "hot" three-way catalyst in accordance to reaction IV. This may explain increased tail pipe carbon monoxide emissions in Table 5, as fuel methanol content increases. Furthermore, hydrogen produced in the catalyst may react with nitrogen monoxide in accordance to reaction VI (Stadsluften, 1990) reducing nitrogen oxides as shown in Table 5. Please note that reactions IV and V are the reverse reaction for methanol synthesis i.e. reactions I and II, respectively. Clemmens and Martin (Clemmens and Martin, 1990) have reported that decomposition of methanol in a catalyst section produces carbon monoxide, carbon dioxide and hydrogen in accordance to reactions IV and V. The technique has been discussed and investigated by the authors as a possible cold starting method for methanol fueled engines. However, the major reason for the reduction of NO using methanol/methanol blends is the heat of vaporization of methanol which decreases the combustion temperature in the engine cylinders and thereby decreases NO formation.

$$\text{MeOH} + \text{heat} \Rightarrow CO + 2H_2 \qquad \text{(IV)}$$

$$\text{MeOH} + H_2O + \text{heat} \Rightarrow CO_2 + 3H_2 \qquad \text{(V)}$$

$$2NO + 2H_2 \Rightarrow N_2 + 2H_2O \qquad \text{(VI)}$$

In a project (Egebäck et al., 1984) several series of tests were carried out in order to study the emissions of CO, HC and NO_X and the fuel consumption when using M15, gasoline and E5 as fuels. Two different passenger cars, a Saab 900 S without catalyst and a Saab 900 EMS with a three way catalyst, were used for the study.

In addition to tests at the ambient temperature of 22 °C the data includes tests at 5 °C and -10 °C on the Saab 900EMS (without catalyst). The data shows a significant increase in the emission of CO and HC at lower temperatures, Table 6a.

Table 6a. Tests on a Saab 900 EMS (without catalyst) at different ambient temperatures, US 73 test (Egebäck et al., 1994).

	22 °C			5 °C			-10 °C		
Fuel	CO	HC	NO_X	CO	HC	NO_X	CO	HC	NO_X (g/km)
M15	12.1	1.13	1.04	17.1	1.97	1.14	22.8	2.53	1.57
Gasoline	21.1	1,20	1.12	17.5	1.48	1.65	43.0	2.78	1.08
E5	12.66	1.16	1.29	21.6	1.34	1.44	35.7	2.35	1.24

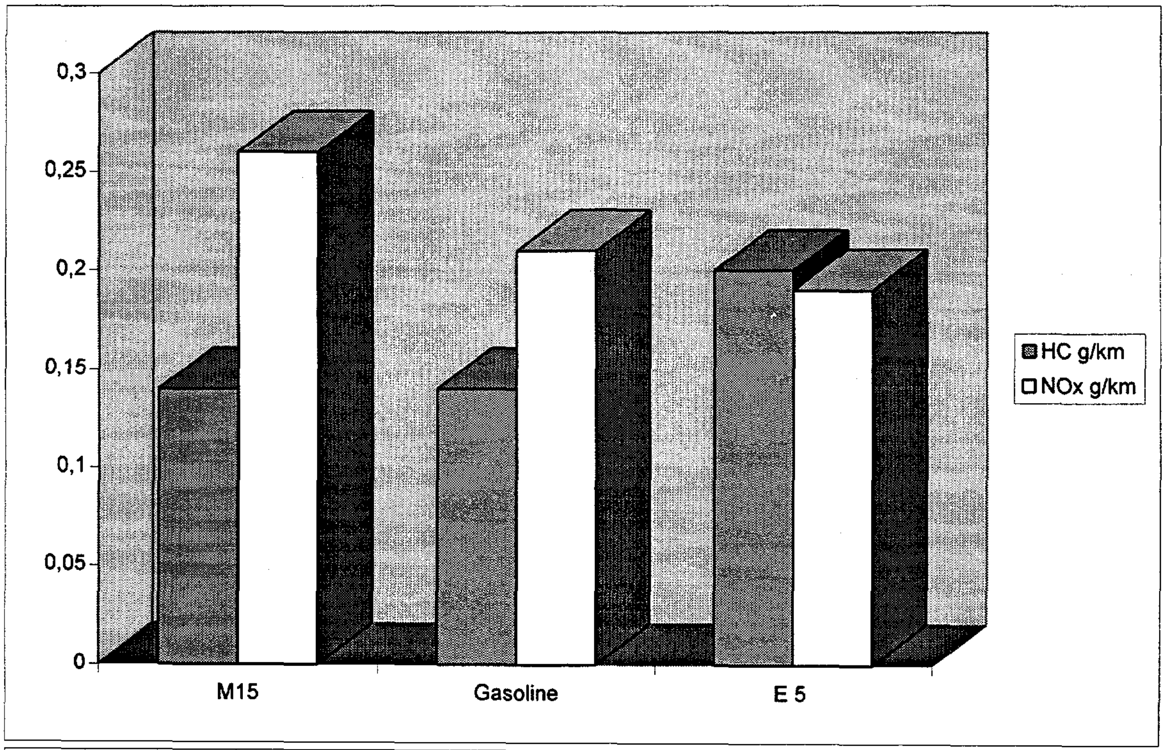
Results from a test according to the Swedish A12 emission regulations of an M100 car has been reported to be 3.86 g/km, 0.49 g/km and 0.02 g/km of CO, HC (FID analysis) and NO_X respectively (Laveskog, 1990). The fuel consumption was 1,90 l/10 km (methanol) and the odometer reading of the car was 210 000 km. The car was also tested in order to study the effect on the emissions when using a heated catalyst. The results without/with the heated catalyst (1 minute after start, 1000 W) were 36.4724.0 g/km, 10.05/8.20 g/km and 0.28/0.26 g/km for CO, HC and NO_X respectively.

Table 6b shows the emission factors emanating from decreased ambient temperatures using a 15% methanol gasoline blend. As may be seen in the Table, emissions increase as the ambient temperature decreases. The emission value measured for formaldehyde at -10 °C may be too low due to the condensation of water in sample lines which disturbs the sampling procedure. The contribution from vehicle cold start emissions to air pollution in general have been more in focus during recent years and countries are considering specific cold temperature regulations if automotive emissions should be reduced further. A critical step in that direction is to decrease the time which is needed for the catalyst section and the engine to reach working temperatures. At Volvo Car Company a heated pre-catalyst system has been constructed which reduces the light off time which results in lower cold start emissions. Depending on the fuel used, the light off time varies. With a 85% methanol gasoline blend as fuel a standard ceramic catalyst has a light off time of around 150 seconds. The corresponding value for gasoline is approximately 125 seconds. However, using the heated pre-catalyst system the light off time for a standard catalyst is about 25 seconds (Olsson et al., 1992).

Table 6b. The impact of lowering ambient temperatures (Egebäck et al., 1984), exhaust emission levels, US 73 driving cycle, mean values of 5 different cars.

Compound	Ambient temperature		
(g/km)	22 °C	5 °C	-10 °C
CO	15	17	24
HC	1.6	2.0	2.8
NO_X	1.5	1.6	1.7
(ug/km)			
PAH (sum of 14)	210	400	930
(mg/km)			
Particulate	20	18	45
Formaldehyde	19	20	13
Acrolein	3.64.	8	6.7

Vehicle	Test	Fuel	CO g/km	HC g/km	NOx g/km	Fc l/10 km
Saab 900S	USA 78	M15	1,3	0,14	0,26	1,21
Saab 900S	USA 78	Gasoline	1,14	0,14	0,21	1,04
Saab 900S	USA 78	E 5	1,41	0,2	0,19	1,11



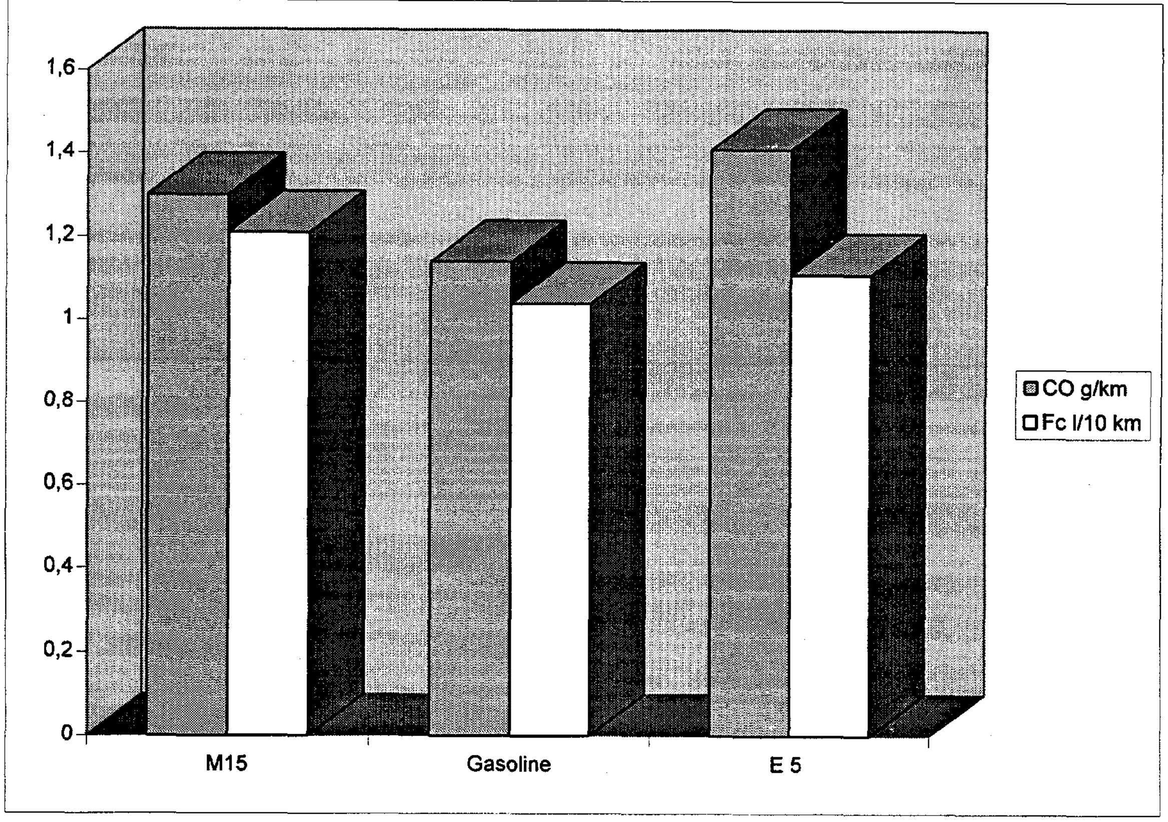
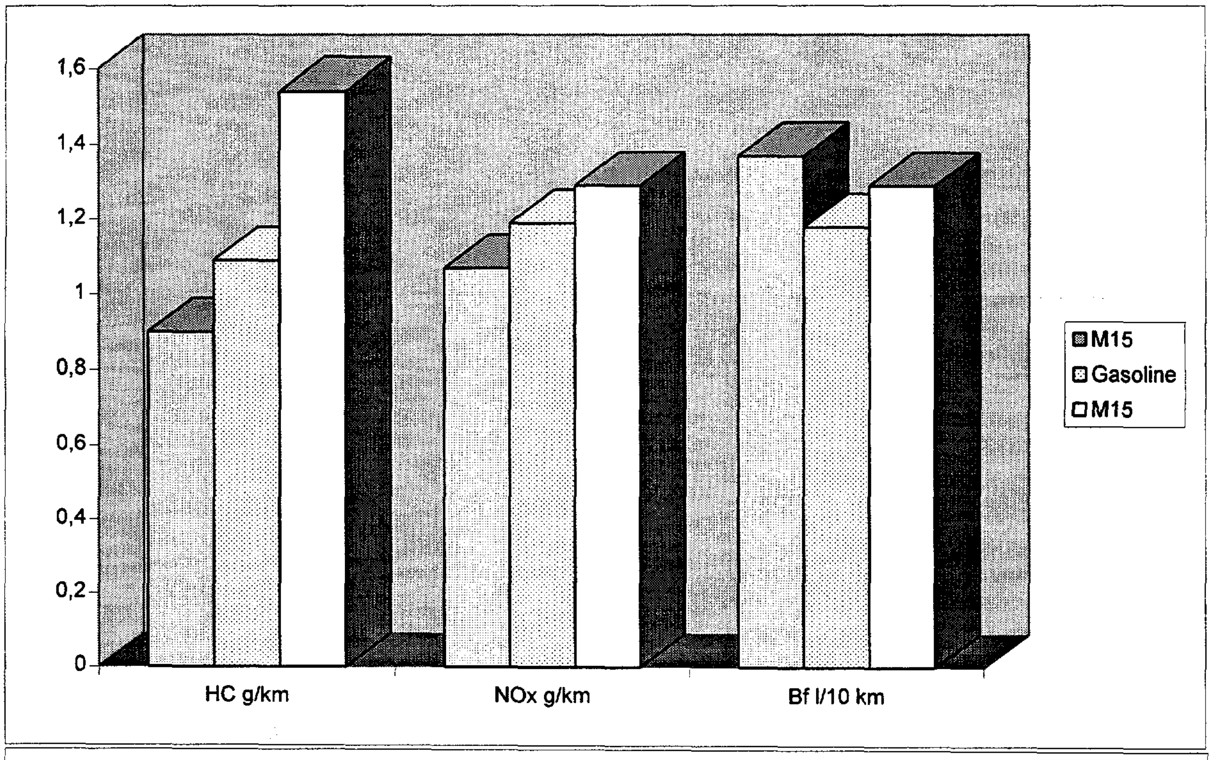


Figure 3a. Comparison of HC, NO_X and CO-emission respectively and fuel consumption when using different fuels, vehicle with 3-way catalyst.

Vehicle	Test	Fuel	CO g/km	HC g/km	NOx g/km	Bf l/10 km
Saab 900EMS	USA 78	M15	9,21	0,9	1,07	1,37
Saab 900EMS	USA 78	Gasoline	15,78	1,09	1,19	1,18
Saab 900EMS	USA 78	M15	9,35	1,54	1,29	1,29



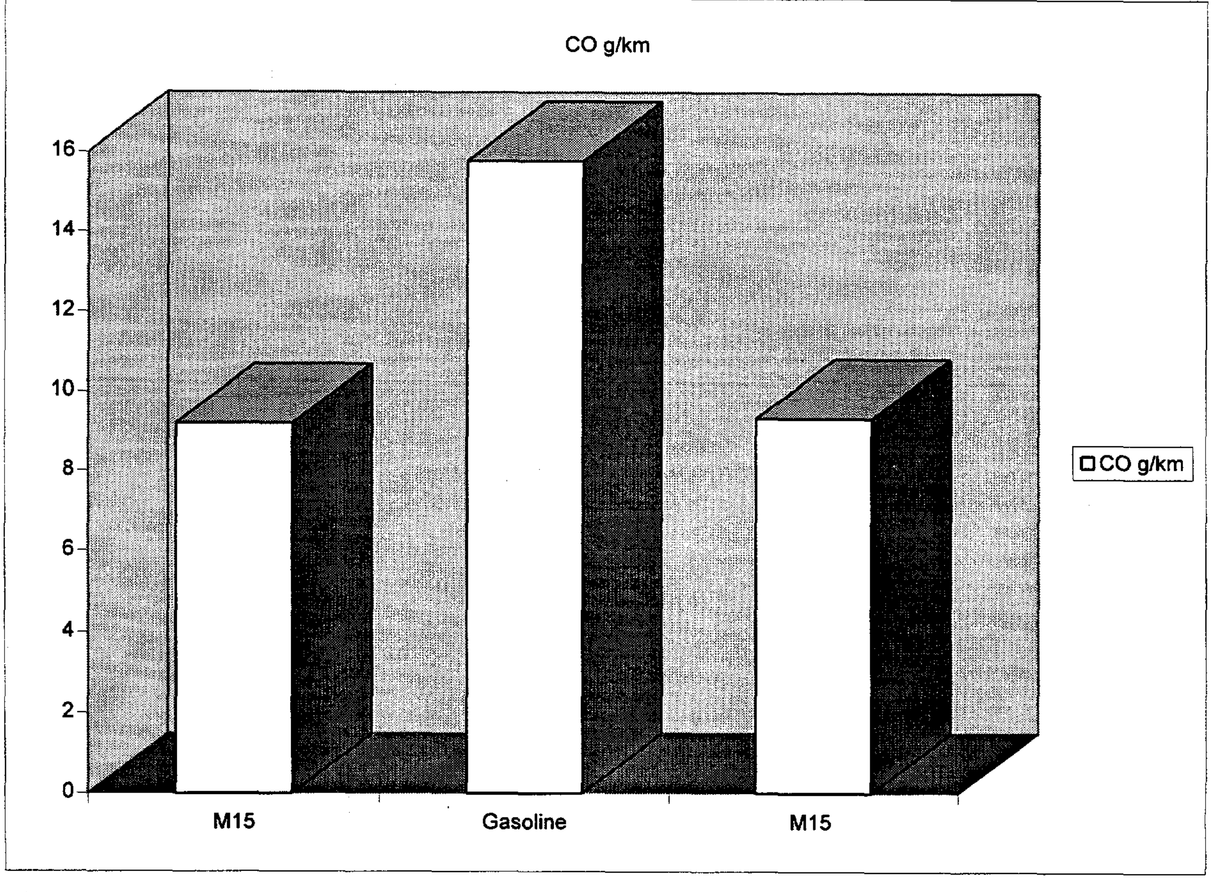


Figure 3b. Comparison of HC, NO_X and CO-emission respectively and fuel consumption when using different fuels, vehicle without catalyst.

Using neat gasoline, the electrically heated pre-catalyst system reduced HC, NO_X and CO emissions by 40%, 10% and 22%, respectively, in a US FTP -75 test. Table 7 shows the emission characteristics of the electrically heated pre-catalyst system emanating from 85% methanol gasoline blend in the US FTP-72 emission test, except HC, CO and NO_X which are measured in the US FTP 75. Summing up the Table, the 85% methanol fuel emissions are relative low, though slightly increased formaldehyde emissions may be indicated. Regarding biological activity determined in the exhaust:- in the absence of metabolic activation no significant biological effects were determined. The overall effects are low and are in the lowest range previously determined in exhaust from catalyst equipped gasoline or gasoline alcohol fuel blend fueled vehicles (Rannug, 1983) cf. Table 4. The heated pre-catalyst system developed at Volvo is commercially available on the market and is presently used by a German auto maker of luxury cars.

Table 7: Emission factors from a electrically heated pre-catalyst system (EHC) (Olsson et al., 1992) compared to standard three way catalyst system (TWC) year model 1993 (Westerholm et al., 1996), US 72 driving cycle except for a notation which is US 75, mean values.

Compound	Fuel/ catalyst concept	
(g/km)	85% methanol/ EHC	gasoline/ TWC
CO	0.54	1.5
HC	0.03	0.16
NO_X	0.08	0.1
(ug/km)		
PAH (sum of 28)	1.0	2.9
B(a)P	nd**	0.09
Methyl nitrite	3.0	na*
Ethyl nitrite	na	na
(mg/km)		
Methanol	1.0	na
Ethanol	na	na
Ethene	na	na
Propene	na	na
Benzene	7.5	7.9
Toluene	7.5	11
Ethyl benzene	1.5	na
Formaldehyde	2.0	0.55
Acetaldehyde	na	0.45
Strain, particulate samples		
(rev/km)		
TA 98 -S9[#]	ns[b]	na
TA 98+S9	0.8	na
TA 100-S9	ns	na
TA 100+S9	2.1	na

*not analyzed, ** not detected, [#] Without -, with + metabolic activation. a. US FTP 75. b. not significant

4.2 Flexible Fuel Vehicles

Flexible fuel vehicles are designed as to be fueled with pure gasoline or with a gasoline/

alcohol blend with up to 85 - 90 % (usually 85 %) of the fuel in the tank of the vehicle. A project is under way, to be carried out in Sweden, which will evaluate, among other factors, the performance and the emissions of the vehicles. A report is under preparation (Rydén and Egebäck, 1997) and Table 8a shows one set of data for regulated and unregulated emissions.

In the project, which is organised by SSEU (The Swedish Ethanol Development Foundation) and partly financed by KFB, 53 vehicles are being tested in the field at many places in Sweden. The characterization of the emission has shown that, in general terms, all the emission components are at the same low level as for a gasoline fueled vehicle equipped with a well functioning emission control system. The driveability of the vehicles is reported to be good even during wintertime at ambient temperatures well under zero degrees Celsius.

Table 8a. Result from emission measurements on vehicles in a fleet of FFV's in Sweden.

Results from tests on a flexible fuel vehicle (Ford Taurus)

Fuel	Test	Temp. °C	Odometer km	CO g/km	HC g/km	NOx g/km	CO2 g/km	Fuel cons. l/10 km
E85	EC2000	-7	2 727	7,15	1,52	0,09	281	1,53
E85	EC2000	+22	2 783	1,67	0,18	0,06	242	1,27
CEC RF-08-A-85	EC2000	-7	2 956	10,77	1,18	0,07	298	1,34
CEC RF-08-A-85	EC2000	+22	2 966	1,21	0,19	0,13	265	1,13
E85	FTP-75	-7	2 738	4,27	1,66	0,06	278	1,49
E85	FTP-75	+22	2 766	0,84	0,11	0,07	277	1,43
CEC RF-08-A-85	FTP-75	-7	2 939	5,09	0,58	0,06	295	1,28
CEC RF-08-A-85	FTP-75	+22	2 977	0,71	0,09	0,08	278	1,17

Fuel: E85=85 % Ethanol+15 gasoline. CEC RF-08-A-85=Europen Reference Gasoline

Results from tests on a flexible fuel vehicle (Ford Taurus)

Names	ECE15:1 [mg/km]	ECE15:2-4 [mg/km]	EUDC [mg/km]	Test Avg. [mg/km]	ECE15:1 [mg/km]	ECE15:2-4 [mg/km]	EUDC [mg/km]	Test Avg. [mg/km]
Methane	1158	15,5	1,2	112	176	12,8	3,5	21,9
Ethane	121	0,0	0,0	11	21	0,0	0,0	1,9
Ethene	1437	0,0	0,0	132	147	0,0	0,4	13,8
Propene	123	0,0	0,0	11	21	0,0	0,0	1,9
Acetylene								
iso-Butene	31	0,0	0,0	3	5	0,0	0,0	0,4
iso-Pentane	222	7,0	2,2	24	40	4,5	1,7	6,0
1,3-Butadiene	31	0,0	0,0	3	4	0,0	0,0	0,3
Benzene	306	1,8	0,6	29	34	0,8	0,5	3,7
Toluene	624	2,4	0,0	58	74	3,8	0,6	8,2
Ethylbenzene	114	0,0	0,0	10	15	0,0	0,0	1,4
m-,p-xylene	314	0,0	0,0	29	42	0,0	0,0	3,9
o-xylene	117	0,0	0,0	11	17	0,0	0,0	1,6
Formaldehyde	25	8,15	1,74	6	20	3,97	0,75	3,4
Acetaldehyde	1162	1,66	0,14	107	208	0,05	0,12	19,3

The use of M50, M85 and E85 was studied by VTT in Finland as a part of an investigation of different alternative fuels within an IEA (International Energy Agency) project.(VTT, 1996). One engine and four FFV's were tested of which 2 vehicles were "Nordic vehicles (codes 5 and 8)", prototype vehicles), one was an "European vehicle (code 6)" and one was an "US vehicle (code 7)". The results of the tests according to the Swedish emission regulations A14 are presented in Table 8b.

Table 8b. Results from tests of four different FFV's fueled with M85 and E85 respectively, g/km. Test temperature 22 °C.

Vehicle code	M85 fuel			E85 fuel		
	CO	HC	NO_X	CO	HC	NO_X
5	2.63	0.36	0.28	2.80	0.38	0.27
6	0.57	0.05	0..04	No result presented		
7	1.43	0.06	0.06	- " -		
8	0.20	0.03	0.19	- " -		

These vehicles were also tested at lower temperatures of which the results from tests at -7 °C on three vehicles (results from only three vehicles are available) are presented in Table 8c.

Table 8c. Results from tests of three different FFV's fueled with M85 and E85 respectively, g/km. Test temperature -7 °C.

Vehicle code	M85 fuel			E85 fuel		
	CO	HC	NO_X	CO	HC	NO_X
5	4.53	1.02	0.27	5.89	1.41	0.29
6	2.56	0.86	0..06	No result presented		
7	4.19	0.39	0.07	- " -		

Within the Auto/Oil Air Quality Improvement Research Program (Auto/Oil, 1996) in the USA investigations of various types of vehicles have been performed in order to carry out emission inventories. One of these investigations covers five vehicle "fleets" of which two comprised FFV's, M85 and E85. Special attention was directed to the problem observed "regarding the ability of the (EPA) urban driving cycle of the federal test procedure (FTP) to examine these off-cycle driving conditions". There is an special concern about the impact on the emissions when driving at higher speeds. In order to study this impact the US EPA has developed a high-speed, high-load driving cycle, referred to as the REP05. The results are presented in Table 8d.

Table 8d. Tests on FFV's fueled with gasoline, M85 and E85 carried out within the Auto/Oil program. The emissions are expressed in g/km and the fuel consumption in l/10 km.

Fuel	Tests according to the FTP cycle						Tests according to the EPA REP05 cycle					
	HC	NMHC	NMOG	CO	NO_X	FC	HC	NMHC	NMOG	CO	NO_X	FC
A	0.147	0.127	0.121	2.27	0.265	1.43	0.176	0.153	0.144	7.96	0.518	0.96
C2	0.111	0.094	0.083	1.86	0.198	1.15	0.161	0.135	0.129	9.14	0.398	0.98
Z1	0.108	0.073	0.157	1.95	0.214	1.90	0.060	0.045	0.042	7.58	0.340	1.60
ZC2	0.100	0.066	0.159	1.54	0.204	1.88	0.047	0.035	0.052	6.71	0.280	1.57
A	0.124	0.106	--	1.28	0.267	1.18	0.143	0.149	--	6.96	0.416	0.92
C2	0.106	0.087	0.093	1.39	0.249	1.28	0.155	0.131	0.137	8.75	0.360	1.07
E85	0.131	0.081	0.137	1.49	0.180	1.53	0.081	0.056	0.050	5.74	0.261	1.27

Fuels: A=Higher levels of aromatics, olefins, benzene, RVP, T_{50}, T_{90} and sulfur and no MTBE compared with fuel C2 which was lower in all parameters and contained 11.2 vol% MTBE. Z1 and ZC2 were two M85 fuels of which Z1 contained more sulfur than ZC2 which contained 1.4 vol% MTBE. These fuels were used for a fleet of three vehicles (Dodge Spirit, Ford FFV Taurus and Chevrolet Lumina). TWC for all three vehicles.

Fuel E85 was, beside the fuels A and C2, used in a fleet of three vehicles (Chevrolet Lumina, Ford Taurus Prototype and Plymouth Acclaim Prototype). DTWC for Ford Taurus, TWC for the other two.

4.3 Heavy Duty Vehicles

Around 1980 some experiences were gained concerning the use of methanol in heavy duty vehicles in Sweden. Two buses own by Stockholm bus authorities and one truck owned by The Swedish Motor Fuel Technology Company (SDAB) equipped with a dual fuel engine, where methanol was the main fuel and diesel oil was injected in by a separate pump and used as an ignition promotor. The engine was emission tested in both Sweden and the USA (IEA, 1986).

According to SDAB (IEA,1986) the main potential of the dual fuel system (methanol/diesel) is that the emission of NO_X and particles can be reduced. A not optimized oxidation catalyst showed an efficient reduction of CO and total unburnt fuel but did not change the emission of formaldehyde.

5. UNITED STATES EXPERIENCE WITH ALTERNATIVE FUELS

In the US today, the production cost for gasoline is 60 cents/gal. When using methanol the fuel consumption is 1.65 times higher (by volume) compared to the fuel consumption when using gasoline. For dedicated methanol vehicles the increase of the fuel consumption would be somewhat lower - 1.40 times the fuel consumption of gasoline. That means that the production cost of methanol should be not more than 35 - 40 cents/ gal to be competitive. When using a direct methanol fuel cell there will be a large improvement in the methanol consumption - 0.8 compared with gasoline, i.e. the competitive production cost for methanol could be 75 - 80 cents/gal. To day the cost of methanol at the pump is $ 2.40/gal and for gasoline $1.55 - $1.60/gal. Therefore, methanol is not yet economically competitive at least when used in a conventional otto or diesel cycle engine.

In the USA there are large resources of coal. At one time, many considered that this could be a major feedstock for methanol production although at this time this seems unlikely for environmental reasons - sulfur and other compounds. In addition, there is a great demand for production of acetic acid and coal will most likely be used for that production.

Natural gas is used for the production of methanol at the present time and there are no short term plans to use biomass. (95 cu. ft. of natural gas equals 1 gallon of methanol.)

According to an investigation there are 180 - 200 locations (refineries etc.) where gases are flared. The use of that gas for production of methanol would give 200 million gallons of MeOH/year.

Whether for environmental or energy security reasons, increased reliance on alternative fuels has been stimulated by several steps in recent years:

- The Alternative Motor Fuel Act of 1989 instructed the US Department of Energy (DOE) to introduce alternative fuel vehicles (AFV's) into the Federal fleet, and conduct a research, development and demonstration program on light and heavy duty vehicle technologies for alternative fuels. Fuels were restricted to alcohols and natural gas.

- Designed primarily to address urban air pollution, the Clean Air Act Amendments of 1990 include requirements for greater reliance on "clean" fuels.

- Executive Order 12759, Section 11, April 1991, instructed Federal agencies to acquire the "maximum number practicable" of AFV's. In response, DOE worked with the General Services Administration (GSA) and other agencies to develop a 5-year plan for the purchase of AFV's on an accelerated schedule.

- The Energy Policy Act of 1992 (EPACT) while avoiding new vehicle fuel efficiency requirements contains a strong push for alternative fuels. The intent of the 1992 Energy Policy Act (EPACT) is to spur supply and demand for fuels other than gasoline or diesel by requiring fleets to purchase an increasing number of vehicles that run on alternative fuels: including electricity, ethanol, methanol, natural gas, propane, liquefied petroleum gas (or LPG), and hydrogen. Vehicles that are dual-fueled (which run on gasoline or an alternative fuel from separate tanks at the flip of a switch) or flexible fuel (which can run on gasoline and an alternative fuel, in any combination, from the same tank) are permitted in this Act. EPACT established specific numerical and percentage requirements for Federal fleet acquisition of AFV's, allowed use of converted vehicles in the Federal fleet, and expanded the eligible alternative fuels to include liquefied propane gas (LPG), hydrogen, and electricity. EPACT also adds numerous non-Federal fleet mandates, regulations, and programs.

- Executive Order 12844, April 1993, directed Federal agencies to adopt aggressive plans to substantially exceed the alternative fuel vehicle purchase requirements established by the Energy Policy Act of 1992.

- The US Department of Energy (DOE) program for Federal AFVs has evolved from a small demonstration and data collection program into a large-scale effort to promote the commercialization of AFV's and the development of alternative fuel infrastructure. From the very beginning, DOE has worked closely with the automakers (original equipment manufacturers or OEMs) to obtain various types of AFV's. It has also funded several studies to evaluate the potential benefits and long term feasibility of alternative fueled vehicles including those which can be derived from biomass.

- In a recent study required under the EPACT, the DOE considered the technical and economic feasibility of replacing 30% of gasoline by alternative fuels by 2010.(DOE 1995b).
  As illustrated below, the report concludes that an approximately 1/3 replacement is feasible, with the primary replacement fuels being methanol or ethanol; which fuel has the greatest penetration depends on whether ethanol is given a tax advantage as is currently the case in the US. Each of these fuels can be produced from biomass. Figure 4. Alternative fuels feasibly study EPACT 502(b).

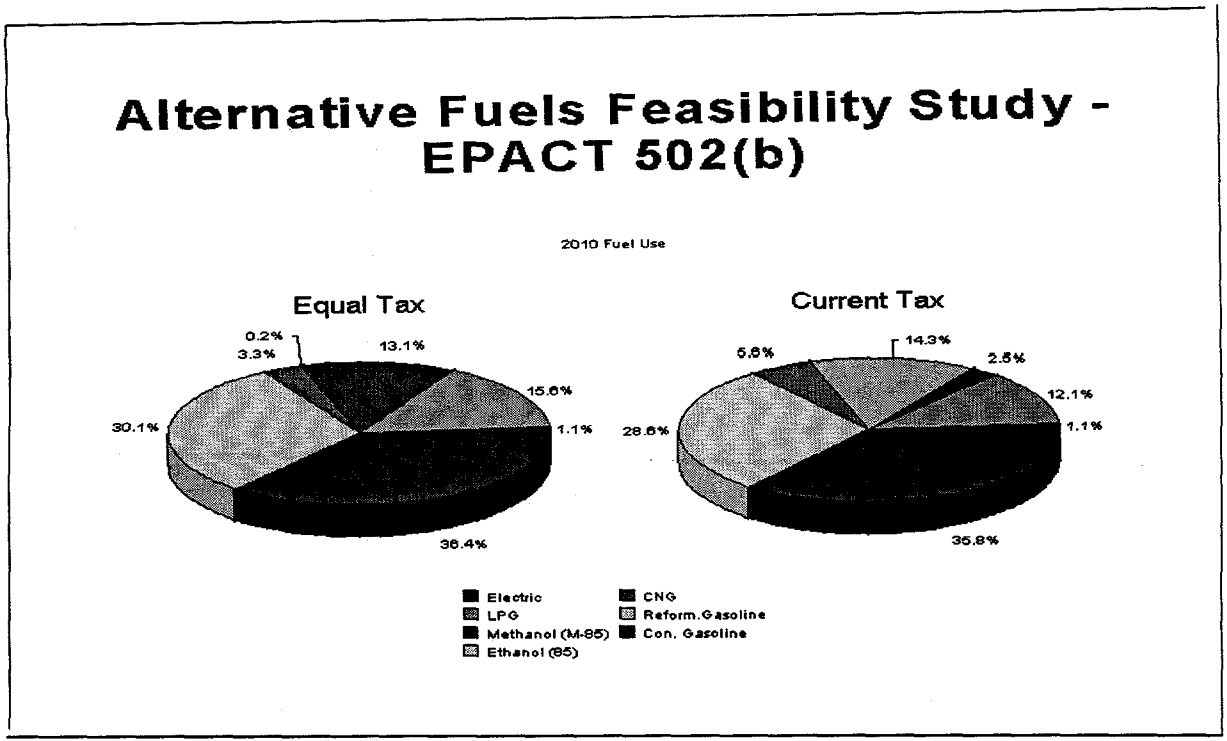


Figure 4a. Alternative fuels feasibly study EPACT 502(b), 2010 fuel use.

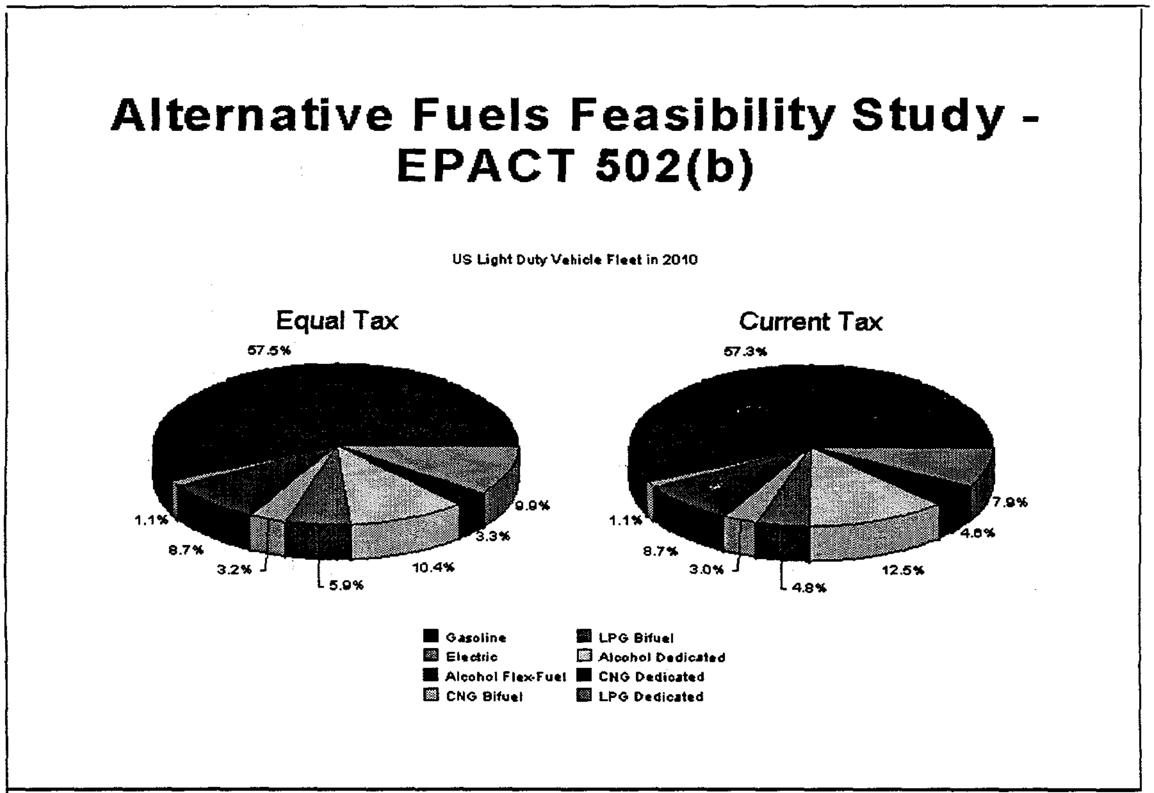


Figure 4b. Alternative fuels feasibly study EPACT 502(b), US light duty vehicle fleet 2010.

The Los Angeles County Metropolitan Transportation Authority (MTA) decided in autumn 1993 to phase out their diesel buses and to start an investment in bus technologies aimed at the use of alternative fuels. The MTA is responsible for the communal public transport system in Los Angeles. As the MTA is the second largest transit bus company in the US, their decision to purchase only bus concepts for alternative fuels was expected to affect the future decisions of other bus companies nationally and internationally (Wuebben, 1993). The decision criteria found most important was: "Environmental impact, cost, reliability and potential emission credits". The fuels that MTA considered interesting were natural gas and methanol. Comparing operating costs for clean fuel buses with a diesel fueled buses over the life time of the bus the cost difference will be less than 2 cents per kilometer. Presently the MTA bus fleet comprises a total 2500 buses of which 343 are alcohol fueled, and of these 70 were fueled with ethanol and 273 fueled with methanol in 1995 (Karbowski and Davies, 1995) and the changing over from methanol to ethanol has accelerated. MTA have gained a lot of knowledge and experience in the field of alternative fueled bus fleets.

Table 9 shows the major alternative fuel vehicle demonstrations in US, as reported by US Environmental Protection Agency in 1993.

Table 9: Major Alternative Fuel Vehicle Demonstrations in the U.S. reported by US EPA in 1993 (US EPA, 1993).

LOCATION	SPONSORS	FUELS	VEHICLES	
			In operation	Planned
California	California Energy Commission	M85	500 sedans 400 sedans (FFV)	200 vans (FFV) 5000 sedans (FFV)
California	Utility Companies	Electricity	90 (mostly vans)	
California	CALTRANS	Hydrogen	1	
California	Utility Companies	CNG	1000 light trucks	
Los Angeles	Southern California Rapid Transit DST.	Methanol CNG	40 buses 11 buses	200 buses
Los Angeles	L.A. Times	LPG	300 delivery trucks (retrofits)	
Los Angeles	Fed Express, SCAQMD DOE, EPA, Others	CNG, Methanol Electricity, Reformulated Gasoline, LPG	~100 delivery vans (some FFV)	
Los Angeles	Southern California Gas Co, UPS	CNG	20 package cars up to 2700 (retrofits) package cars (retrofits)	
New York City	Triboro Coach Assn; Command Bus Co; EPA, DOT, Federal Transit Admin.	Methanol CNG	6 buses 2 buses	12 buses 12 buses
New York	Brooklyn Union Gas, NY City, Consolidated Edison Co.	CNG	350 cars, trucks, vans, (retrofits)	
Houston	Houston Metro	LNG/Diesel	300 buses	
Various	DOE, General Services Administration (GSA)	M85 CNG	65 sedans (FFV) ~800 light trucks	~700 (FFV)
Various	American Gas Assn, Gas Research Inst, Utility Companies	CNG	100-200 trucks	
Wisconsin, Illinois	State of Illinois, State of Wisconsin, DOE	E85	50 sedans (FFV)	
Minnesota	City of Duluth	LPG	300 snowplows trucks (retrofits)	

A problem that needs to be addressed is the potential possibility of misfueling vehicles due to the availability of several fuel qualities at gas filling stations. This problem may be accentuated due to an expected future increase in fuels available on the market. The Society of Automotive Engineers (SAE) and The California Energy Commission are co-operating in a project with the aim of developing technology that allows "the car to tell the gas pump" which fuel the engine should have. By this interactive electronic device the potential risk of misfueling the vehicle is avoided.

There are nearly 13 000 FFV's in California. A school bus program has 150 methanol fueled buses. Metropolitan Transportation Authority MTA has 70 ethanol fueled buses (see under visit at MTA, Los Angeles).

Accordingly to the US Environmental Protection Agency there are several hundred thousand alternative fuel vehicles operating in the US. The above chart focuses on larger demonstrations fleets reported by US EPA (US EPA, 1993). The vehicles are "dedicated" to run exclusively on a specific alternate fuel, unless otherwise indicated. Retrofits are vehicles built to run on gasoline which are later converted to use a gaseous fuel i.e. compressed natural gas (CNG) or liquid petroleum gas (LPG). Flexible-fuel vehicles (FFV's) can operate on either gasoline or alcohol i.e. ethanol, methanol or any combination of methanol/ethanol.

5.2 Flexible Fuel and Dedicated Alcohol Fueled Vehicles

In 1992 the Auto/Oil air quality improvement research program (Auto/Oil, 1992) reported exhaust emission factors from pre-1990 prototype Flexible-fuel vehicles (FFV's) fueled with neat gasoline, 10% and 85% methanol gasoline blends. The vehicles were designed to operate on M85 or neat gasoline or any mixture of methanol i.e. 0 to 85 % methanol in gasoline. Table 10 shows the emission results. Comparing M85 with M10 reveals that CO, OMHCE (organic material hydrocarbon equivalent), benzene, 1,3-butadiene and acetaldehyde emissions are decreased, however, NO_X, methanol and formaldehyde emissions are increased, and NMOG is basically the same. Comparing M85 with neat gasoline industry average, emissions are lower or similar except for NO_X, methanol and formaldehyde which are larger i.e. 20 %, >200 % and >500 %, respectively. The relatively large methanol and formaldehyde emissions determined using M85 may be explained by unburned methanol and partial combustion of methanol into formaldehyde. Running losses determined were relatively large from the investigated flexible/variable vehicles. This was explained by the fact that the vehicles were not designed to reduce/control running losses.

Furthermore, in another report by Auto/Oil (Auto/Oil, 1992b), exhaust emissions from three dedicated (i.e. operating on a single fuel) methanol vehicles have been published. The vehicles constructed by Nissan (Sentra) and Toyota (Corolla) were designed to run on M100 and the vehicle constructed by General Motors (Lumina) was designed to run on M85 only. Table 11 shows the emission factors which have been determined. A comparison with prototype flexible-fuel vehicles presented in Table 10 reveals that the vehicles, Table 11, are in general for the determined emission factors lower, with Nissan excluded. This is explained by the fact that the Nissan engine was designed as a lean burn engine and the catalytic converter exhaust after-treatment system was used to control HC and CO only. Reduction of NO_X was mainly due to the lean burn engine design. However, it is important when comparing emission factors from different fuels and projects to take into consideration that a relative large variation between vehicles and vehicle to vehicle may occur. This is one conclusion emanating from a study including six vehicles and ten fuels (Gabele and Black, 1993).

Table 10: Emission of regulated and unregulated compounds from prototype flexible-fuel vehicles, pre 1990 in comparison to neat gasoline (Auto/Oil, 1992).

Compound	M10	M85	neat gasoline Industry average
(g/km)			
CO	1,6	1,2	1,75
NMOG*	0,15	0,17	0,15
OMHCE**	0,17	0,11	0,18
NO_x	0,25	0,30	0,25
(mg/km)			
Benzene	7,3	1,5	9,1
1,3-butadiene	0,6	0,06	0,8
Methanol	6,2	124	0
Formaldehyde	1,6	9,2	1,8
Acetaldehyde	0,4	0,12	0,5

*non methane organic gases. **organic material hydrocarbon equivalent. NMOG includes the total weight of the non-reactive oxygen portion of those compounds, methane included.

Table 11.Emission of regulated and unregulated compounds from dedicated methanol vehicles, (Auto/Oil, 1992b).

Car make/fuel	General Motors	Nissan	Toyota
Compound	M85	M100	M100
(g/km)			
CO	0.50	0.51	1.0
NMOG*	0.06	0.22	0.12
OMHCE**	0.04	0.10	0.06
NO_x	0.14	0.32	0.24
HC	0.03	0.08	0.05
(mg/km)			
Benzene	0.62	nd	nd
1,3-butadiene	nd#	nd	nd
Methanol	0.04	0.21	0.11
Formaldehyde	3.5	16.9	4.7
Acetaldehyde	nd	nd	nd

*non methane organic gases. **organic material hydrocarbon equivalent. NMOG includes the total weight of the non-reactive oxygen portion of those compounds, methane included. #not determined.

Decker and co-workers (Decker et al., 1993) report about a field experiment using multi-fueled Volkswagen (VW) vehicles. VW have been involved in the California Energy Commission (CEC) Light Duty Methanol Fueled Flexible Demonstration Program in USA/California. About 80 multi-fueled Jettas were included in the demonstration. The fuels used were methanol, ethanol and gasoline or any possible mixture of these. In this present report only results and experiences emanating from methanol or methanol/gasoline methanol blends are considered. It was confirmed that it is necessary to specify hydrocarbon emissions when investigating fuel impact on exhaust emissions i.e. 85 specific HC compounds were analyzed. The compounds dominating from M85 fueled vehicles, with respect to ozone forming potential in the exhaust are methanol and formaldehyde. These two compounds are responsible for more than 60 % of the total ozone forming potential. To meet TLEV, LEV and ULEV standards it is most likely necessary to use electrically preheated catalysts. However, it is stated in the report that "clean fuels, preferably methanol, seems to be a promising approach to the problems of environmental pollution and mainly ozone smog formation".

5.3 Heavy Duty Vehicles and Engines

It is stated that 80% of all criteria pollutant emissions and 70% of global-warming gas emissions(CO_2 andCH_4) are related to energy production, transport and conversion (AQMD, 1995). The TAO (Technology advance Office) has actively promoted commercial application of clean, renewable energy sources, such as solar, wind, geothermal, fuel cells and methanol conversion from landfill gas. When considering which vehicles can readily be fueled with methanol, it is fleets of buses which are leading the way. The TAO program in northern California began in 1983 and, through sponsorship, has now resulted in a fleet of 330 buses with the DDC 6V-92TA methanol engine, this being the largest fleet of such buses in the US. ("Building markets for low-emission technologies" 1995). Each month more than one million miles are accumulated on methanol buses and hundreds of tons of NO_X and PM10 emissions have been avoided in this area. Emission levels of 50% less NO_X and 75% lower PM10 have been reported.

Methanol combustion in diesel engines was the subject of an investigation carried out in Pennsylvania (Mitchell et al.1992). The US Department of energy (DoE) stated that the advantages of the above were that there were multiple resources from which to produce methanol, the technology is well developed, large scale production capacity is in place, existing distribution system can be fully adapted at low cost and utilization technology, compatible with simultaneous use of existing fuels is available.

Modification of two-stroke diesel engines for use with methanol had already taken place in Detroit by 1983, (Toepel et al., 1983). The report speaks of the possible sources of methanol, including natural gas, crude or residual oils, coal, lignites and biomass, and stated that the US has an abundance of all of these raw materials.

In a project sponsored by the Californian Energy Commission, (Jackson and Unnasch, 1985), the suitability of neat methanol as a fuel for transit buses was demonstrated The outstanding features of the emission data found in this project were the low oxides of nitrogen and low particulates. Here the tradeoff between NO_X and particulate does not occur, as in the case of diesel engines. In the case of the M.A.N. engine, the particulate emissions were found to be essentially eliminated. The poor results for the GM engine may have resulted from a contaminated test tunnel or an oil leakage into the airbox. In a comparison with diesel engines the road performance results were shown to be substantially the same, there was no difference in driveability except a problem with stalling for the GM engine which was on its way to being solved. Fuel consumption measurements gave the same results for the M.A.N. engine and its diesel counterpart while the GM methanol was better than the GM diesel by 14%. The costs of operating methanol engines was found to be higher than that for operating diesel engines but then, 1985, it was early days to say how the situation would develop.

Emissions from methanol powered buses were characterized and reported by Ullman (Ullman et al., 1986). They compared the M.A.N SU240 bus with catalytic exhaust aftertreatment and the GMC RT II 04 bus, with no aftertreatment of the exhaust. The results showed that the M.A.N. bus gave lower emissions except in the case of NO_X. They predicted, however, that substantial reductions in emissions would be possible with careful implementation of methanol fueling. When comparing the GMC methanol bus with a diesel bus it was found that the former gave higher emission levels, and even the fuel economy was worse.

Aldehydes and unburned fuel emissions were measured for two methanol fueled heavy duty diesel engines (Lipari and Keski-Hynnila 1986) and it was found that formaldehyde accounted for ca 98% of the total aldehydes from both engines. Aldehyde and unburned fuel concentrations were highest in the idle modes but could be reduced by catalytic treatment. They did, however, compare favorably with the emissions from conventionally fueled diesel engines. Particulate and NO_X emissions were very low for both engines and it was predicted that the former would meet the 1991 urban bus particulate standard.

A combustion system developed for use with neat methanol in a direct-injection four-stroke-cycle engine was found to give low fuel consumption and long component life (Kroeger 1986). It was found that glow plug assisted combustion with neat methanol was feasible, giving equivalent thermal efficiency compared to the baseline diesel engine. This combustion system was also found to be flexible and could be adapted for other cetane fuels in addition to methanol.

Another series of tests of neat methanol and diesel engines was carried out with the object of comparing various compositions of the fuel, by means of a thermodynamic analysis of the cylinder pressure and measurement of the exhaust emissions (Baranesco et al., 1988). It was found that the specification of the alcohol fuels was essential from the exhaust quality point of view and that glow plug assisted engine concepts were most promising. Hot surface ignition gave lower emissions than spark ignition. The preferred fuel was found to be neat methanol, butanol in the fuel, for example, giving higher NOX and HC emissions. M85 methanol, as used for SI engines, containing 5% higher alcohols and 10% HC, caused only slightly increased NO_X and HC emissions while the HC fraction of M85 fuel does not result in increased exhaust emissions.

The redesign and testing of the Detroit Diesel 6V-92TA engine, with seven alcohol fuel blends, which could ensure that it met the 1991 urban bus emission standards was reported (Carroll and Ullman, 1990). The fuels used were methanol or ethanol blended with water, unleaded gasoline and /or an ignition enhancer. When cold-start operation of the engine was possible, hesitation in response to command inputs were noted until the engine had run for two to five minutes. During hot-start operation the engine responded well. The engine met the 1994 federal HC standard of 1.3 g/hp-hr (1.74 g/kW-hr) only on M99A fuel. Based only on hot-start transient emission results, the engine met the 1991 Federal CO and NO_X standard on all fuel blends used. The 1994 Federal particulate standard of 0.10 g/hp-hr, using M99A and E160A fuels was only slightly exceeded, and was just below for E180, E160, M100 and E160A fuels and blends including gasoline giving greater particulate emissions. Increasing the ignition quality of the fuel by using Avocet tended to decrease OMHCE and CO emissions, increase NO_X emissions and had little effect on particulate emissions for both methanol and ethanol blends. It was stated that further development was needed to reduce OMHCE and particulate emissions below the stringent 1994 federal emission standards.

In California the above mentioned engine was tested with chemical grade methanol (M100), with 15% gasoline in the methanol (M85) and with an exhaust catalyst (with M100 as above) (Eberhard et al., 1990). The bus with M100 gave lower particulates, NO_X and heavy aldehydes than the diesel bus, formaldehyde and organic emissions were higher though. By using M85 and 100 + catalyst, the formaldehyde and organic emissions were reduced but heavy aldehyde emissions were increased. The exhaust catalyst reduced particulate emissions. The addition of water to M100 seemed to have no measurable impact on methanol engine performance.

Ignition improved methanol operation was the subject of a research project in California aimed at retrofitting the DDC 6V-92TAC diesel engine to operate on methanol (Wuebben et.al., 1990). The engine was modified by installing higher compression ratio pistons, higher flowrate mechanical fuel injectors and a different blower. The bus fuel system was also modified. A high-pressure electric fuel pump and fuel cooler were used to prevent methanol from boiling. Several different diesel engines have been converted to operate on methanol with ignition improvers. In the case of the DDC methanol engine this would have meant purchasing a new engine and installing electronic control wiring on the bus. By converting the diesel engine the existing engine can be used with only simple bus wiring modifications. Half of the 4 500 transit buses in the Los Angeles area were, at this time, equipped with DDC engine. The cost of a bus retrofit was about 22 000 dollars, requiring, as it did, stainless steel fuel tanks, a special dry-break filler and custom built mechanical fuel injectors. Evaluation was planned of the suitability of using less expensive materials.

Poppet valve and two-stage needle lift fuel injection, reduced swirl liners, increased compression ratio, catalytically-coated glow plugs and angle step-gap piston rings were among the methods of improving the compression ignition of methanol test (Laing and Winsor, 1990). The tests were performed on DDC's 6V-92TA methanol engines at several steady state operation conditions to evaluate possible reduction in fuel consumption and to improve exhaust emissions. Special attention was paid to measuring hydrocarbon emission performance, which tends to be indicative of improved ignition and combustion. Two-stage injection, reduced swirl, increased compression ratio and angle step-gap piston rings all provided significant HC reductions, with no benefits from using catalytically-coated glow plugs or poppet fuel injectors. The attempts at developing a new injector were aimed at the elimination of the spray hole type tip used in the injectors at the time of the investigation. The advantages of this would be reduced penetration and flame quenching from fuel on cylinder walls, reduced tip breakage and plugging and reduced maximum injector pressure. During the course of the program several additional ideas were conceived to further improve methanol combustion and it was envisaged that they would be investigated.

An extensive report has been prepared by Southern California Rapid Transit District (SCRTD) in order to document the methanol demonstration program currently in progress (Krabowski and Pellagrini, 1991). In the documentation the different phases of the introduction of transit buses are presented. This bus demonstration program has been an important element in the development of measures for reducing harmful exhaust emissions from urban buses. The efforts of the SCRTD have taken theoretical concepts and made them into a practical means of operating and maintaining a fleet of methanol buses. The objectives were to develop the subsystems necessary to operate the DDC 6V92 methanol fueled transit bus engine and to integrate this technology into a diesel powered bus fleet. This involved establishing bus engine and fuel system requirements, developing fueling facilities and training personnel. The integrity of data collected by the project was given a high priority.

During the two-year project two technicians from the SCRTD's Alternative Fuels Section performed all fuel system and methanol related repairs and also recorded all other pertinent data. The design and construction of the methanol fueling facility came prior to the deployment of the methanol buses. The location chosen to operate the methanol powered buses was also scheduled for construction of a new bus maintenance shop as well as diesel and gasoline fueling station. This allowed the development of the methanol fueling and maintenance facility as part of the original construction design. Service personnel were required to wear long sleeve white coveralls, eye shields, gloves and safety shoes, as part of standard diesel and methanol fueling procedure. The only modification necessary for methanol was the specifying of a methanol compatible glove, which is now standard for all fuels. All employees involved received training related to methanol familiarization. These training programs stressed liquid and vapor exposures as well as fire safety and spill procedures. The program format was developed using slides and video presentations, as well as lectures, which included handout material and question and answer sessions. The documented results of the demonstration project has lead to the development and maturing of the methanol powered transit bus as an environmentally sound and fundamentally practical, low emission strategy. Integration of this technology has been shown to be dependent on the three areas of vehicle technology, facility development and personnel training.

The Southern Californian Rapid Transit District has tested methanol, compressed natural gas and particulate trap technologies in order to meet exhaust emission standards (SCRTD, 1992). By the middle of 1992 they had accumulated ca 4.5 million miles on 71 buses. The District had by then ordered several hundred methanol buses and special storage facilities for the fuel since a methanol bus requires twice the amount of fuel by volume to be pumped and delivered as does a diesel bus. The establishment of replacement part supply storage had also caused some extra effort, and special maintenance staff had to be instructed. The District has also opened a Heavy Duty Vehicle Emissions Testing Facility (ETF) to evaluate emissions from such trucks and buses. All the testing was conducted by ETF staff. Emission data generated for these tests included all regulated emissions such as HC, CO, NO_X and PM as well as fuel economy, unregulated emissions of CO_2, OMHCE, methanol and formaldehyde.

In July 1988 the US Dept. Of Transportation, Urban Mass Transportation Administration, published the Training Manual for Methanol Fuel Use in Transit Operations, (UMTA, 1988), for personnel to be able to learn how to deal with methanol. Knowledge of fire safety and human toxicity is essential and these are well covered as are other aspects of handling and assessing methanol in this comprehensive manual.

The Californian Legislature had directed the Energy Commission in 1986 to carry out a program of technology development to expand the use of methanol fuel as a means of reducing air pollution (Wiens et al., 1993). The Methanol Fueled Heavy Duty Truck Demonstration Program which was begun in 1988, has made possible the evaluation and demonstration of nine vehicles operating at eight sites, this being the first US test of methanol fueled engines in heavy duty trucks. The nine vehicles in the program had, by 1993, accumulated of 300,000 miles. The results obtained indicate potentially significant air quality benefits from continued development and increased deployment of heavy duty methanol trucks. Tests shower substantially lower emissions, especially NO_X, an important fact for ozone-impacted areas such as the Los Angeles basin. All the demonstrated vehicles met the 1991 NO_X emission standard of 5 g/bhp-hr, and could satisfy a future standards of 4.0 g/bhp-hr. Further refinement of some of these engines in transit programs show achievable NO_X levels below 2 g/bhp-hr. In the case of PM, CO and HC the engines with oxidation catalysts easily met the standards and some engines achieved the 1996 formaldehyde standard. Some problems have been experienced such as failing glow plugs, scuffed pistons and liners, cracked cylinder head (in one case) and failing fuel injection pump (in one case). There were also problems with vapor lock in the fuel system during periods of hot weather.

The effects of platinum and palladium catalysts on the enhancement of methanol combustion were investigated in a high pressure flow reactor and in a single-cylinder D.I. Diesel engine (Mitchell et al., 1992). The use of the platinum and palladium coating on the exhaust valves enabled the use of significantly lower glow plug operating temperatures, by approximately 400 K, which may increase glow plug life. The catalytic exhaust valves showed better overall performance than the non-catalytic ones. The palladium catalyst produced more CO and less NO_X than the platinum one, both catalysts showing slight increases in NO_X over the baseline case. The Pd catalyst produced lower concentrations of UHC (unburned hydrocarbon) and UBM (unburned methanol) than the Pt one, aldehydes concentrations being approximately equal. Both catalysts showed significant reductions in UHC, UBM and aldehydes.

Detroit Diesel started development of an alcohol fueled engine in 1981, since which time they have had over 550 such engines in use (Parry et al., 1993). The engines serve 14 major US cities and first appeared in urban transit buses and heavy duty trucks where the DDC 6V-92TA alcohol engine easily met the stringent emission standards in California since 1991 and the rest of the US since 1993. The engine looks almost identical to the diesel configuration and generally fits into the same vehicle chassis. The differences that do exist include higher compression ratio, modifying the blower and control system, the use of injectors capable of higher flow and incorporating glow plugs for use in starting and assisting combustion during warm-up. Since Clean Air 1, the first DDC methanol fueled bus began service in 1983, the population of methanol fueled engines has grown to well over 550 and has accumulated in excess of ten million miles of direct field experience. Future alcohol applications include an engine program for methanol - with- Avocet experience involving component changing to minimize the amount of Avocet required. High output mechanical unit injectors deliver 160 hp in, for example, generator set and airport shuttle buses 200 hp for yard tractors was reported as a follow-on program to this. Another program involved an ethanol truck engine (using the same pistons, injectors, glow plug controllers etc. as those for methanol), together with the cylinder heads and bypass blower from a high output military diesel engine.

California's methanol experience is again described in another report (Modetz et al., 1993). The project described was aimed at verifying the maturity of methanol vehicles and fuel technologies by means of a demonstration involving 5000 methanol fuel flexible vehicles with the necessary establishment of storage and dispensing systems. In the summer of 1992 Acurex surveyed 34 retail M85 sites, nine M85 non-retail sites and five M100 sites. The survey showed that the methanol fuel was in substantial agreement with the fuel specifications but some limits in the fuel specifications were exceeded which could eventually damage the performance of the vehicles operating on the fuel. Conductivity of initially dispensed samples may rapidly increase the corrosion of aluminum etc. which can lead to high particulate levels. Protecting the aluminum parts from coming into contact with the methanol is required. Nickel plated nozzles and swivels was a suggested method for the above but work was required to develop hoses more resistant to methanol.

The viability of methanol as a fuel for heavy duty vehicles is discussed in a report (Wiens et al., 1993). From the economic point of view the extra cost of using methanol is judged to be of minor importance compared to the emission advantages, and this extra cost can even be offset by state and local regulations which will allow trading and /or selling either the NO_X or particulate credits generated by using methanol or other alternative fuels. Transit properties have demonstrated that methanol will satisfy the tough stop and go duty cycles on a large scale. School districts have been satisfied with methanol fuel for use in children's school transportation.

Even though methanol technology provides substantial emission benefits the regulatory trend in the 1990s is not to require the best available technology but to set standards that will allow diesel technologies to compete in the market place. Programs have been set up that will allow mobile source trading of emissions. Methanol buses generate about 500 kg of NO_X reduction (less NO_X emissions) per year (than there were no such buses). A possible price of these credits is 10,000 dollars per ton. Thus each year a methanol bus may generate a revenue of about 5000 dollars. This revenue nearly offsets the added fuel cost of methanol. In the early years the methanol fuel industry provided methanol at a cost that reflected the value of the NO_X credits. In this approach the user would assign the NO_X credit to the methanol supplier who would, in his turn, collect the revenue. Revenue from the sale of the credits would, in this example, offset the methanol price reduction offered to the user. Other incentives may include long term fixed or formula pricing that would reduce some of the perceived price risks of methanol. Additional development work is needed to continue to lower the currently higher maintenance costs associated with methanol.

6. EXPERIENCES WITH ALCOHOLS IN OTHER PARTS OF THE WORLD

6.1 The Brazilian Alcohol Program

The Brazilian alcohol fuels program was the world's pioneer (Walsh, 1996). Beginning in the late 1970's in response to the rapid increase in the price of imported oil and restrictions on availability, the program took advantage of Brazil's surplus production of sugarcane and the technical feasibility of converting this to ethanol, to dramatically increase its use as a motor vehicle fuel. Today, ethanol is used as an octane enhancer in gasoline in the form of 22 percent anhydrous ethanol (E-22) or in neat ethanol (E-100).

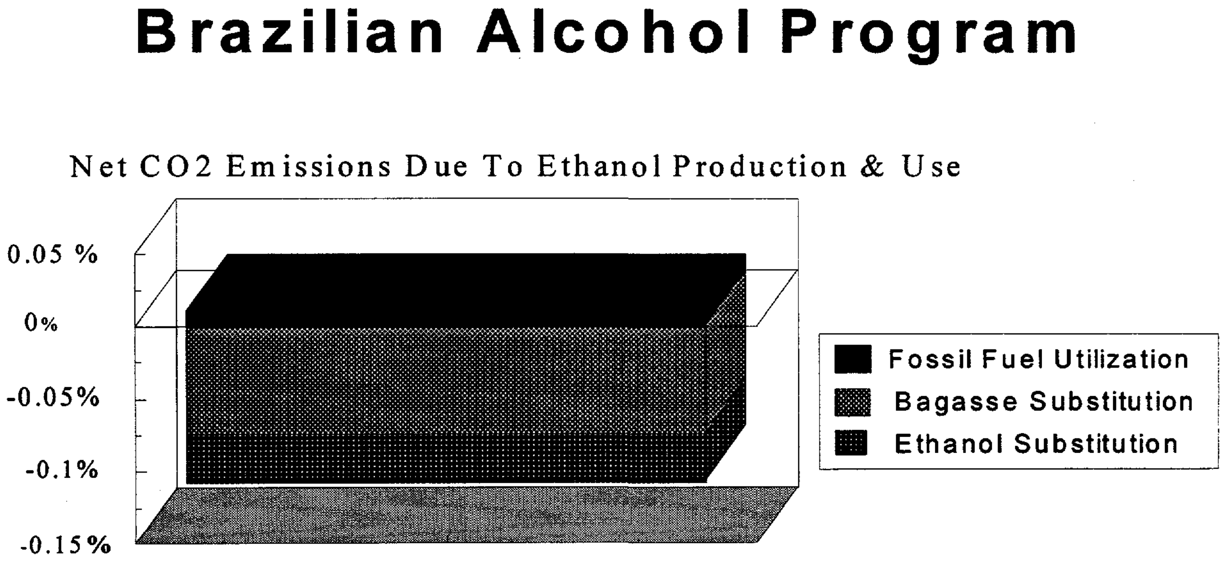


Figure 5. The Brasilien alcohol program.

Several properties of ethanol make it an excellent transportation fuel - high octane, low vapor pressure and therefore low evaporative emissions, low flammability in air reducing fire risks, etc. To take advantage of these characteristics and to reduce the corrosive aspects of ethanol relative to gasoline, several modifications have been made to cars in Brazil, especially those designed to run on E-100. These include higher compression ratios, larger fuel tank volumes, colder spark plugs and coating of virtually all parts which come in contact with ethanol to eliminate corrosion.

One significant point of controversy with the Brazilian program has been whether it actually leads to a net CO_2 reduction or whether the fossil fuel utilization in the agricultural industry offsets the savings due to ethanol substitution for gasoline. As illustrated above, Brazilian authorities believe that there is a significant net reduction in CO_2 (Goldemberg et al., 1994).

Another concern has been the availability of ethanol from sugarcane and its dependence on world sugar prices. At one time, Brazil planned to move entirely to an alcohol fuel based program and there have been several starts and stops along the way. The problem has been that the world sugar price has been volatile. When sugar prices are low, sugar beets are used to produce ethanol and there is a glut on the market, when sugar prices rise, ethanol shortages emerge. With sugar prices currently higher than in the past, a shortage of ethanol emerged during 1990. To compensate, methanol was imported as a substitute. Since 1990 the States of Sao Paulo and Minas Gerais have consumed more than six billions liters of a 60% ethanol - 33% methanol - 7% gasoline blend. This blend has proven to be fully compatible with the local alcohol engines, which do not require adjustments for its use. However, the proportion of new cars designed to operate on E-100 compared to E-22 has declined substantially since the late 1980's.

While the Brazilian program has been a landmark in showing that with a strong commitment it is possible to implement a large scale biomass based transportation fuels program, it is also clear that advanced technologies using woody biomass feedstocks could substantially improve the yield (vehicle - km/hectare/year), probably by a factor of two or more. It has been argued that for a woody feedstock yield of 15 dry tons/hectare/year, which is believed to be achievable in large scale production, the ethanol yield could be more than twice that from grain; if the US Department of Energy's year 2000 goals for performance and cost are met, ethanol produced this way would be competitive with gasoline for oil prices less than 25$ per barrel, energy balances would be favorable and life cycle emissions of CO_2 would be dramatically reduced from such vehicles operated on reformulated gasoline (Williams et al, 1995).

6.2 Japan's Low Pollution Vehicle Program

The Environmental Agency (EA) of Japan has initiated a program to promote the use of low-pollution vehicles. Detailing the program, which will start during the new fiscal year, officials from the agency's Air Quality Maintenance Bureau said EA will choose certain bus, garbage collection, and welfare service routes and official vehicles used by municipalities. The agency will encourage the municipalities in charge of those services to serve as model project vehicles.

The agency plans to assign 10-20 vehicles to each municipality that it selects from its own budget but ask the municipalities to foot one-third of the bills related to fuel, building of fuel stations, maintenance, and other peripheral costs.

As of March of 1995, only 2,500 low-pollution vehicles were in use on public roads, according to the agency. EA wants to increase the fleet size to at least 20,000-30,000 in the near future and as indicated below to almost 500,000 by the turn of the century.

In Japan, low-pollution vehicles refer to electric, natural gas, methanol-powered, and hybrid vehicles that use a combination of gasoline or diesel and new energy sources.

The Government of Japan has targeted natural gas as an important motor vehicle fuel and is promoting a plan to introduce approximately 200,000 NGV's by the year 2000. "According to the plan, an estimated 80 percent will be used as substitutes for diesel powered vehicles; the remainder will be small vans and other vehicles. To accommodate refueling needs, plans call for 600 quick refueling stations and 39,000 vehicle refueling appliances. Nearly 730 million cubic feet of natural gas will be sold; NOX emissions will be reduced by 7,000 tons per year; CO_2 emissions will be reduced by 0.4 percent."[4]

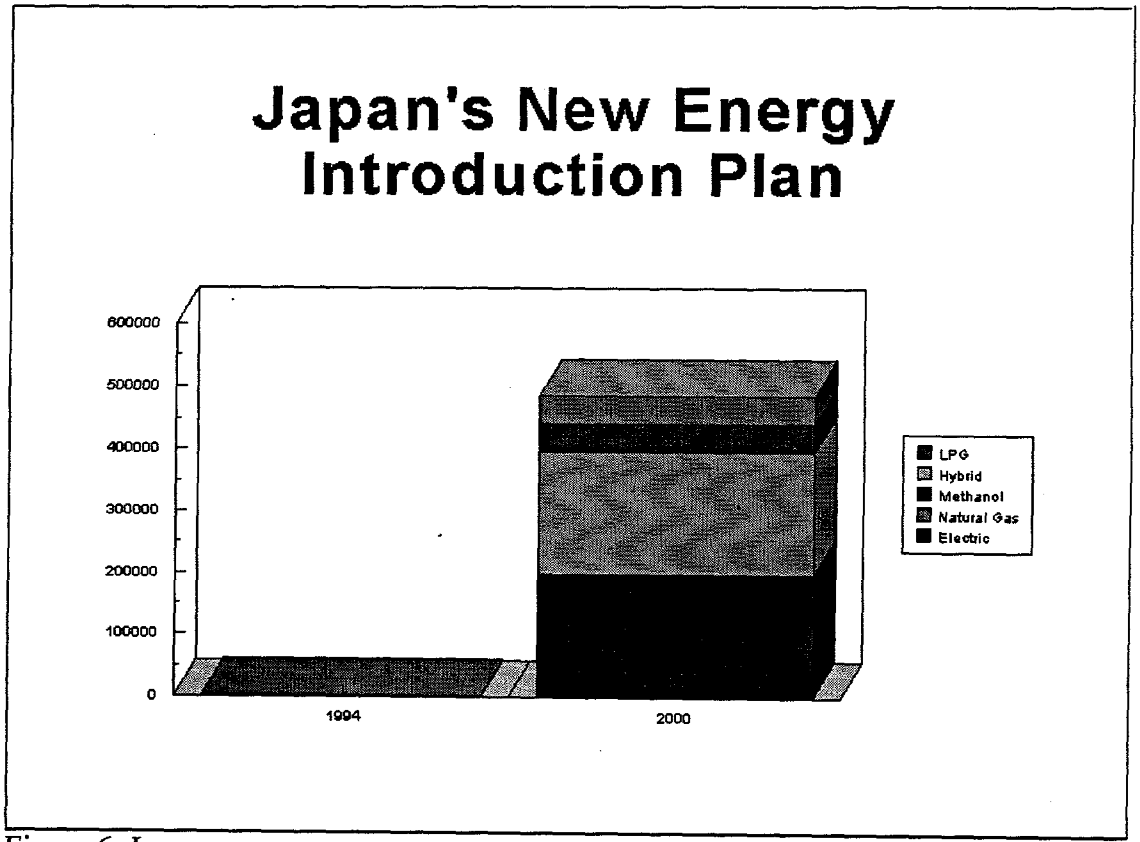


Figure 6. Japan new energy program.

In Japan, 260,000 taxis, 94% of the total number of taxis, use LPG as their fuel.

The performance and exhaust emissions of methanol city bus engines, conducted jointly by MITI PEC and JARI, comprising five methanol heavy duty buses, (Seko et al., 1993) gave the following results;

---

[4] "NGV's in Japan: Poised to Take the Market by Storm", Natural Gas Fuels, July 1995.

- Formaldehyde, unburned methanol, HC and CO emissions were very low when using a catalytic converter, but CO and HC emissions of the M85 fueled vehicle were almost the same as those of a diesel vehicle.
- NO_X emission were between 20 % and 50'% lower but NO_2 emissions were higher
- With a warmed catalyst the HC emission of the M100 fueled engine consisted mostly of methane.
- It seems that NO_X emission is reduced in oxygen-rich exhaust through catalytic reaction.
- Formaldehyde and methanol emissions were higher just after cold start. The use of catalyst and heater is recommended for cold start.
- Fuel economy is almost the same as for a diesel vehicle at high speeds but 20% inferior at low speeds.

The authors feel that a need has been demonstrated for improved fuel consumption at low load, reduced hazardous exhaust gas components, such as formaldehyde and methanol, and improved catalyst performance.

A fleet of methanol fueled vehicles was tested in Tokyo starting in 1986, (Nishida, 1990), with ca 600 000 km having been driven (by 1990), 58000 km on a single vehicle. The engine used is the Komatsu 4D direct injection type with 3.26 liter displacement. This diesel engine was modified by the addition of an ignition system with spark plugs and by altering or plating the materials used in the fueling system. The engine was also equipped with a catalytic converter to reduce the aldehyde content in the exhaust gas. No problems which occurred on the 40 vehicles could be ascribed to methanol itself and the vehicles performed well from the air pollution point of view, there being only some minor points in function which are inferior to the usual diesel engine trucks.

In another Japanese study (Kawaguchi et al., 1992) the characteristics of exhausted smoke from a methanol DI diesel engine which is ignited by diesel fuel was investigated to clarify the soot formation process. By analyzing the micro-structure of the soot it was found that the soot emitted from the methanol diesel engine is composed of inner core and outer shell, similar to that of the conventional diesel engine. From more detailed qualitative analysis the calcium percentage from the lubricating oil in the outer shell is much higher than that of the conventional diesel engine. By investigating soot characteristics, spray structure and combustion characteristics the soot formation process was clarified. It was found necessary to oxidize the inner core of soot before the complete soot was formed to reduce soot formation. If the amount of diesel fuel and the injected quantity of methanol are increased the inner core cannot be oxidized perfectly because of an excess of inner cores, a drop of flame temperature and lack of oxygen, then soot is present in the exhaust gases.

Since Japan imports virtually all its fuel it does not have a program directed specifically at assuring that the fuel is derived from biomass. However, they will endeavor to assure that they will have vehicles available to run on whatever fuels are available domestically and internationally.

6.3 Austria's Experience With Alcohol Fuels

In a report from Austria (Zelenka and Kapus, 1992) the development of a multi-fuel DI alcohol engine a passenger car by AVL was described. This work started with a glow-plug assisted DI methanol engine, followed by a turbo-charged compression ignition engine. Special attention was devoted to setting parameters, e.g. injection timing, EGR-rate, fuel metering etc. for the various alcohol fuels and blends. The tests proceeded from steady state to dynamic, even road operation. The results were very promising for high fuel economy and future emission standards. Since EGR heat is used to achieve stable combustion with a minimum of required glow lug power, EGR rate was optimized for NO_X low fuel consumption and low glow plug power. EGR only shut off near and at full load.

The NO_X emission of the methanol engine was only one third of the diesel engine's emission. The results for ethanol were not so good since the engine was optimized for use with methanol, but a reduction of 31% compared with diesel was obtained. Lower NO_X levels can be obtained, says the report, and by using a start and an under-floor catalyst the HC and CO emissions can be kept very low.

7. THE DRIVING FORCES TODAY FOR BIOMASS BASED FUELS

Three major issues have stimulated interest in alternative fuels around the world in recent years: energy security, urban and regional air pollution, and global climate change. The current status of each of these issues will be discussed below.

7.1 Energy Considerations

As noted above, the primary motivation for the Brazilian Alcohol program was energy related concerns. This concern has eased in most countries of the world as oil prices have declined and oil availability seems quite secure, at least in the short term.

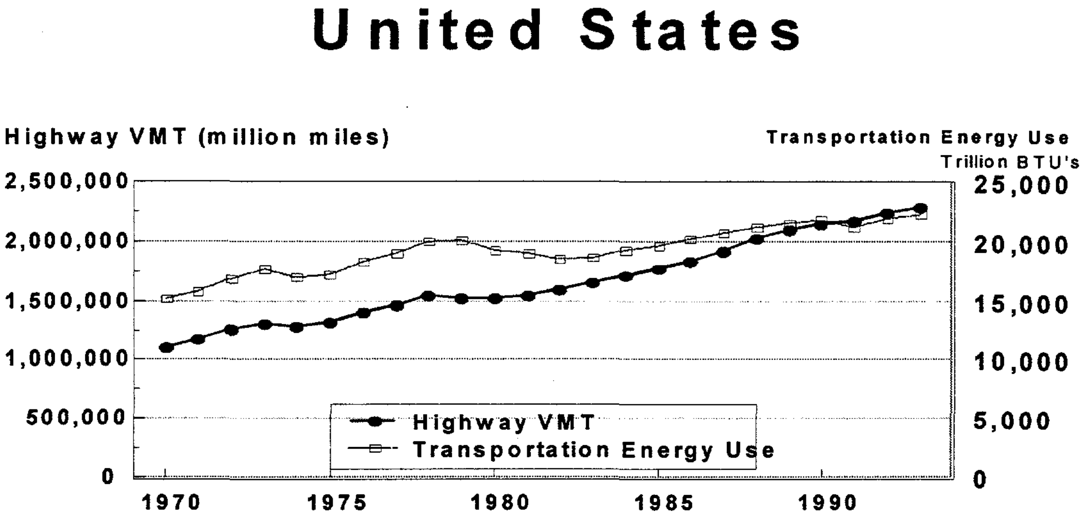
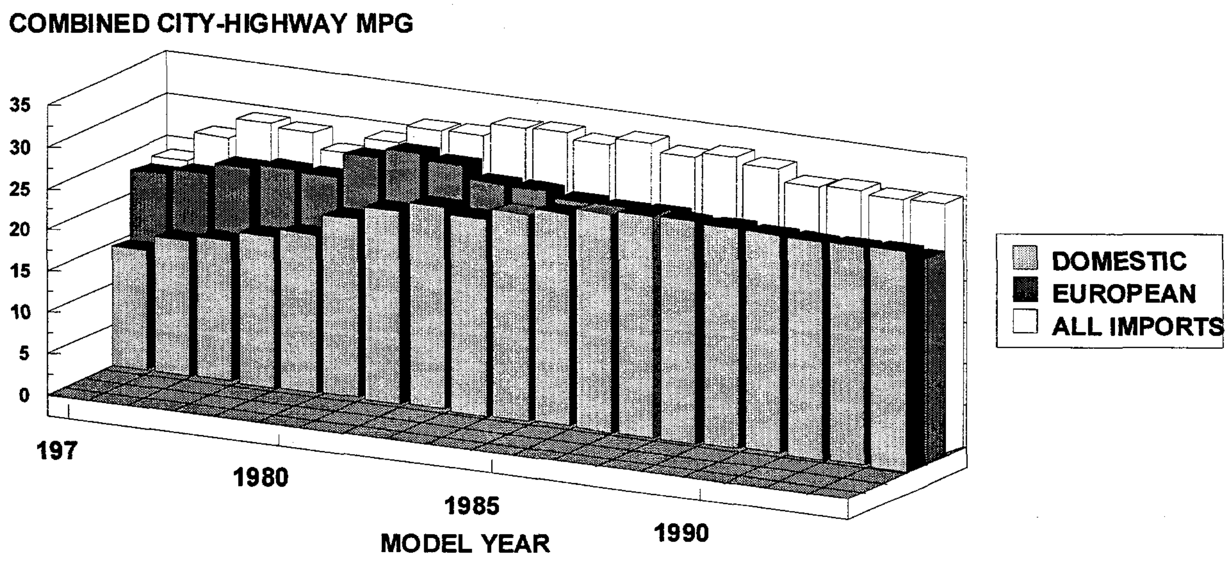


Figure 7. Transportation Energy use in the USA.

7.1.1 The US Experience

In the US, the Corporate Average Fuel Economy (CAFE) standards increased significantly during the 1970's and early 1980's but have remained fairly flat since the mid 1980's, actually declining over the past few years. In spite of the auto improvements, as illustrated in Figure 7, overall transportation energy consumption has continued to go up. This is due to a variety of reasons. For example, as illustrated in Figure 8, as auto fuel efficiency improved, sales of light trucks have increased substantially. Since many of these light trucks tend to be used much like passenger cars and have much lower fuel efficiency than the cars they are replacing, overall light duty vehicle efficiency gains are less than it would appear. In addition, CAFE did not apply to heavy duty vehicles, this category subject only to a voluntary program. Further, national legislation was modified during the 1980's to allow speed limits to climb to 65 MPG thereby further undercutting energy conservation since fuel consumption increases as highway vehicle speeds climb. During the last decade the auto industry has been moving back toward the horsepower wars of the 60's, substantially increasing power output and reducing 0 to 60 MPH wide open throttle acceleration times over this period.

Simultaneously, people are using private cars and light trucks to drive to work much more than in the past with the result that public transit usage is down. When considering the improvements in new car fuel economy and the return of gasoline prices to pre OPEC levels, the cost of fuel for driving in real terms is much lower in the US today than at any time in the last two decades further encouraging additional driving. Not surprisingly, annual vehicle miles traveled has been increasing across the US by about 50 billion miles per year and because the amount of driving is increasing faster than the improvement in M.P.G., annual fuel consumption continues to increase.



Source: US EPA/AA/TDG/93-01
"Light Duty Automotive Technology and Fuel Economy Trends Through 1993"

Figure 8. Combined City-Highway MPG.

The United States has had a mandatory fuel efficiency program since 1975. The Energy Policy and Conservation Act, passed that year to come into effect in model year 1978, amended the Motor Vehicle Information and Cost Saving Act to require new passenger cars to get at least 27.5 miles per U.S. gallon (8.55 liters/100 km) by 1985, as measured by EPA test procedures. (See Table 12)

Vehicle manufacturers are required to test some percentage of all vehicles destined to be sold in the United States so that a fuel - consumption rating can be assigned to each product line.

The test involves both city and highway driving cycles. From these figures, a sales-weighted average fuel-consumption figure is calculated for all the passenger cars produced by each manufacturer. Fuel efficiency (in mpg) calculated this way must exceed the Corporate Average Fuel Economy (CAFE) standard specified for the appropriate model year. Since the 1979 model year, the CAFE program, as it is called, has been expanded to cover light-duty trucks as well as passenger cars.

Failure to meet the CAFE requirements can result in substantial financial penalties. For each vehicle produced, a manufacturer whose fleet-average fuel consumption does not meet the CAFE standard is fined $5 per vehicle for every 0.1 miles/U.S. gallon by which the standard is not met. These fines may be offset by credits accrued in other model years, however. In 1990, GM, Ford, and Chrysler all failed to meet the 27.5 mpg standard. Since 1983, the federal government has collected $164 million in CAFE fines.

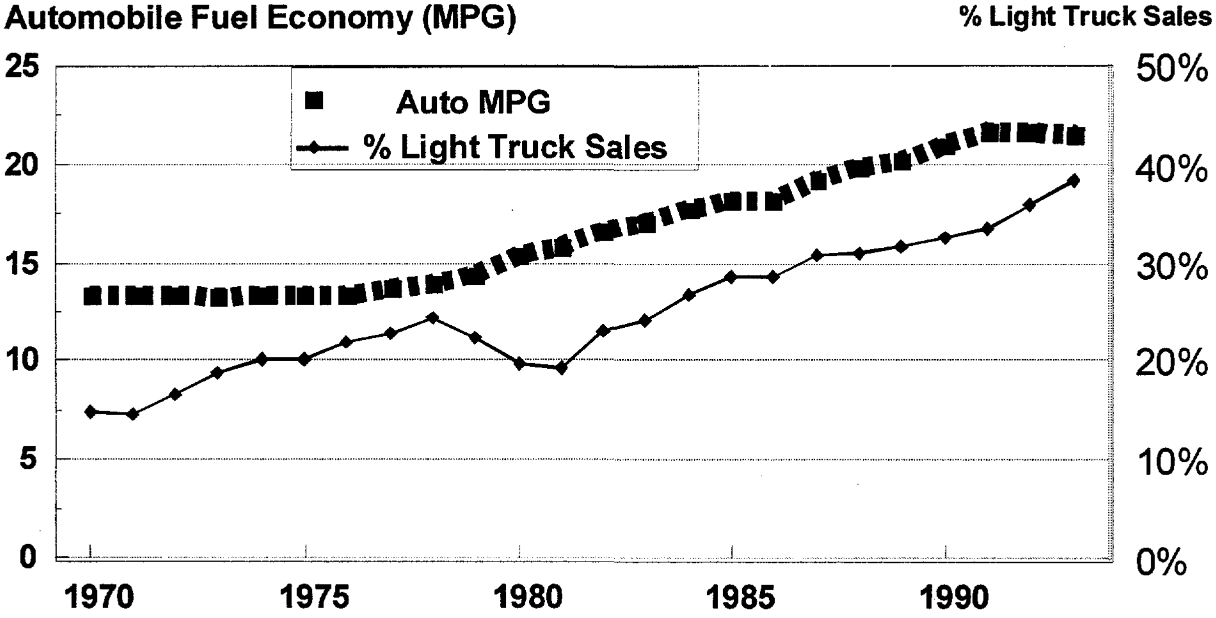


Figure 9. Recent trends in United States.

While new car efficiency, as measured by EPA, has increased to about 28 mpg, doubling between 1974 and 1988, the on-road fuel efficiency of the entire auto fleet has risen by only 50 percent, to about 20 mpg. Moreover, for several reasons the EPA-measured fuel efficiency of 28 mpg corresponds to a real-world value of only about 24 mpg, a 15-percent difference. Highway driving speeds are greater than those assumed by EPA and automobiles are less efficient at high speeds; the fraction of miles driven in cities (where fuel efficiencies are generally less) is greater than assumed in the federal test procedures; and urban areas are becoming increasingly congested reducing fuel efficiencies even further. Total fuel consumption for the United States is also higher because light trucks and minivans are increasingly being used in place of automobiles. At any rate, the average fuel efficiency for the entire passenger-car fleet should plateau at about 24 mpg (9.8 l/100 km) unless new-car efficiency improves.

Significantly, U.S. efficiency improvements began with the industrialized world's least-efficient car fleet. Only after the dramatic improvements observed to date are typical U.S. cars as generally efficient as those in the same weight class in other countries. Figure 10 shows that in fact, while domestically produced cars have improved, European and Asian produced cars sold in the US have declined.

Light-duty trucks, including jeeps and mini-vans had to meet a corporate fuel economy standard of 20.6 miles per gallon starting with their 1995 model year vehicles according to the National Highway Traffic Safety Administration.

In recent years, as fuel prices have dropped and the CAFE pressures to improve fuel efficiency have diminished, U.S. new-car fuel efficiency has begun to slip. According to EPA, the fuel efficiency of new U.S. cars declined 4 percent between 1988 and 1990. Domestic vehicles declined 3 percent while Asian models (from Japan and Korea) declined 6 percent. Over this same period, the new-car fleet (domestic and imports) showed a 6-percent weight gain and a 10-percent increase in horsepower. According to EPA, "if this backslide continues, problems with nationwide fuel consumption will increase and global warming trends will worsen at a pace faster than is generally being assumed by analysts."

Table 12. US new car fuel efficiency standards (CAFE), miles per US Gallon.

Model Year	Passenger Cars	Light Trucks 2 WD	4 WD
1978	18.0	-	-
1979	19.0	16.0	14.0
1981	22.0	16.7	15.0
1982	24.0	18.0	16.0
1983	26.0	19.5	17.5
1984	27.0	20.3	18.5
1985	27.5	19.7	18.9
1986	26.0	20.5	19.5
1987	26.0	21.0	19.5
1988	26.0	21.0	19.5
1989	26.5	21.5	19.0
1990	27.5	20.5	19.0
1991	27.5		-

EPA data suggest that the fuel efficiency wars of the late 1970s gave way to horsepower wars in the 1980s. Throughout the decade, manufacturers substantially increased cars' power output. Unfortunately, in the real world, drivers with more horsepower available tend to accelerate their vehicles faster, thus using more fuel and needlessly increasing on-road emissions of nitrogen oxides, volatile organic compounds, and carbon monoxide.

There is little doubt that the rise in sales of trucks and big cars and the decline in U.S. motor-vehicle fuel efficiency both stem largely from the substantial drop in real fuel prices since the mid-1980s. Gasoline prices (expressed in constant 1989 dollars) were about as low in 1989 as they had been in the previous 39 years. Apparently, fuel prices speak louder than the federal CAFE standards that require manufacturers to produce lighter and more efficient vehicles.

People who buy especially inefficient new cars do pay some financial penalties for the privilege. "Gas guzzler" taxes are levied on vehicles that do not achieve certain minimum fuel economy figures (See Table 13). In 1986, the tax ranged from $500 for a 0.1 mile/U.S.

gallon shortfall to a maximum of $3850.[5]

Table 13. Minimum fuel efficiencies for guzzler taxes

1984	19.5 miles/U.S. gal	(12.1 l/100 km)
1985	21.0 "	(11.2 ")
1986 and after.	22.5 "	(10.5 ")

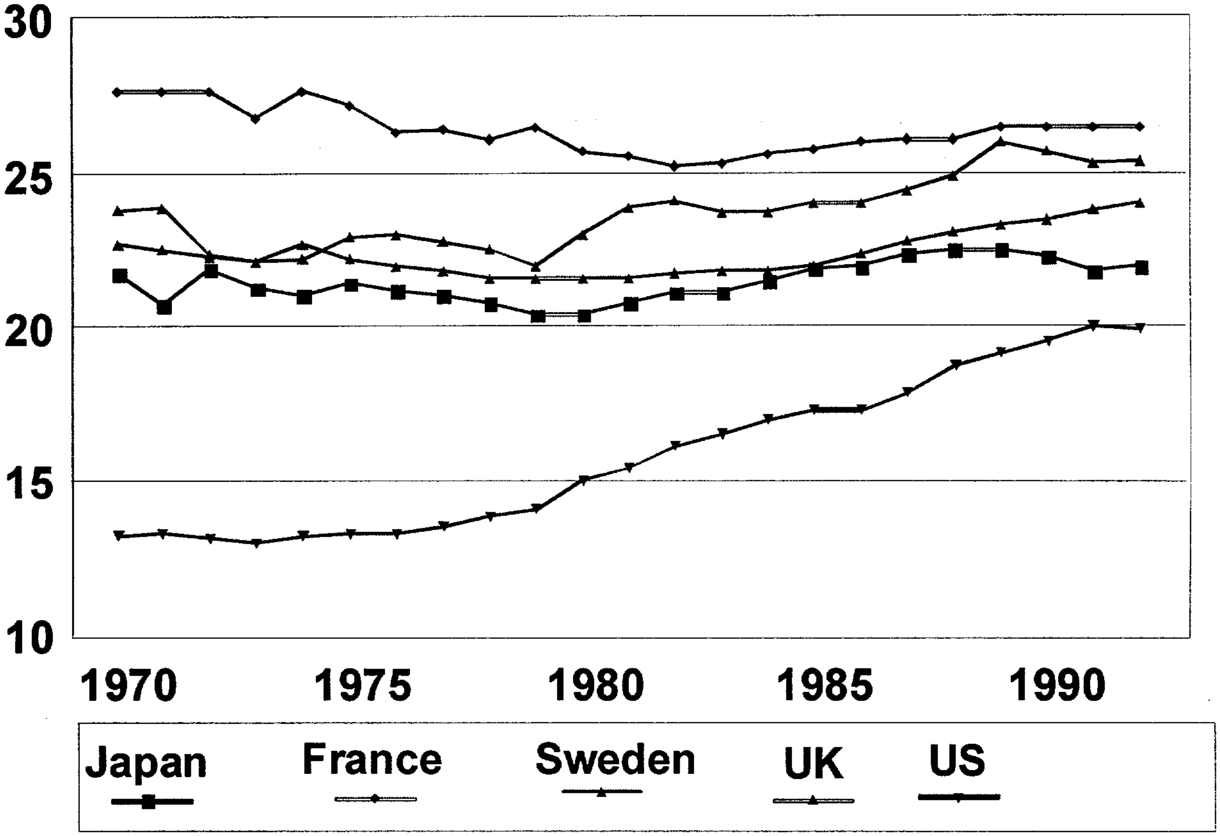


Figure 10. Fuel Economy and Gasoline Fueled Cars in Japan, France and Sweden, mpg.

Besides the CAFE requirements, the federal program also provides consumers with information about the relative efficiency of new cars. The 'Gas Mileage Guide' published by EPA and the Department of Energy lists the city and highway fuel consumption test results of each vehicle model and is intended to provide information to new-car buyers. Also required on new cars are stickers indicating the vehicle fuel consumption as determined by EPA, an estimate of the annual fuel cost based on 15,000 miles of operation, and the range of fuel economy achieved by similar sized vehicles of other makes. The mpg estimates on these stickers have been adjusted by EPA to give a somewhat more realistic estimate of the on-the-road fuel consumption that the owner can expect under average driving conditions and to allow a comparison between different vehicle models.

---

[5] It should be noted that the European Community challenged this tax as a violation of the GATT agreement since the tax tends to fall most heavily on European luxury car manufacturers. This challenge did not succeed.

7.1.2 Rest of the World

The trends in U.S. vehicle growth and fuel consumption generally resemble global patterns. As illustrated in Figure 11 the global vehicle fleet continues to grow faster than the population.

As shown in Figure 10, while most countries' autos were much more efficient than those in the US, the gap has narrowed substantially. The primary reason, as shown in Figure 8, is that despite a great deal of rhetoric, gasoline car fuel efficiency has hardly improved anywhere but in the US.

CO_2 from passenger cars accounts for about half of CO_2 emissions from Transport, and about 12 percent of total CO_2 emissions in the European Union.[6] Under a "business as usual" scenario, CO_2 emissions from cars are expected to increase by about 20 percent by the year 2000 and by about 36 percent by the year 2010 from 1990 levels. In one year, an average medium size car in the European Union emits some 3 tons of CO_2.[7] The road transport sector has stood out in recent years as one of the few sectors in the Union experiencing CO_2 emissions growth.

In the UK, a recent government report noted that "fuel consumption is rising fastest in the road transport sector, and there has been no improvement in fuel efficiency over the last 20 years. Fuel use for road transport has increased by 90 percent since 1970, accounting for a quarter of total energy consumption. Gasoline prices rose by just 2 percent during that period, compared with an 11 percent rise in household fuel.

The motor industry "admitted that fuel efficiency had been reduced in part by safety requirements which called for heavier cars, and by environmental features such as catalytic converters."[8]

---

[6] Derived from "A Community strategy to reduce CO2 emissions from passenger cars and improve fuel economy", COM (95) 689, Communication from the Commission to the Council and the European Parliament, Adopted by the Commission on December 20, 1995.

[7] Assuming 12,600 km per year and an average on road fuel consumption of 9.6 liters per 100 kilometers.

[8] "Car named as environmental villain", *Financial Times*, March 14, 1996.

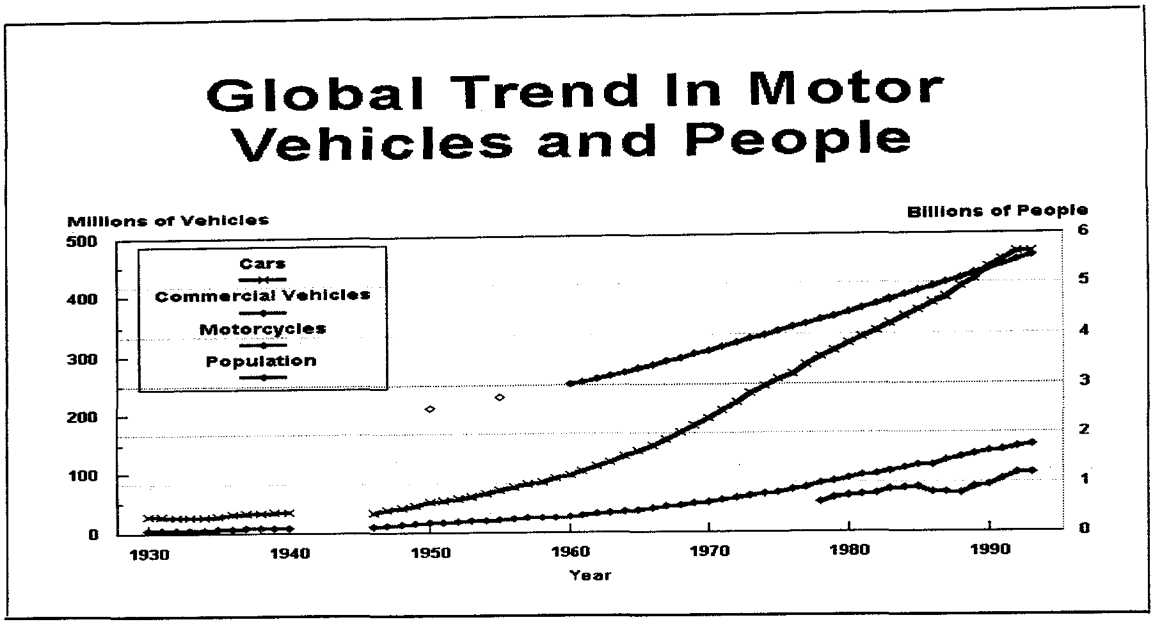


Figure 11. Global trend in motor vehicle and people

In an era of low oil prices (~17$ per barrel) and ready availability of oil, there seems to be very little real interest in biomass based fuels to address energy concerns. This is dramatically illustrated in Figure 12 which shows the continued increase in energy use for personal transportation in many parts of the world.

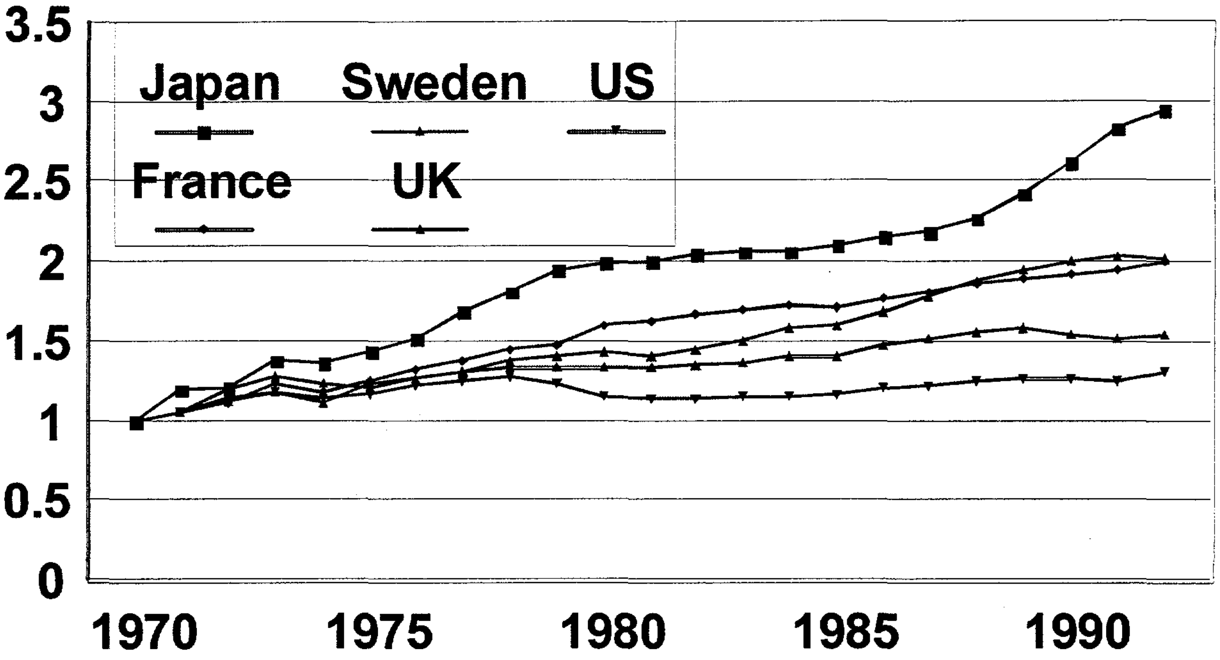


Figure 12. Energy Use by Personal Cars in Japan, UK, France, US and Sweden as Normalized to 1970.

7.2 Urban and Regional Air Pollution

Urban air pollution remains a serious problem in many parts of the world, with serious implications for public health and the environment. Cars, trucks, motorcycles, scooters and buses emit significant quantities of carbon monoxide, hydrocarbons, nitrogen oxides and fine particles and as a result tend to be major sources of these pollutants and their derivatives in many parts of the world. Where leaded gasoline is used, it is also a significant source of lead in urban air. As a result of these emissions many major cities around the world are severely polluted. This section will review some of the consequences of these pollutants.

7.2.1 Carbon Monoxide (CO)

Carbon monoxide -- an odorless, invisible gas created when fuels containing carbon are burned incompletely -- poses a serious threat to human health. Persons afflicted with heart disease and fetuses are especially at risk. Because the affinity of hemoglobin in the blood is 200 times greater for carbon monoxide than for oxygen, carbon monoxide hinders oxygen transport from blood into tissues. Therefore, more blood must be pumped to deliver the same amount of oxygen. Numerous studies in humans and animals have demonstrated that those individuals with weak hearts are placed under additional strain by the presence of excess CO in the blood. In particular, clinical health studies have shown a decrease in time to onset of angina pain in those individuals suffering from angina pectoris and exposed to elevated levels of ambient CO (Aronow Ferris, 1977)

7.2.2 Nitrogen Oxides (NO_X)

As a class of compounds, the oxides of nitrogen are involved in a host of environmental concerns impacting adversely on human health and welfare. Nitrogen dioxide (NO_2) has been linked with increased susceptibility to respiratory infection, increased airway resistance in asthmatics, and decreased pulmonary function.(Ferris 1978, US EPA 1980) It has been shown that even short term exposures to NO_2 have resulted in a wide ranging group of respiratory problems in school children - cough, runny nose and sore throat are among the most common (Mostardi, 1981) Further, in France, in an ingenious experiment, Dr. Orehek has shown that asthmatics are especially sensitive to even one hour exposures (Orehek, 1976) A small group of asthmatics were initially exposed to carbachol, a bronchoconstrictor representative of urban pollen, and then to NO_2; adverse effects such as increased airway resistance were experienced by some of the individuals at levels as low as 0.1 parts per million for 1 hour.

The oxides of nitrogen also participate in the formation of the family of compounds known as photochemical oxidants and in acid deposition. Finally, as a result of secondary transformations in the atmosphere, NO_X emissions are converted to nitrates thereby increasing the accumulation of particulate in the air.[9]

7.2.3 Photochemical Oxidants (Ozone)

The most widespread air pollution problem in areas with temperate climates is ozone, one of the photochemical oxidants which results from the reaction of nitrogen oxides and hydrocarbons in the presence of sunlight. Motor vehicles are a major source of both of these precursor pollutants. Ozone causes eye irritation, cough and chest discomfort, headache, upper respiratory illness, increased asthma attacks and reduced pulmonary function (US EPA, 1978).

---

[9] Atmospheric nitrate is essentially secondary, formed from reactions involving oxides of nitrogen to form nitric acid.

It has also been demonstrated in numerous studies that photochemical pollutants seriously impair the growth of certain crops. For example, the Congressional Research Service of the U.S. Library of Congress found that "the short-run or immediate impacts of ozone are evident in annual crop yield decreases estimated at $1.9 to $4.3 billion" (Biniek, 1982)

7.2.4 Particulate (PM)

A series of studies released in the last few years indicate that particulate may be the most serious urban air pollution problem. By correlating daily weather, air pollutants and mortality in six US cities, scientists have discovered that non accidental death rates tend to rise and fall in near lockstep with daily levels of particulates -- but not with other pollutants (Dockery, 1993) Because the correlation held up even for very low levels -- in one city to just 23 percent of the federal limit on particulates -- these analyses suggested to the researchers that as many as 60,000 US residents per year may die from breathing particulates at or below legally allowed levels (Schwartz, 1991):

More recently, another study has emerged showing a strong linkage between particulate air pollution and mortality (Pope, 1991). The study is distinctive in that it used a prospective cohort design that allowed for direct control of other individual risk factors such as cigarette smoking, diet, etc. In addition, the study was larger and represented a larger geographic area than any other study to date.

Air pollution data from 151 US metropolitan areas were linked with individual risk factors in 552,138 adults who resided in these areas when they were enrolled in this study in 1982. Deaths were ascertained through 1989.Sulfates and fine particulate air pollution were associated with a difference of approximately 15 to 17% between mortality risks in the most polluted cities and in the least polluted cities. Even in cities that meet the US Federal clean air standards, the risk of death is 2 to 8 percent higher than in the cleanest cities.

Certain particles appear to be especially hazardous. For example, diesel particles, because of their chemical composition and extremely small size, have raised special health and environmental concerns. Diesel particulate matter consists mostly of three components: soot formed during combustion, heavy hydrocarbons condensed or adsorbed on the soot, and sulfates. In older diesels, soot was typically 40 to 80 percent of the total particulate mass. Developments in in-cylinder emissions control have reduced the soot contribution to particulate emissions from modern emission controlled engines considerably, however. Much of the remaining particulate mass consists of heavy hydrocarbons adsorbed or condensed on the soot. This is referred to as the soluble organic fraction of the particulate matter, or SOF. The SOF is derived partly from the lubricating oil, partly from unburned fuel, and partly from compounds formed during combustion. The relative importance of each of these sources varies from engine to engine.

A comprehensive assessment of the available health information on diesel particulate was carried out by the International Agency For Research on Cancer (IARC) in June 1988 and concluded that diesel particulate is probably carcinogenic to humans (IARC, 1988).[10]

Studies conducted at the Fraunhofer Institute have suggested that the diesel particle itself,

---

[10] The term 'carcinogen' is used by the IARC to denote an agent that is capable of increasing the incidence of malignant tumors.

stripped of the organic and other materials on the surface, may also be carcinogenic. Confirmatory studies under the auspices of the Health Effects Institute, a jointly funded Industry - Government program, recently verified this conclusion. These "results, and recent findings from other laboratories, suggest that (1) the small respirable soot particles in diesel exhaust are primarily responsible for lung cancer developing in rats exposed to high concentrations of diesel emissions, and (2) at high particle concentrations, the mutagenic compounds adsorbed onto the soot play a lesser role, if any, in tumor development in this species"(Mauderly, 1994). This is quite significant as it indicates that it is important to control the particles themselves and not just the organic material sitting on the surface of the carbon.

In a subsequent analysis, the HEI raised questions about this conclusion (HEI, 1995). The authors argue that because the rats were exposed to very high concentrations over their full lifetimes, the observed effects are more likely the result of the impairment of the rat's ability to clear particles from its lungs, leading to inflammation and rapid cell proliferation. They note that similar effects did not occur in hamsters and results were mixed with mice.

While further studies are carried out to determine which element in diesel particles is most hazardous, the prudent course of action seems to be to reduce both the organics and the particulate mass.

To put the concerns with diesel NO_X and particulate into perspective, one recent study attempted to quantify the health benefits associated with reducing diesel particulate and nitrogen oxides (Small and Kazimi, 1995). Based on a careful review of the available health information, the authors concluded that reducing one gram per mile of particulate or NO_X, over a 100000 mile vehicle lifetime would produce benefits of $11432 and $ 1175, respectively. Focusing specifically on the 1992 heavy duty vehicle fleet in Los Angeles, the authors conclude that a 50% reduction in NO_X and PM-10 emissions, would be worth $9200 and $13500 per vehicle, respectively. A 90% reduction would have a value of $16600 and $24300 per vehicle respectively. It is important to emphasize that these amounts reflect the value of the health benefits alone. Earlier studies have indicated that the economic benefits of reduced soiling and improved visibility are also quite significant.

(1) Physics And Chemistry of Particulate (US EPA 1995)

Atmospheric particles originate from a variety of sources and possess a range of morphological, chemical, physical, and thermodynamic properties. Examples include combustion-generated particles such as diesel soot or fly ash, photochemically produced particles such as those found in urban haze, salt particles formed from sea spray, and soil-like particles from re-suspended dust. Some particles are liquid, some are solid; others contain a solid core surrounded by liquid. Atmospheric particles contain inorganic ions and elements, elemental carbon, organic compounds, and crustal compounds. Some atmospheric particles are hygroscopic and contain particle-bound water. The organic fraction is especially complex. Hundreds of organic compounds have been identified in atmospheric aerosols, including alkanes, alkanoic and carboxylic acids, polycyclic aromatic hydrocarbons, and nitrated organic compounds.

Particle diameters span more than four orders of magnitude, from a few nanometers to one hundred micrometers. Combustion-generated particles, such as those from power generation, from automobiles, and in tobacco smoke, can be as small as 0.01 mm and as large as 1 mm. Particles produced in the atmosphere by photochemical processes range in diameter from 0.05 to 2 mm. Fly ash produced by coal combustion ranges from 0.1 to 50 mm or more.

Wind-blown dust, pollens, plant fragments, and cement dusts are generally above 2 mm in diameter.

Recent measurements of the size distributions of primary particles confirm U.S. Environmental Protection Agency conclusions that most fugitive dust emissions are in particles larger than 2.5 μm and that the majority of emissions from combustion sources are in sizes smaller than 2.5 μm. As illustrated below diesel truck emissions are almost all less than 1.0 μm in size; particles in this size range are especially hazardous because when breathed in, they are able to penetrate to the deepest part of the lung where the critical gas exchange takes place.

(2) Sources of Suspended Particles

The ambient atmosphere contains both primary and secondary particles; the former are emitted directly by sources, and the latter are formed from gases (SO_2, NO_X, NH_3, VOC's). Fugitive dust is a primary pollutant. Major sources of particle emissions are classified as major point sources, mobile sources, and area sources; these are anthropogenic. Natural sources also contribute to ambient concentrations.

Fugitive dust is a major contribution to PM_{10} at nearly all sampling sites, although the average fugitive dust source contribution is highly variable among sampling sites within the same areas, and is highly variable between seasons.

Primary motor vehicle exhaust in the US makes up as much as 40% of average PM_{10} at many sampling sites. Vegetative burning outdoor and residential wood burning are significant sources in residential areas. Fugitive dust from paved and unpaved roads, agricultural operations, construction, and soil erosion constitute ~90% of nationwide primary emissions in most countries. Fugitive dust consists of geological material that is suspended into the atmosphere by natural wind and by anthropogenic activities from sources such as paved and unpaved roads, construction and demolition of buildings and roads, storage piles, wind erosion, and agricultural tilling.

Mobile sources are major emitters of primary particles, oxides of nitrogen, and volatile organic compounds. They are also minor emitters of sulfur dioxide and ammonia. On-road motor vehicles using gasoline-and diesel-fueled engines are by far the largest component of mobile source emissions in most countries, and the emissions estimation methods are most highly developed for these vehicles. Motor vehicle exhaust contains high concentrations of organic and elemental carbon, but their ratios are much different from those found in wood combustion with the abundance of elemental carbon being nearly equal to the organic carbon abundance.

7.2.5 Lead

There has been an explosion of knowledge during the last two decades with regard to the adverse health impact of long term exposures to low levels of ambient lead (Needleman, 1980; US EPA 1977). In response to this growing body of data, most industrialized countries and several developing countries have introduced unleaded gasoline and several have or will soon prohibit the use of leaded gasoline entirely.

The toxic properties of lead at high concentrations have been known since ancient times as lead has been mined and smelted for more than 40 centuries. Precautions in its use have been widespread for centuries but it has only been recently that its adverse impacts at very low levels have been fully appreciated. The seminal work in this area is the 1979 report by Dr. Herbert Needleman and his colleagues which showed that children with high levels of lead accumulated in their baby teeth experienced more behavioral problems, lower IQ's and decreased ability to concentrate (Needleman, 1979). More recent evidence indicates that it is not only the length and severity of exposure to lead which results in the health damage but the age at which exposure occurs. This is especially important because "Of all the persons in the community, the newborn child is the most prone to injury from overexposure to lead for several reasons, and the damage that may be caused then will have the greatest long-term social and economic consequences" (Moore, 1980).

Another series of health studies in the UK confirmed these findings (Yule 1981). They add further evidence that lead contributes to behavioral problems, lower IQ's and decreased ability to concentrate. Even after taking up to 15 social factors into account, a 3 IQ number deficit was consistently found. While not necessarily statistically significant in any individual study (which is largely influenced by the size of the sample among other factors), the body of data consistently shows the effects.

In addition, the studies of Dr. Winneke in Germany offer further evidence that "neuropsychological effects are causally related to very low blood lead levels" (Winneke 1983). The effects are not necessarily the dominant ones in any particular instance but they are real, a matter of concern and preventable.

A subsequent study, in which 249 children were monitored from birth to two years of age, found that those with prenatal umbilical-cord blood lead levels at or above 10 micrograms per deciliter consistently scored lower on standard intelligence tests than those at lower levels (Needleman, 1989).

British researchers reviewed every epidemiologic study on lead and IQ published since 1979 that had over 100 children and measured IQ as a function of blood or tooth lead levels. Based on a meta-analysis of all the data, they concluded that a doubling of body lead burden from 10 to 20 µg/dl in blood levels was associated with a mean fall of about 1 to 2 IQ points (Pocock 1994).

In summary, the available evidence indicates that "there is no known physiological function served by lead in mammalian metabolism. As far as cells are concerned, each molecule of lead has the potential to disrupt the chemical basis of normal cellular function. For nerve cells, this interference is particularly destructive because communications between cells in the brain depends upon precisely controlled movements of such molecules such as calcium, sodium, potassium and chloride. Lead can interfere, on a molecule by molecule basis, with these essential elements" (Silbergeld, 1982).

7.2.6 Lead Scavengers

When lead additives were first discovered to improve gasoline octane quality, they were also found to cause many problems with vehicles. Notable among these was a very significant build up of deposits in the combustion chamber and on spark plugs, which caused durability problems. To relieve these problems, lead scavengers were added to gasoline at the same time as the lead to encourage greater volatility in the lead combustion by-products so they would be exhausted from the vehicle. These scavengers continue to be used today with leaded gasoline.

Ultimately, a significant portion of these additives are emitted from vehicles. This is important because, unfortunately, these lead scavengers, most notably ethylene dibromide, have been found to be carcinogenic in animals and have been identified as potential human carcinogens by the National Cancer Institute (Sigsby, 1982). Therefore, their removal along with the removal of lead may result in significant benefits to health.

7.2.7 Other Toxics

The 1990 Clean Air Act (CAA) directed the US EPA to complete a study of emissions of toxic air pollutants associated with motor vehicles and motor vehicle fuels. The study found that in 1990, the aggregate risk is 720 cancer cases in the US. For all years, 1,3-butadiene is responsible for the majority of the cancer incidence, ranging from 58 to 72 percent of the total motor vehicle toxics risk. This is due to the high unit risk of 1,3-butadiene. Gasoline and diesel particulate matter, which are considered to represent motor vehicle polycyclic organic matter (POM), are roughly equal contributors to the risk. The combined risk from gasoline and diesel particulate matter ranges from 16 to 28 percent of the total, depending on the year examined. Benzene is responsible for roughly 10 percent of the total for all years. The aldehydes, predominately formaldehyde, are responsible for roughly 4 percent of the total for all years.

A variety of studies have found that in individual metropolitan areas, mobile sources are one of the most important and possibly the most important source category in terms of contributions to health risks associated with air toxics. For example, according to the US EPA, mobile sources are responsible for almost 60% of the air pollution related cancer cases in the US per year.

7.2.8 Conclusion Regarding Urban and Regional Effects

Clearly conventional pollutants from vehicles are a major contributor to urban and regional air pollution. While this would seem to therefore provide a potential impetus for alcohol fuels, the question also depends on the potential for conventional technologies to reduce this pollution in coming years. As summarized in Appendix A, however, conventional fuel and vehicle pollution control technology continues to improve rapidly. As emissions standards get lower and lower, and in the case of gasoline fueled vehicles literally approach zero, any potential advantage of alcohol fueled vehicles is rapidly disappearing. (Sections 4 and 5 reenforce this conclusion.) The only caveat to this conclusion in the short term would seem to apply to diesel vehicles where technology to simultaneously reduce NO_X and PM is proceeding more slowly than the ozone and PM health data would indicate is necessary.

7.3 Global Warming

The third major force which could stimulate alternative fuels is climate change or the greenhouse effect. Greenhouse warming occurs when certain gases allow sunlight to penetrate to the earth but partially trap the planet's radiated infrared heat in the atmosphere. Some such warming is natural and necessary. If there were no water vapor, carbon dioxide, methane, and other infrared absorbing (greenhouse) gases in the atmosphere trapping the earth's radiant heat, our planet would be about 33 °C colder, and life as we know it would not be possible.

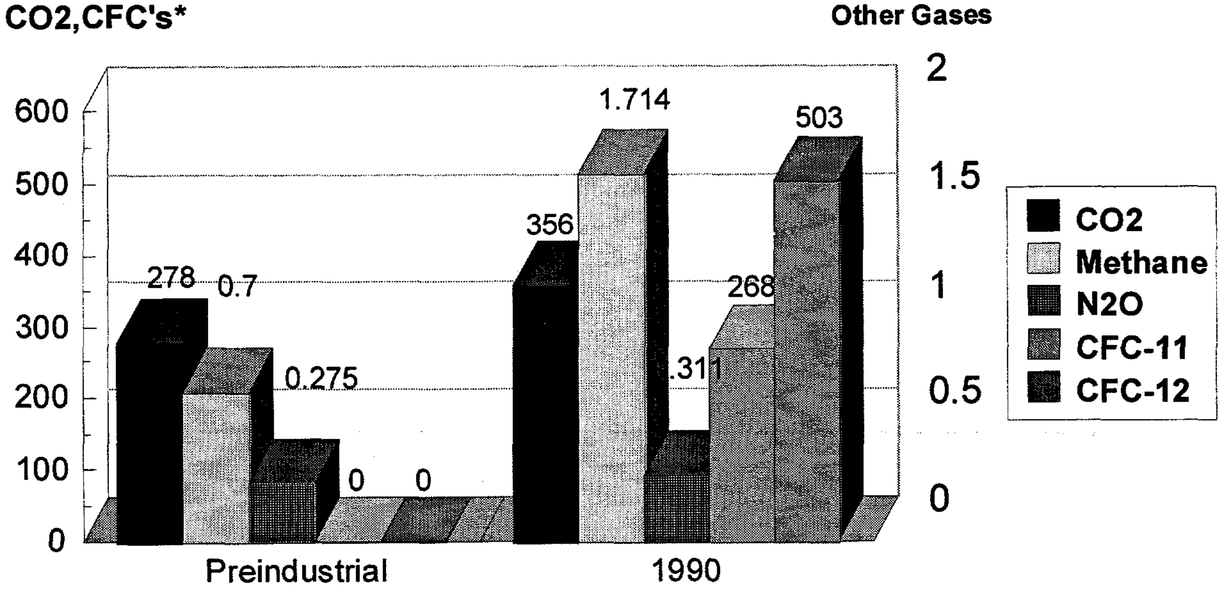
Over the past century, however, human activities have increased atmospheric concentrations of naturally occurring greenhouse gases and added new and very powerful infrared absorbing gases to the mixture. Even more disturbing, in recent decades the atmosphere has begun to change through human activities at dramatically accelerated rates. According to a growing scientific consensus, if current emissions trends continue, the atmospheric build up of greenhouse gases released by fossil fuel burning, as well as industrial, agricultural, and forestry activities, is likely to turn our benign atmospheric "greenhouse" into a progressively warmer "heat trap," as Norway's former Prime Minister, Ms. Gro Harlem Brundtland, has termed this overheating.

Various human endeavors contribute to climate change. Recent estimates indicate that by far the largest contributor (about 50 percent) is energy consumption, mostly from the burning of fossil fuels. The release of chlorofluorocarbons (CFCs), the second largest contributor to global warming, accounts for another approximately 20 percent. Mostly known for depleting the stratospheric ozone layer, these stable, long lived chemicals are also extremely potent greenhouse gases. Deforestation and agricultural activities (such as rice production, cattle raising, and the use of nitrogen fertilizers) each contribute about 13 to 14 percent to global warming.

Carbon dioxide (CO_2) accounts for about half of the annual increase in global warming. The atmospheric concentration of carbon dioxide, now growing at about 0.5 percent per year, has already increased by about 25 percent since preindustrial times (see Figure 13). Half of this increase has occurred over just the past three decades.

Globally, about two-thirds of anthropogenic carbon dioxide emissions arise from fossil fuel burning, the rest primarily from deforestation. In the United States, electric power plants account for about one third of the carbon dioxide emissions, followed by motor vehicles, planes, and ships (31 percent), industrial plants (24 percent), and commercial and residential buildings (11 percent).

The third largest contributor (after the CFCs) is methane (CH_4), accounting for about 13 to 18 percent of the total warming. Sources of this gas include anaerobic decay in bogs, swamps, and other wetlands; rice growing; livestock production; termites; biomass burning; fossil fuel production and use; and landfills. Methane may also be arising from the warming of the frozen Arctic tundra. The atmospheric concentration of methane is growing by about 1 percent annually.



*=parts per trillion

Figure 13. Global Atmospheric Concentrations of Greenhouse Gases.

Ozone (O_3) in the lower atmosphere (the troposphere) is the principal ingredient of smog. This gas is created in sunlight driven reactions involving nitrogen oxides, NO_X (as distinct from nitrous oxide, N_2O) given off when either fossil fuels or biomass are burned, and volatile organic compounds from a wide spectrum of anthropogenic and natural sources. In the United States, highway vehicles are the source of about 31 percent of NO_x emissions and about 44 percent of volatile organic compounds. Tropospheric ozone contributes about 8 percent to global warming.

Exactly where nitrous oxide (N_2O) comes from is still uncertain, but prime suspects include the use of agricultural fertilizers and, perhaps, the burning of biomass and coal. A growing source of N_2O is motor vehicles with three way catalysts. Nitrous oxide accounts for about 6 percent of current enhanced warming and also contributes to depletion of the stratospheric ozone layer.

As greenhouse gases accumulate in the atmosphere, they amplify the earth's natural greenhouse effect, profoundly and perhaps irreversibly threatening all humankind and the natural environment. While most scientists agree on the overall features of such warming, considerable uncertainties still surround its timing, magnitude, and regional impacts. Major unanswered questions include whether the additional clouds that are likely to form will have a net cooling or warming effect, how the sources and sinks of greenhouse gases will change, and whether the polar and Greenland ice sheets will grow or retreat. The complexity of the global climate system is daunting and the interactions between the atmosphere and the oceans are still imperfectly understood.

Unless measures are soon taken to reduce the release of greenhouse gases, by as early as 2030 they could reach levels equivalent to twice the carbon dioxide concentrations of pre industrial times. According to the most informed scientific opinion, continued "business as usual" growth in greenhouse gas emissions will lead to;

- an increase in the global average temperature of 2 degrees Celsius (3.6 degrees F), with a range of 1.4 to 2.8 degrees Celsius (2.5 to 5 degrees F), over preindustrial levels by the year 2030;

- sea level rises great enough to threaten wetlands, accelerate coastal erosion, exacerbate coastal flooding, and increase the salinity of estuaries and aquifers;
- changes in rainfall patterns;
- more intense tropical storms;
- more severe droughts, especially in mid continental regions, resulting in dislocations and reduced agricultural output; and
- the loss of many unmanaged ecosystems.

Some of these changes could be gradual. The United Nations sponsored Intergovernmental Panel on Climate Change (IPCC) has estimated that sea levels may rise an average of approx. 15 to 50 centimeter (6 to 20 inches) above current levels by 2050 if present trends continue. However, the totally unanticipated opening of the Antarctic ozone hole heightens scientists' anxiety about how quickly such significant and poorly understood phenomena can develop. Many experts fear that climate changes, once initiated, could occur faster than expected. As noted in Science, "the possibility that a considerably larger, though less likely, temperature rise presents the greater risk remains ignored. The latter eventuality is more to be feared, principally because of the high cost of its effects, the draconian and expensive steps needed to avert it, and the time required, first, to obtain global agreement on the need to act, and then to transform world energy production into a non fossil fuel using system."

Two recent events have heightened this concern. In late November 1995, the IPCC Working Group 1 concluded that "the balance of evidence suggests that there is a discernible human influence on global climate"(Science, 1995). Even more recently, a provisional report issued by the British Meteorological Office and the University of East Anglia concluded that the earth's average surface temperature climbed to a record high in 1995 (NY Times, 1996). In spite of commitments by most industrialized countries to stabilize or reduce CO_2 emissions, very little progress has occurred in the transportation sector. Strategies such as mandatory increases in fuel economy or substantial increases in fuel taxes have proven elusive in recent years. Biofuels with their potential to dramatically lower CO_2 emissions are therefore now emerging as one of the more attractive and least painful approaches to lowering greenhouse emissions.

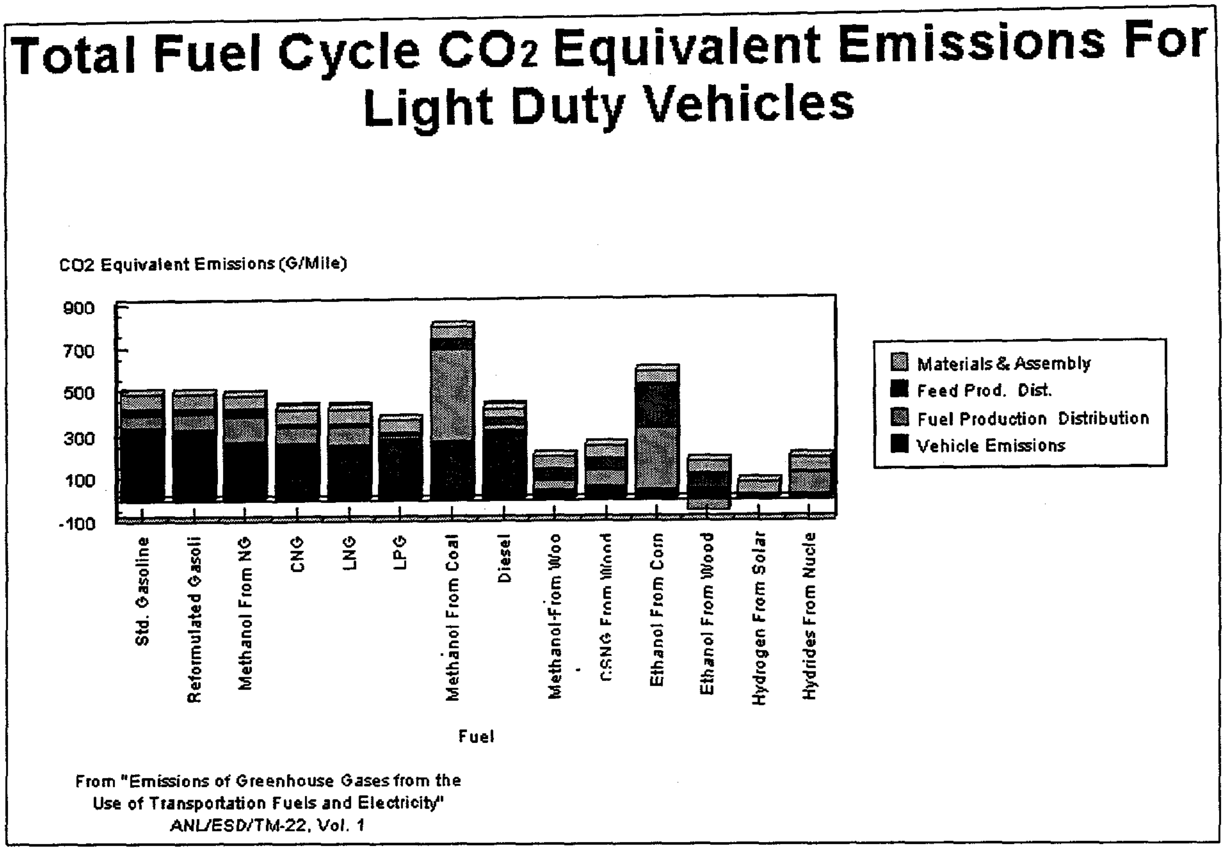


Figure 14.Emission of greenhouse gases.

One seminal study released in late 1991 assessed the greenhouse gas emissions from a variety of potential fuels and some of the results are summarized in Figure 14. (DOE 1991) This study concluded that in considering total fuel cycle CO_2 equivalent emissions including not only direct vehicle emissions but fuel production and distribution, feedstock production and distribution and vehicle materials and assembly, methanol or ethanol produced from wood are among the two most attractive fuels available, exceeded only by solar power. It thus appears that biomass based fuels have very high potential for reducing the transportation contribution to global warming.

8. Technology for the use of methanol as a fuel for motor vehicles

When using a new fuel for a motor vehicle, such as a methanol-gasoline blend, the interrelation between the fuel and the engine will change compared to the use of gasoline not blended with methanol. The fuel properties of methanol-gasoline blends, which may have an influence on the vehicle and its performance are, among others:- heat of evaporation, physical properties such as viscosity and surface tension that affects the dispersion of the fuel in the combustion air, (self) ignition properties, flame speed of combustion, and chemical composition that will be of importance for the formation of the different combustion products (IEA, 1986). Generally speaking, the vehicle and engine should be completely adapted to the fuel in order to take the full advantage of a new fuel such as an alcohol.

The octane number of methanol is as high as ca. 110 RON and 90 MON and it is therefore most suitable for used in spark ignition (otto) engines. Despite the low cetane number of methanol, 3, it is also used also in compression ignition (diesel) engines under certain conditions which will be described below in section 8.2. In section 8.1 the use of methanol-gasoline blends and neat methanol will be discussed.

The energy content of methanol is 15.8 MJ/l (19.8 MJ/kg), which is lower than the energy content of ethanol, 21.1 MJ/l, and of gasoline, about 32 to 33 MJ/l (depending on the blend). Because of the lower energy content of methanol the engine has to be adapted to the fuel if blended in gasoline to a rate of more then 15 or 20 per cent, or used as non blended with gasoline or other fuels. As has been pointed out, there is also a limit from the technical point of view, to the amount of methanol blended in gasoline. A rate of more than 15 percent may lead to problems with cold starting and deteriorated driving conditions.

One problem with the use of methanol or ethanol as automotive fuels is that they are aggressive to some materials (some membranes, some rubber hoses, some alloys etc.) in the fuel distribution system and in the engine. For the use of higher blends of methanol more parts of the vehicle must be changed, such being incompatible with the fuel (IEA, 1986). Problems related to the material in the engine and especially the fuel system have been experienced in flexible fuel vehicles (FFV's) and some of these problems are still present when using methanol (Ford, 1995). According to Ford the use of ethanol had not presented any specific problems with the material in the fuel system. Therefore Ford was in favor of the use of ethanol.

An important issue is the contamination of methanol when gasoline distribution systems are used. However, this problem will probably be solved when larger amounts of methanol are passed through the gasoline distribution systems. Tin plated fuel tanks may have to be replaced by tanks made of low carbon steel and parts in the fuel system may have to be nickel-plated or changed to other material (IEA, 1986).

Both methanol and ethanol my be seen as solvents and therefore fuel tanks, hoses and other parts in the fuel distribution system are cleaned from dirt and paint and this will lead to a contamination of fuel filters, fuel injectors etc. Problems with deteriorated gaskets in the fuel system and also with certain alloys have been reported. All of these problems must be carefully investigated and solved before there can be any real success with the use of alcohol fuels among ordinary car owners.

According to reported experiences gained during the use of both low-level blends and higher-level blends as well as neat methanol, engine wear is not a matter for concern and conventional engine lubricating oils can be used. In extreme cases, when the vehicle is cold started followed by a short driving distance, the lubricating oil could be diluted with the fuel (IEA,1986). Concerning the influence of methanol on the material such membranes and hoses this problem is valid also when using low-level blends. However, vehicles produced today are usually adapted to the use of low levels of alcohol in the fuel.

Experiences gained by those who have used both methanol and ethanol are that the problems reported above are more serious when using methanol than when using ethanol (Parry, 1995; Ford, 1995; MTA, 1995). The problems caused by methanol have been so serious and difficult to solve that some of the owners of fleets of vehicles are in favor of using ethanol instead of methanol. However, it could be said that the problems mentioned above will certainly be solved in the long run but for the car owner it would be better if resources could soon be allocated in order to completely solve these problems which are connected to the use of methanol.

A more thorough presentation of experiences with the use of methanol will be presented in sections 8.1, 8.2 and 8.3.

8.1 Methanol in Otto engines

In section 2 fuels containing methanol and neat methanol fuel were discussed. Concerning engines and vehicles for these fuels at least three categories of vehicles equipped with Otto engines can be identified:

- Vehicles which are adapted to be fueled with a low alcohol blend in gasoline.
- Vehicles which are adapted or developed for higher alcohol blends in gasoline.
- Vehicles dedicated to be fueled with a high blend of alcohol in gasoline or with neat alcohol.

The *first* mentioned category of vehicles are generally ordinary gasoline fueled vehicles which have been developed so as to tolerate alcohols in the fuel. Various parts in the fuel system may not be constructed of materials, such as rubber and plastic materials, which will be damaged when using a blend of alcohol (especially methanol) in gasoline.

The *second* category of vehicles are either such vehicles with an adaptive fuel metering system, which may tolerate up to 15 vol % methanol in the fuel or flexible fueled vehicles (FFV's), which will tolerate an alcohol content in gasoline from 0 % up to at least 85%. In this category of vehicles are included even such vehicles which have been developed to be fueled with a certain volume of alcohol, for example a blend of 50/50 alcohol/gasoline. Flexible fueled vehicles are designed so as to adjust themselves to the fuel used and therefore good emission characteristics have been demonstrated.

The *third* category of vehicles are those which have been developed so as to be fueled with a certain amount alcohol in gasoline or other hydrocarbons or with neat alcohol. These types of vehicles would be very advantageous both in terms of fuel economy and emissions, if they are designed so as to take full advantage of a clean fuel such as an alcohol.

When considering the functions of the fuel, there is no doubt that alcohols are much more suitable as fuels for Otto cycle engines. Methanol and ethanol have a high knock resistance i.e. a high octane number, as opposed a low cetane number.

8.1.1 Low alcohol - gasoline blends

According to experiences from an investigation of vehicles fueled with a blend of 16% ethanol in gasoline there were no unacceptable problems with cold starting and driveability (Aspen, 1995). The fuel was composed of 79% alkylate, 16% ethanol and 5% xylenes. One of the vehicles, a Volvo 850 GLT with adaptive fuel metering system, was emission tested using this fuel (Laveskog, 1995). This investigation has shown that a higher blend of alcohol in gasoline can be used without intolerable influence on the driving conditions of the vehicle.

To sum up the discussion about the use of a blend of methanol for light duty vehicles from technical point of view the following conclusive remarks are given;

- for modern cars it is suggested that the content of methanol could be raised above the maximum 3.5% (equivalent mass of oxygen) which is allowed today according to the EEC directive 85/536/EEC and this could be done without any unacceptable effect on the driveability of the car;

- the gasoline base fuel should be adjusted so as to minimize the increase of the vapor pressure above the level which is normal for a typical unblended gasoline;

- when using methanol blended fuel it should be taken into account that methanol is a solvent and very aggressive, which can lead to problems with dirt being dissolved during distribution of the fuel. There seems also be a risk for a deterioration of the material in the fuel system caused by using higher blends of methanol.

8.1.2 Higher-level blends corresponding to up to 85% methanol in gasoline

Despite the strong demand for decreasing the emissions from heavy duty vehicles not much work has been directed to projects where heavy duty Otto engines running on alcohol have been developed. One reason for the poor interest may be lower efficiency of an Otto cycle alcohol engine compared with a diesel cycle alcohol engine. Investigations and field testing have shown that the brake thermal efficiency of a diesel cycle alcohol engine is, in some cases better, when compared with a diesel-fueled compression combustion engine. In the case of alcohol engines, much experience has been gained from the development and field testing of alcohol engines used in light duty vehicles. It is well documented that an engine equipped with a three-way catalyst system is considered to be a low emission engine. The only drawback concerning experience with this system is that there seems to be a lack of demonstration projects and field testing of engines in heavy duty vehicle applications.

In one project (Nylund and Eklund, 1988) a diesel fueled truck engine, displacement 6.6 liters, was converted to be run on ethanol as an Otto cycle engine. The engine was not optimized for the purpose of being fueled with ethanol and it has therefore been suggested that the performance and fuel consumption could be improved by such measures as turbo charging, improved fuel injection, mixture formation, valve timing and ignition system. Application of a closed loop fuel system and three way catalyst could drastically reduce the emissions. Tests on the engine at the stage of development showed a thermal efficiency of 34%. Because of the poor fuel economy of an Otto cycle engine at low loads, the increase of fuel consumption was about 20% compared with the diesel-fueled version of the engine.

8.1.3 High gasoline-alcohol blends or neat alcohol

The intention when using low-level blends of alcohols in gasoline is that the amount added shall not have an unacceptable influence on the cold start behavior and driveability of the vehicle. For older vehicles in service, and especially those equipped with a carburetor, such disturbances could occur. Newer types of vehicles equipped with a fuel injection system, and especially those having a closed loop fuel system, have been proved to tolerate a higher rate of alcohol in the fuel.

The technology used today for fuel metering systems in state of the art gasoline fueled vehicles allows the use of higher blends of oxygenates than those corresponding to 3.5% oxygen which is the absolute maximum allowable content today. It is assumed that methanol-gasoline blends with up to at least 15% methanol can be used in vehicles equipped with such fuel metering systems.

When considering the technology to be used it must be taken into account that, over a certain limit of the content of methanol in gasoline, the fuel metering system and other parts of the vehicle must be adapted to the type of fuel. All parts of the vehicle which are incompatible with methanol must be changed to parts which are not affected by the fuel. Retrofitting of gasoline fueled vehicles is possible and has been practiced in the USA but in Sweden this is considered not to be an efficient way to make full use of the fuel. However, the new types of fuel metering systems are rather tolerable to higher blends (30 to 50%) of alcohol in gasoline and therefore a modification of the fuel control unit could allow operation at higher-level of methanol.

An alternative to the retrofitting of vehicles in service would be to redesign the vehicle and especially the engine in order to take advantage of the energy and environmental potential of the fuel. Such a redesign can be carried out to produce either flexible fuel vehicles or dedicated vehicles and engines i.e. such vehicles which are designed for a fixed content of alcohol in the fuel.

Flexible fueled and variable fueled vehicles are designed to use a variable content of alcohol in gasoline and the technology for such vehicles is already available even if there is a need for further field testing of such vehicles in order to approve the durability during long range use. As already pointed at there have been some complaints about the aggressivity of methanol to some of the alloys.

Another technology which could be considered when developing engines for the use of an alcohol fuel is to direct the development towards so called dedicated engines and vehicles. A blend of 50% of alcohol in the fuel could be a suitable content which could be considered in order to keep a good cold startability of the vehicle also during the winter season. The benefit of having a dedicated vehicle is that the engine can be more completely adapted to the fuel than for a FFV, within a reasonable cost for the development of the engine.

The most efficient technology from the environmental point of view would be to develop dedicated vehicles for the use of either 85% alcohol in the fuel or to a fuel of close to 100% alcohol. The latter is assumed to be the best choice because then the full advantage of the fuel could be exploited.

In order to exploit the potential of the fuel a new design of the vehicle and especially the (spark ignition) engine is needed. The use of the following features should be taken into account when evaluating the benefit of using alcohols instead of gasoline (IEA, 1986);

- a high compression rate because of the high knock resistance of alcohols;
- a higher volumetric efficiency, resulting in increased power and lower compression energy demand, as a result of the high heat of evaporation of the alcohols;
- decreased spark advance, resulting in improved efficiency due to high flame speed;
- lower flame temperature and emissivity, leading to improved efficiency of the engine through lower heat losses;

8.1.4 Some drawbacks in the use of alcohols compared to the use of gasoline

Special measures have to be taken in order to prevent spot pre-ignition, which, however, is counteracted by the soot-free combustion of alcohol fuels;

- special measures have to be taken in order to improve the cold startability of the engine and to obtain an acceptable driveability;
- larger fuel tanks are required in order to obtain the same driving range as for gasoline fueled vehicles;
- special materials are required in order to prevent damage and increased deterioration of the engine.

The above problems, including dirt in the fuel and deterioration of material in the fuel system of the vehicle, seem to be general problems as do not appear in just one area or one country and therefore they should be identified and addressed by cooperative efforts.

8.2 Methanol in diesel engines

At least three categories of vehicles with a compression ignition engine can be found when considering the use of methanol for diesel fueled vehicles:

- Vehicles using an emulsion of alcohol in diesel oil.
- Vehicles using a dual fuel system with alcohol as the main fuel and diesel as a pilot fuel.
- Vehicles using neat alcohol.

8.2.1 Vehicles using an emulsion of alcohol in diesel oil.

According to Oak Ridge National Laboratory several investigations have been carried out in order to study the effect on the function of the engine and the emission characteristics when using an emulsion of alcohol in diesel (Becthold, 1986). Many researchers have been involved in the investigations; the conclusions are:

- A stabilizing agent is required when using emulsions of alcohol in diesel fuel in order to keep alcohol and diesel fuel from separating.
- The content of alcohol in the emulsion affects the cetane number more than the equivalent amount of alcohol in the fuel.
- If the fuel injection system is adjusted in order to compensate for the lower heating value of the emulsion there will be only a minor effect on the engine operation characteristics.
- Alcohol in diesel fuel, in general, tends to increase HC and CO at low loads; NO_X can increase ordecrease depending on the engine. Particulate and smoke are reduced in most cases.
- There seems to be a positive correlation between aldehydes and HC as they often increase.
- Alcohol/diesel oil shows a flammability which is more like the flammability of gasoline than of diesel oil.

8.2.2 Vehicles using a dual fuel system with alcohol as the main fuel and diesel as a pilot fuel.

The investigations carried out by Volvo using alternatively methanol and ethanol have shown very promising results (Bertilsson and Gustavsson, 1987). Three alcohol fueled engines, TM 101 G for trucks and two THM 101 E for busses were tested. One of the bus engines was equipped with an inter-cooler (TH 101 E-JC). A diesel-fueled bus engine was also included in the test fleet. When the methanol bus engine and the diesel fueled truck engine were tested according to the 13 mode-test procedure, the HC emissions were at the same level as for the diesel fueled version. The emission of NO_X was reduced by about 15 per cent for the engine without catalyst and about 50 per cent for the engine with an inter-cooler when compared with the diesel fueled engine. The emission level when testing the engines according to the 13-mode test procedure was 4 to 5 g/bhph for NO_X and about 0.6 g/bhph for HC. Tests according to the U.S. transient test cycle resulted in 4.4 to 5.5 g/bhph for NO_X, 3.5 to 4.5 g/bhph for HC and O,9 to 2.0 g/bhph for particulate emissions. An important observation is that transient driving leads to a higher HC emission and also higher particulate emissions if the amount of diesel injected is not reduced. This observation was one of the results from an investigation carried out at an early stage of the development (Björkman och Egebäck, 1987). At that stage, the matching of the injection was not such that it favored the emissions.

The main problem experienced by Volvo when running on alcohol and a diesel pilot fuel was cavitation and wear of the fuel system and, in addition, cracked nozzles.

8.2.3 Vehicles using neat alcohol.

Despite the potential of reducing the emissions from heavy duty diesel fueled engines, the need remains for further emission reductions of especially NO_X and particles. Concerning these two pollutants, the lower level, which seems to be in sight, is around 4.0 g/bhph for NO_X and 0.1 g/bhph for particulate emissions.[11] Research work and investigations carried out on engines designed for alcohol fuels have indicated that much lower emission levels can be reached when utilizing the whole emission potential of alcohol fuels. To reach this goal, different techniques can be used. The more important of those investigated so far are: Compression ignition engines of different types such as direct and indirect injection engines, stratified charged engines etc. utilizing different techniques to start or to improve the ignition of alcohol. The techniques used are pilot fuels (dual fuel) ignition improvers (additive in the fuel), spark plugs, glow plugs or some other hot surface ignition technique, thus obtaining a continuous ignition without misfire when running the engine. Some of the techniques used for alcohol utilization in compression ignition engines are the following (Hochmann and Gruden, 1988):

- Fumigation: Alcohol is introduced into the engine intake system by carburation or vaporization.

- Dual fuel or alcohol with ignition improver.

- Ignition improver: Some type of ignition improver such as ethyl hexyl nitrate is added to the alcohol used.

- Spark ignition: Alcohol is spark ignited in the combustion chamber of the compression

---

[11] Recent work in the United States indicates that levels of 2.0 NO_X and 0.1 particulate should be possible by 2004.

ignition engine.

- Glow plug ignition: Combustion is initiated by a hot surface in the combustion chamber.

- A new approach of the dual-fuel system technique is the "Aspirated ether Ignition System for Methanol Fueled Diesel Engines" developed in New Zealand (Galvin, 1988).The main feature of the system is the use of dimethyl ether as a pilot fuel, this being mixed with the engine inlet air. Dimethyl ether is produced in the engine system by using a catalytic, methanol-to-dimethyl ether reactor.

There is an ongoing activity in order to develop catalysts for alcohol fueled heavy duty vehicles. In Sweden the Royal Institute of Technology is carrying out a project sponsored by KFB and NUTEK aiming at the development of tailored catalysts for vehicles fueled with alcohol (Pettersson et al., 1997). As already discussed there is activity in Japan concerning the development of engines to be fueled with an alcohol (preferably methanol).

The Japan Ministry of transport is interested in this activity and has been involved in the development of catalysts. Yamamoto and his Co-wokers have studied the possibility of reducing the emission of NO_X from a methanol fueled diesel engine by using an aluminum catalyst. Yamamoto and his team has confirmed that aluminum catalysts are effective in reducing NO_X in oxygen rich atmosphere (Yamamoto et al., 1996).

(1) Glow Plug Engines

When changing over from auto-ignition to some type of forced ignition using a glow plug or a spark plug, it could be said that the engine has been changed from a diesel-cycle engine (compression ignition engine) to some type of spark ignition engine. However, the engine is still a high compression engine running on a lean mixture. The advantage of using forced ignition is that the engine can be run on pure alcohol and that the fuel efficiency of the engine is still as high as for a diesel fueled engine.

Besides spark plug engines, the glow plug concept is widely used to start and improve the ignition of alcohol in the combustion chamber (Yui et al., 1988; Havenith, 1988; Jaye et al., 1988; Barenescu et al., 1988; Cui and Ji, 1988;, Murayama et al., 1988; Seko et al., 1988). Glow plugs may be used in all types of engines and constitute the only method available for neat alcohol fuels (Murayama et al. 1988). However, one of the problems with glow plugs is that ignition takes place with difficulty at low engine loads. The ignition performance depends on the fuel amount, ignition timing, layout of the glow plug, the glow plug temperature and certain other factors. Concerning the emissions, a considerable amount of data is available, showing that the emission of especially NO_X and particulate can be reduced substantially when compared with a diesel fueled engine. The low range of emission of HC, CO and NO_X, 1.0, 9.0 and 1.5 g/bhph, respectively, has been achieved by Detroit Diesel Allison, using a two stroke turbo charged engine (Jaye et al. 1988). One disadvantage of a two stroke engine is the low exhaust gas temperature, which calls for some special arrangement when using a catalyst to reduce the emission of unburned fuel, CO, aldehydes and other components which can be oxidized.

Despite the fact that alcohols have not been used as fuels for compression ignition engines for more than a few years and in a limited number of vehicles, some promising results have also been achieved for four stroke engines. Kloeckner-Humboldt-Deutz AG has obtained some experience from the development of a glow plug-assisted heavy duty engine (Havenith, 1988). The emission level, when tested according to the US transient test procedure, was about 5 g/bhph for HC, 4 g/bhph for NO_X and 0,12 g/bhph for particles. Unfortunately, this experiment showed that the life-time of the glow plug was not satisfactory, which calls for expanded work to improve the reliability and life time of the glow plugs.

Judging from the experience generated so far and the emission test results, a feasible goal to be reached concerning the emissions when using glow plugs could be 0.5 and 1.5 g/bhph for HC and NO_X, respectively. The particulate emission could be far under 0.1 g/bhph and emissions of components such as aldehydes, alkyl nitrites etc. could be reduced to a low level if using a well-functioning catalyst.

Forced ignition by use of glow plugs is considered to consume more electric power than forcing the ignition by spark plugs. In actual fact, the glow plug is expected to have a better performance concerning ignitability and fuel economy than the spark plug (Yui et al., 1988). A glow plug temperature of 800 - 820°C is most favorable for optimum fuel consumption. Improvement of the reliability and life time of the glow plug is necessary (Havenith, 1988). The lifetime of the glow plugs can be expanded by using them only during cold starting, motoring running conditions and at low loads.

(2) Spark Plug Engines

Spark plugs have been used for investigation purposes and in many programs designed to demonstrate the possibility and problems of using alcohol in heavy duty compression engines (Murayama et al., 1988; Seko et al., 1988; Saito et al., 1988; Ishizuki, 1988; Hikino, and Suzuki, 1988; Johns, 1988; Yanagihara et al., 1988; Shiino and Nakashima, 1988; Takada et al., 1988; Tsunemoto et al., 1988; Hira et al., 1988; Ullman and Hare, 1986; Wollny and Blödorn, 1985). The advantage of using spark plugs is that they need less electric power than glow plugs. Using spark plugs also make it possible to have a lower compression ratio than when using glow plugs. Furthermore, the spark-assisted system has the advantage of easy conversion from a conventional diesel engine and easy ignition of an air-fuel mixture. The disadvantages of spark plugs are short life time and poor fuel economy. Comparing emission test results from spark plug engines with glow plug engines shows somewhat higher NO_X emissions when using spark plugs.

The importance of the position of the spark plug has been investigated at the Hokkaido University (Murayama et al., 1988) and it was found that in their methanol engine system the optimum position of the spark plug was outside and a little downstream of the fuel spray in a strong vortex flow. Regarding the emissions and durability, extended testing has been carried out on a part of the methanol engine concept.

In one investigation (California Energy Commission 1986; Unnasch and Jackson, 1986) tests according to the 13 mode test procedure were carried out on a M.A.N. bus equipped with a methanol engine and an oxidation catalyst to control the emissions of HC and aldehydes. The test results were 0.28, 5.75 and 0.16 g/bhph for CO, HC and NO_X, respectively. At an investigation carried out by Mitsubishi Motors Corporation (Yui and Nakashima, 1988) a spark plug methanol engine was compared with a glow plug engine using the same fuel. The comparison showed that the concentration of HC, CO and NO_X was much lower when using glow plugs than when using spark plugs, especially at low loads, for HC and CO and at high loads for NO_X.

Concerning the durability of the spark plug, the need still remains for improvements. Today the life time of a spark plug is too short to be accepted, 4000-5000 miles and shorter for a bus in city traffic. Other failures which have been detected are associated with the injectors, engine wear and catalyst performance.

A major problem when using fuel alcohols in diesel engines is to overcome the poor ignition quality due to the low cetane number. One technology used to solve this problem is to add some type of commercial ignition improver to the fuel. There might be different reasons for not using ignition improvers. For example the cost of the additive may be considered too high, especially when a relatively high percentage is needed. Another problem not fully investigated may be the emissions of unwanted species caused by the ignition improver itself. Several compounds have been used as ignition improvers i.e. polyethylene glycol (Björkman and Egebäck, 1987; Grägg and Egebäck, 1987), hexyl nitrate (Fahlander and Walde, 1980; Westerholm et al., 1984), 2-ethyl hexyl nitrate (Westerholm, 1981). At the exhaust emission research laboratory at Studsvik (Sweden) measurements were carried out on a diesel engine fueled with ethanol which was treated with ethanol/ethyl hexyl nitrate (EHN). Samples were taken with and without catalyst after-treatment (Björkman and Egebäck, 1987). In order to compare two different ignition improvers EHN and poly ethylene glycol (PEG) in ethanol vehicle equipped with an oxidizing catalyst was emissions tested (Grägg and Egebäck, 1987).

The effect on the NO_X emissions has been studied when using ethyl hexyl nitrate as an ignition improver for ethanol. In comparison with a conventional diesel fuel, for the same engine, an increased nitrogen dioxide emission was detected even if the total NO_X emission was decreased (Westerholm, 1984). The emission of nitrogen dioxide was approximately 2-4 times higher in the driving modes which were investigated. Up to 200 per cent increase has been observed by Hira and co-workers (Hira et al., 1988). A possible explanation is the loss of the nitro group originating from the ignition improver. This indicates that, when using organic nitrates in fuels (both alcohols and some types of diesel fuels), an increased nitrogen dioxide emission occurs. The increased nitrogen dioxide emissions might lead to increased nitro polycyclic aromatic hydrocarbon emissions (Nitro-PAH) due to nitration of PAH present in the exhaust stream. Nitro-PAH are known to be considerably more mutagenic/carcinogenic than the corresponding PAH. However, it is obvious that the results from these tests call for more thorough development work to be carried out if the emission potential of alcohols is to be taken care of. Because of the high emission of especially unburned fuel, alkyl nitrites and aldehydes when using alcohols in engines of different types, all such engine systems should be equipped with a reliable catalyst. Measures should also be taken to reduce the NO_X emissions.

Scania has developed a second generation of compression ignition engines fueled with ethanol and equipped with an oxidation catalyst. Some other measures have also been take to reduce the emissions. The percentage of ignition improver has also been reduced substantially from about 8 to 2-3 per cent.

An extensive investigation of the Scania etanol fueled engine has been carried out at Luleå University of Technology in order to study the impact on the emissions when changing different engine parameters (Egebäck and Pettersson, 1996). In one of the trials a study was made of two different ignition improvers having trade names Avocet (a nitrate ester) and Beraid (a poly ethylene glycol) respectively. When comparing the emission of NO_X it was shown that the level of NO_X was lower when using Avocet than when using Beraid.

8.3 Other Concepts

Most of the alcohol fueled engines are converted conventional Otto or Diesel engines. The introduction of alternative fuels has been based on the knowledge generated during many years of driving with gasoline and diesel-fueled vehicles. So far, these types of vehicles are considered to be the most cost effective and reliable of the different alternative engines known today. Concerning the emissions, the gasoline fueled Otto engine equipped with a three-way catalyst has proved to be outstanding. The only challenge could be an alcohol-fueled Otto engine equipped with the same type of emission control device i.e. a three-way catalyst. When considering the emissions, there is a strong desire to find an alternative to the diesel fueled engine. Judging from the situation today there does not seem to be a reliable and efficient emission control technique to sufficiently lower NO_X and particulate from diesel fueled engines. Therefore, as noted in Section 7.2 it is likely that most of the effort to find alternative engines will be directed towards an engine to be used in heavy duty vehicles as a replacement for the diesel-fueled engine. At the VIIIth International Symposium on Alcohol Fuels (ISAF) held in Japan, some of the new ideas were presented, a number of which may be seen in the near future. One of these was a new type of internal combustion spark ignition engine. The new idea is called "Direct Fuel Injection Impingement Diffusion Stratified Charge System" called OSAKA (Kato et al., 1988). The idea is that the fuel jet is injected against an impinging area of the control piston cavity. Experiments made during the development of the engine have shown that the indicated mean effective pressure was 1.3 Mpa and the maximal indicated thermal efficiency was 46%. These figures call for further development work on this engine type. Concerning the emissions, the experiments show that the emissions can be reduced by EGR, by injection timing and by matching the engine parameters such as swirl, and others.

Another project has also been under way where the stratified charge combustion has been demonstrated. These experiments were carried out on a spark-ignited, air-cooled single cylinder, four cycle engine having a full transistor type ignition system. The engine was developed for ethanol fuel (Nagakura and Fukudome, 1988). Concerning the emission ability, only a limited number of data has been presented. The low load HC emissions and combustion stability were improved by injecting fuel against the swirl. In one of the projects, the ability of the Stirling engine as a "clean" engine has been evaluated (Katohno et al., 1988). Comparing methanol with natural gas showed that the concentration of CO and NO_X are much lower when using methanol and are thus considered to be very low. An approach which has been under investigation is the decomposition or dissociation of methanol. Development and research work performed at Japan Automobile Research Institute (JARI) (Yamaguchi et al., 1985) on a dissociated methanol fueled spark ignition engine showed twenty per cent improved thermal efficiency compared to a gasoline fueled engine and similar emission value to those of gasoline engines indicating a development potential. Two status reports were presented at the VIIIth ISAF (Karpuk et al., 1988; Pettersson and Sjöström, 1988). The objective of the work has been to design, test and in one case to fabricate a dissociated methanol vehicle. If the development of this type of engine is to be successful, there is a good possibility that the demand for a low emission engine will be met with.

9.FUTURE METHANOL SCENARIOS

There are two not well developed areas where methanol may play a role in the future. The investigations and development carried out up to today have shown promising results and therefore the following discussion seems to be of some value.

9.1 Fuel Cells

Fuel cell technology is essentially just a battery, using an external supply of fluids as its energy source, and solids to separate those fluids, connected to an electric motor. Unlike a battery, however, a fuel cell does not run down or require recharging; it will operate as long as both fuel and oxidant (oxygen in air) are supplied to the electrodes and the electrodes remain separated by the electrolyte. The electrodes act as catalytic reaction sites where the fuel and oxidant are electrochemically transformed, producing D.C. power, water, and heat.

Since fuel cells are not limited by Carnot's theory of heat engines (as a all conventional internal combustion engines), their potential efficiency is much greater. Studies have demonstrated that fuel cells have the potential to approximately double or more vehicle fuel efficiency. At the same time they have the potential to substantially lower if not eliminate some of the conventional pollutants. CO and HC should be virtually eliminated. Further, since fuel cells operate at much lower temperatures than IC engines, NO_X emissions should be very low (Walsh, 1990).

Fuel cells chemically convert hydrogen and oxygen into water and electricity and would effectively make the hydrogen vehicle a highly efficient electric vehicle. Methanol is the preferred liquid carrier at present. Via steam reforming, CH_3OH can be converted to a mixture of H_2 and CO_2 from which the fuel cell extracts the H_2 fuel. While ethanol is also readily storable and safe, it requires relatively high reforming temperatures and therefore higher NO_X emissions.

9.2 Dimethyl ether

Dimethyl ether is a relatively new fuel which has been introduced as a suitable fuel for compression ignition engines. According to the available literature, DME was tested as an ignition promoter for the combustion of methanol in a compression ignition engine by Brook and his colleagues in South Africa as early as 1984 (not in the reference list) and Galvin, New Zealand, reported at a 1988 symposium the results of an investigation where he had tested DME as an ignition aid when fueling a diesel engine with ethanol (Galvin, 1988). More such similar investigations have been reported but during 1994/95 a new interest in the use of DME arose. A new method for the production of DME was developed and an initiative was taken to study the possibility of using neat DME as a fuel for compression ignition engines. As DME, similar to LPG, is a gas at normal temperature and pressure a special technique must be used in order to introduce the fuel into the combustion chamber of the engine.

In Table 14 some important properties of diesel fuel DME and other alternative fuels are presented and it should be noticed that the cetane number is above 55 for DME, which is an advantage when using the fuel in diesel engines. On the other hand the lower calorific value is only about 65% of the calorific value of the diesel fuel and the kinematics viscosity is less than 1 cSt, which means that a viscosity raising additive must be used. By increasing the pressure of the fuel to over 5 bars the fuel can be liquefied and handled in about the same way as LPG.

able 14: Combustion Relevant Properties of Diesel and Alternative Fuels (Kapus and Ofner, 1995).

	DME	Diesel Fuel	Methanol	Ethanol	CNG (Methane)
Chemical Structure	CH_3O-CH_3	-	CH_3-OH	$CH_3.CH_2-OH$	CH_4
Lower Calorific Value (MJ/kg	27.6	42.5	19.5	27.1	50.0
Density (g/ml)	0.66	0.84	0.79	0.80	-
Cetane Number	> > 55	47-50	5	8	-
Auto-ignition Temperature (°C)	235	250	450	420	650
Octane Number (-)	-	-	111	108	130
Stoicheiometric A/F Rate (-)	9.0	14.6	6.5	9.0	17.2
Boiling Point (°C)	-20	180-370	65	78	-16
Heat of Evaporation (kJ/kg)	460 at -20°C 410 at 20°C	250	1110	904	-
Explosion Limits (% Gas in Air)	3.4-18	0.6-6.5	5.5-26	3.5-15	5-15
%wt. Carbon	52.2	86.0	37.5	52.2	75.0
% wt. Hydrogen	13.0	14.0	12.5	13.0	25.0
% wt. Oxygen	34.8	0	50.0	34.8	0

At the VIIIth International Symposium on Alcohol Fuels, 1988, dimethyl ether was presented as a new approach to a dual-fuel system; "Aspirated ether Ignition System for Methanol Fueled Diesel Engines" (Galvin, 1988). Engine dynamometer tests were carried out on a 1.2 liters two cylinder air cooled direct injection diesel engine fueled with methanol. Some modifications of the test engine were necessary in order to convert it to be operated on methanol. Among other modifications a catalytic methanol-to ether (DME) reactor was connected to a gas mixer located in the inlet duct. With this system it was possible to "manufacture" DME and introduce it in the inlet air.

The conclusion of the engine testing was that DME can be used as a pilot fuel for injected methanol in an unmodified direct injection diesel engine. According to the author (Galvin, 1988) an aspirated DME ignition system offers a considerable potential as a relatively simple methanol conversion system for both new and existing diesel engines.

The use of DME as an ignition promoter when using methanol as the main fuel has also been studied at the University of the Witwatersrand in South Africa (Cipolat et al., 1991). Actually, according to the references in their report, the first investigations of DME as an ignition promoter for alcohol fueled compression ignition engine was carried out at this university as early as 1984. Cipolat and his colleagues (Cipolat et al., 1991) used a direct injection two cylinder, water cooled, four stroke engine (Petter model PH2W) for their studies. One of the cylinders of the engine was fitted with a piezoelectric transducer in order to measure the pressure in the combustion chamber and a similar transducer was used to record the variation of pressure in the fuel supply line - a method used to locate the point when fuel was injected into the combustion chamber.

The quantity of DME aspirated of the engine was 25 - 50 % of the total combustibles with the lower limit corresponding to the point where the engine started to misfire and the upper limit to that of knock. In the summary of the investigation it is concluded that DME releases energy in two stages both of which are completed before top dead center (TDC) and that this leads to increasing negative work with increasing DME rate of total combustibles. The suggestion is that DME is completely burnt before the ignition of methanol. The result of this combustion phenomena was a reduction of the thermal efficiency with increasing DME rate of the fuel supply.

Two methods, an aspiration method and a torch ignition method, for the introduction of DME in to the combustion chamber of a compression ignition engine were investigated by using a four stroke single cylinder, natural aspiration, direct injection methanol fueled engine (Murayama, 1992). The intention was to study the possibility of using DME as an ignition improver.

By the aspiration method DME was introduced into the intake manifold, a rather simple method of using DME. The drawback of this method was that it lead to unfavorable emission characteristics and that it required large amounts of DME for ignition of the methanol. Thermal efficiency changes with the rate of DME of the total fuel supply, and the optimum was found for each load. Concerning the emission it was found that the DME aspiration method emits large amounts of unburnt fuel and formaldehyde, especially at low loads. Also, the emission of CO was on a high level.

In order to overcome the problems which were experienced with the DME aspiration method a torch injection (TIC method) was developed. With the TIC method DME was introduced into a TIC chamber during the intake stroke. By using this method it was expected that the TIC chamber should limit the diffusion of DME during the compression stroke, resulting in a reduction of the emission of unburnt fuel and requiring a lower DME rate of the fuel.

In the concluding remarks it is pointed out that there was a significant improvement in the minimum DME rate and the emission of CO and HC with the TIC method compared with the aspiration method. The experience was also that "it was difficult to operate the engine with DME-dissolved methanol fuel even when the DME fraction was 40 % in heating value, at which the engine operation was sufficient with the aspiration method".

Ignition assistance can also be obtained by means of a "chemical spark". The dynamics of the methanol ignition process was investigated in a methanol diesel engine, where it requires, amongst other things, a longer vaporization time than diesel, the ignition delays causing difficulties at high engine speed operation. Research carried by Industrial Research Ltd in New Zealand (Gong and Waring, 1993) has investigated the relationship between the injection process and the ignition timing and its effect on engine performance. They improved the ignition of the methanol by decreasing the injection pressure and pre-heating the inlet air to compensate for this, thus advancing the fuel ignition and making possible stable operation at high speeds. They also investigated the effects of excessive pilot fuel rates and found that the pilot fuel should be aspirated within the range of 20 - 40% to avoid methanol ignition inhibition. Smooth and stable operation over the whole speed range has been achieved, but more investigations are planned for achieving optimum timing, on high power output and on low emissions.

The interest in using neat DME as a fuel for compression ignition engines seems to have started at the beginning of the 1990's. The first tests of the use of DME in compression ignition engines and the study of the possibility of a large scale production of this fuel was published by Amoco Corporation, Haldor Topsøe A/S, Navistar and AVL at a conference as was also data and experiences from the use of DME in engines (Fleisch and Meurer, 1995; Hansen et al., 1995; Kapus and Ofner, 1995; Sorensen and Mikkelsen, 1995).

The idea of using DME as an automotive fuel was arrived at more or less by chance. One of the technicians at the Haldor Topsøe laboratory, as an matter of curiosity, used DME in a lawn mower and to his surprise he found that it worked. After that he tried it in a forklift and found that it worked without having the spark plugs connected (Science/Technology, 1995). This resulted in Topsøe collaborating with Amoco, an American diesel-engine manufacturer called Navistar and a diesel-engine research institute in Austria called AVL for further research in which DME is honored as being "still green after it has been burnt", exhaust from a DME-driven diesel engine containing no sulfur, almost no soot and only about 20% of nitrogen oxides compared to that produced by diesel which, with the dramatic reduction in hydrocarbons in the exhaust (only CO_2 remaining at the level for diesel) means that DME could meet the Californian emission limits planned for 1998.

DME can be produced by fixed bed catalytic dehydration of methanol and is a colorless gas with a high cetane number, which makes it to a proper fuel for compression ignition engines. The fuel can also be produced by combining the methanol and DME synthesis by integration of the two process steps into one single process for conversion of synthesis gas direct to DME. By using this combined process the production costs can be reduced (Hansen et al., 1995). So far DME has been used as an aerosol propellant due to the fact that it is not harmful to the ozone layer as are CFC gases.

According to Topsøe (Hansen et al., 1995) the combined process permits the methanol, water gas shift and DME reactions to take place simultaneously which is advantageous in terms of production costs. Synthesis of DME from syngas involves three reactions:

Table 15: Combined methanol and DME synthesis

$CO_2 + 3\,H_2 \rightarrow CH_3OH + H_2O$ (50.1)* (1)

$H_2O + CO \rightarrow H_2 + CO_2$ 40.9)* (2)

$2\,CH_3OH \rightarrow CH_3OCH_3 + H_2O$ (23.4)* (3)

*Heat of reactions in KJ/mol.

A methanol synthesis is achieved by the first two reactions, but as the equilibrium does not favor methanol formation, the methanol synthesis requires high synthesis pressure (80-120 bar), the third reaction relieves the thermodynamic restrains by forming methanol into DME.

The Haldor Topsøe combined process for the production of DME is illustrated by the following Figure, Figure 15.

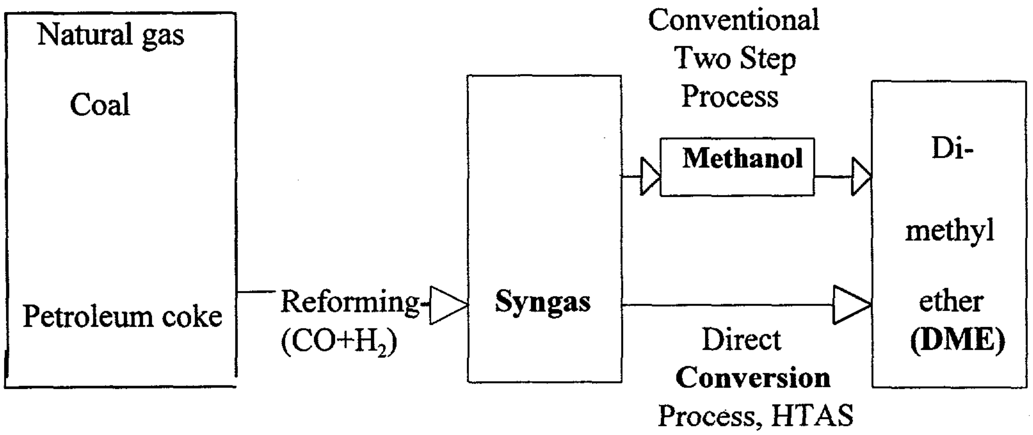


Figure 15. DME Manufacturing process

The DME production process consists of the following main steps (Hansen et al., 1995):

- Desulfurization
- Pre-reforming (optional) Auto-thermal Reforming
- CO_2 Removal
- Combined methanol and DME synthesis
- Final Purification Unit

Desulfurization: In order to not poison the reforming catalyst, sulfur in the gas is removed.

Pre-reforming: If the gas contains a large amount of higher hydrocarbons it is advantageous to convert these in an adiabatic pre-reformer at low temperature before the gas enters the Auto-thermal Reformer (ATR)

ATR: The auto-thermal reformer is compact and consists of a refractory lined pressure vessel with a burner, a combustion chamber and a catalyst bed.

Combustion zone. Step 1: $2CH_4 + 3\ O_2 \Rightarrow 2CO + 4\ H_2O$

Thermal and catalytic zones.
Step 2: $CH_4 + H_2O \Rightarrow 3\ H_2 + CO$
Step 3: $CO + H_2O \Rightarrow CO_2 + H_2$

The added amount of steam and oxygen and exit temperature and pressure define the reformed gas composition. For the production of DME the ratio of $(H_2\text{-}CO_2)/(CO+CO_2)$, should be close to 2, as this ratio will ensure the maximum conversion to DME and methanol.

CO_2 Removal: CO_2 must be removed to a certain level (lower $CO_2 \Rightarrow$ higher ratio) in order to adjust the ratio.

Combined methanol and DME synthesis: The combined synthesis takes place over the multiple function methanol/DME catalyst in a loop including three adiabatic reactors with inter-stage cooling in order to achieve a high conversion of CO and CO_2.

The loop: The gas is mixed with recycled gas and preheated in a feed/effluent exchanger before it is led to the first reactor. The following overall exothermic reaction take place:

$$3\ H_2 + CO_2 \Rightarrow CH_3OH + H_2O$$

$$H_2O + CO \Rightarrow H_2 + CO_2$$

$$2\ CH_3OH \Rightarrow CH_3OCH_3 + H_2O$$

Final Purification Unit: The lay-out for this unit depends on the demands regarding the purity of the gas. The main processes are the separations by distillation of DME, methanol and water.

DME has been called a perfect fuel for compression ignition engines in the case of commercial applications in urban operation where ultra-low emissions will be "a must" in the future. (Fleisch and Meurer, 1995). This was the conclusion arrived at in answer to the question if DME will be important the 21^{st} century. The answer was based on the facts that DME has the most efficient combustion process giving smokeless, quiet and ultra-clean diesel engines, and that DME can be handled easily and safely. The authors do, however, stress the need for new types of low pressure (300 bar) fuel injection systems.

Fleisch and Maurer have also been studying the production of DME in order to estimate the cost of the fuel on the market. According to the authors the most important contribution to the lower cost comes from the possibility of producing DME at "Megaplants" which are four times larger than the plants used today for production of methanol. The capacity should be 4900 tons diesel equivalent DME per day.

From a new plant in Venezuela with a production capacity of 42000 barrels (about 6600 m^3) per day the cost of DME will be on about the same level as diesel fuel when shipped to the Gulf Coast. As distribution of DME requires a new infrastructure such as pipelines, trucks and pumps the end use cost before taxes is estimated to be about 35 % higher than diesel fuel.

DME has been successfully tested as an alternative fuel for a small (0.273 liters), non-turbocharged, direct injection diesel engine with only minor fuel system modifications, (Sorenson and Mikkelsen, 1995). When comparing pure DME with commercial diesel fuel they found;

- NO_X emissions reduced by ca 75%;
- Near-zero smoke in the exhaust;
- Lower engine noise;
- Equivalent thermal efficiency;
- Equivalent CO and HC emissions.

In a comparison between pure DME and a simulated technical grade DME containing water and methanol they gave equivalent thermal efficiency and NO_X emission but increased HC and CO at light load, with no negative effect on smoke. Since it was a small engine that was used for the investigation and since the emission measurements were only carried out some steady state modes, it is not, therefore, possible to refer the results to any standard test procedure.

With 30% EGR, a 90% reduction in NO_X was obtained with no loss in thermal efficiency and no visible smoke but with a 7% increase in CO emissions. The following results were achieved when testing the DME fueled engine at steady state operation

Satisfactory initial operation was obtained without modification to the standard diesel injection pump. After 500 hours operation, with no lubricating additive in the DME, there was some deterioration in emissions. At 590 hours the conventional pump failed so the addition of a lubricating agent is obviously needed to reduce wear in the pump.

DME has been found promising as a new alternative fuel for compression ignition engines. (Fleisch et al., 1995) judging from test results which indicate that all current and proposed world wide emission standards can be achieved with DME, without the need for major engine design changes. DME blends give emission levels which will meet and surpass the Californian Ultra Low Emission Vehicle (ULEV) regulations for medium duty vehicles (commercial trucks and buses and even passenger cars). Even older, high emitting engines can be "cleaned up" on a cost effective basis. The production of DME by the Haldor Topsøe process can give a clean fuel for low emission vehicles if, however, government policies and market dynamics permit. It is stated further that the conversion of natural gas into DME and its use as a diesel fuel is a major advancement in gas conversion technologies, DME being the lowest cost chemical conversion alternative and a very attractive fuel.

The following results were obtained when the DME fueled engine was tested according to a simulated transient cycle (the AVL 8-Mode Transient Cycle Simulation):

	g/bhp-hr	g/kWh
NMHC (non-methane hydrocarbons)	0.21	0.29
CO (carbon monoxide)	3.2	4.4
NO_X+NMHC (oxide of nitrogen + NMHC)	2.4	3.3
PM (particulate matter)	0.033	0.045
HCHO (formaldehyde)	0.022	0.030

The engine was also tested according to ECE R49 with a NO_X emission of 3.85 g/kWh.

In a study carried out to establish fuel injection equipment (FIE) and combustion system parameters that generate a basis for future optimization of engines operated on new alternative fuels such as DME, (Kapus and Ofner, 1995), new simulation techniques and identification methods were used to analyze fuel properties and their effects on FIE and engine behavior and to clarify the behavior of DME in a DI engine. A low NO_X emission level was achieved by the use of single hole pintle nozzles for fuel injection. It was also seen that the use of EGR could further reduce the NO_X emissions. No tests were carried out according to a standard test procedure.

After discussion about FIE parameter optimization through simulation techniques and the determination of so far unknown fuel data and flow phenomena, some important conclusions were drawn from this study, such as that with the new alternative fuel it is possible to achieve the quiet and smokeless diesel engine that can meet future emission legislation without exhaust gas after-treatment. The NA engine could well survive the turn of the century when fueled with this fuel. NO_X levels of below 2 g/kWh were achieved with an NA engine. For a turbo-charged engine 1.34 g/kWh seems to be possible. When using DME it will be necessary to match the fuel system and the combustion system, but due to the fuel properties of DME a low pressure, low cost fuel system can be developed in conjunction with a manufacturer specificity for the use of DME.

The potential of a DI/TCI DME engine (direct injection turbo charged diesel engine with intercooler) to meet ULEV emission levels when installed in passenger cars was studied in Austria, (Kapus and Cartellieri, 1995). The impact of changes in the combustion chamber and of the fuel injection system - injection nozzles etc. on fuel consumption and emissions, especially NO_X and noise, was studied. The displacement of the engine was 2.04 liters.

Very promising results have been reported with respect to meeting ULEV NO_X emissions without any soot emissions and without the need for a DENOX catalyst, and with fuel consumption very close to DI diesel values. An oxidation catalyst will however be necessary to meet the stringent CO and HC ULV emission limits however, see Table 16. The vehicle tested was a 2 liter, 4 cylinder, i.e. full size passenger car and the tests included variation of a number of parameters, such as rate of injection, number of nozzle holes, compression ratio, piston bowl shape and exhaust gas recirculation. Combustion tailoring for NO_X control can be achieved by means of injection rate shaping and decreasing the ignition delay period. This results in decreased combustion noise, the noise level coming very close to what is possible in present day gasoline engines. The NO_X - fuel consumption - noise tradeoff depends manly on the FIE and its rate shaping capabilities. Special fuel injection equipment will need to be developed to match engine and vehicle requirements, leakage problems and safety issues.

The engine was tested according to a simulated FTP 75 cycle (based on steady state test results) and the results of the projected emissions are presented in Table 16.

Table 16: Comparison of a DME fuel engine and a diesel engine in a FTP 75 cycle simulation.

Emission-Fuel cons.	DME In line Pump	Diesel fuel Unit Injector	ULEV Limits
NO_X g/mi (g/km)	0.2 (0.124)	0.7 (0.435)	0.2 (0.124)
Soot -"- -"-	0	0.024 (0.015)	0.04 (0.025)
HC -"- -"-	0.4 (0.25)	0.35 (0.22)	0.04 (0.025)
HC -"- -"-	0.04 (.025)	0.07 (0.044)	
CO -"- -"-	6.0 (3.73)	1.58 (0.98)	1.7
CO -"- -"-	0.6 (0.37)	0.30 (0.19)	
Fc mpg (l/100 km)	34.7 (6.77)	36.0 (6.53)	--

At the Contractors Review Conference held by DOE in Pittsburgh, 1995 there was a presentation entitled "DME - A High Performance Transportation Fuel?" (Applied Catalysis, 1995) the answer was positive with the two biggest hurdles being (I) the quantities currently available are far too small and (II) there is a need to develop an infrastructure similar to that which is currently utilized for liquid propane (LPG). A report from the Conference states Fleisch as seeing DME entering the market in three phases. In phase 1, methanol would be converted to DME by dehydration and would be fitted into existing niches (e.g. California, Germany) before the year 2000. Between the years 2000 and 2005 he expects DME production to be piggybacked into existing plants such as unused ammonia plants. Greenfield plants would be introduced beginning about 2005. Fleisch sees DME as ***a***, not ***the***, fuel of the 21st century, it is reported.

Making diesels smokeless and quiet could involve using DME which has been kept in the liquid state at a pressure of abut 5 bar; the pressure having to be 15 - 30 bar at engine operating temperatures, says AVL List, (Kunberger, 1995). DMS's high cetane number (above 55) results in good self-ignition characteristics and cold-starting behavior, while its high oxygen content - comparable to alcohols - is responsible for the smoke-free combustion. Because the energy density of DME is about 60% that of diesel fuel, a storage system similar to that used with LPG is required. In concentrations above 3.4% by volume, said AVL List, an explosive mixture is formed.

Science/Technology (Rouhi, 1995) carries a report of the desirable features of DME as being
- Ultralow emissions
- Smokeless operation

- No exhaust aftertreatment
- Quiet combustion
- Diesel thermal efficiency
- Low-pressure, low-noise, low-cost fuel injection
- Naturally aspirated or turbocharged

Sorenson is quoted as saying that with conventional diesel fuel there is a trade off between NO_X emission and soot. "That trade-off is eliminated with DME" he says.

Concerning the cost of DME both Amoco and Haldor Topsøe are quoted and both of them estimate that DME will be more expensive than conventional diesel fuel. Amoco (Fleisch) believes that consumers can accept a higher price because DME gives a higher fuel efficiency, lower maintenance and overall better performance of the engine.

It is said that there is a significant interest in DME among the Big Three automakers, US Department of Energy and California government agencies and also in the DME engine technology circles.

The problem with the introduction of DME seems to be that plants are needed for large production quantities of the fuel and the vehicle owners must be convinced to use DME. The hope is that the latter problem may be overcome by convincing the public that DME is customer friendly in that it combines the high fuel efficiency of the diesel engine with ultra low tailpipe emissions.

10. Discussion and Conclusion - Methanol or Ethanol?

While technological improvements in petroleum-powered vehicles are essential to achieving short-term increases in the vehicle fleet's fuel efficiency, they will not be sufficient for the long haul if the global vehicle fleet continues growing. For this reason, longer-term international efforts to develop new transportation energy sources that emit no fossil carbon dioxide will have to be intensified as emissions are reduced. A program of research, development, demonstration, and, ultimately, the introduction of such vehicles should become a matter of high public priority for all the principal vehicle-producing nations. It appears increasingly likely that biomass based fuels will play an increasingly important role in solving transportation related environmental problems in the future.

Both methanol and ethanol have been tested as automotive fuels in laboratories and in the field in many countries. Most of the experience of the use of methanol in motor vehicles has been acquired in the USA and Japan, while ethanol has been used on a large scale in light duty vehicles in Brazil and in heavy duty vehicles in Sweden.

Alcohols can be used in automobiles in different ways which has been described earlier in this report. Since both methanol and ethanol have high octane ratings they are most suitable for use in spark ignition (Otto) engines and the usual ways they are used in these engines are as:-

- low blending of alcohols in gasoline
- M85-M95 or E85-E95 (85% alcohol and 15% gasoline or some other hydrocarbons)
- M100 or E100 (which have been tested on a small scale)

- a component for the production of an ether such as MTBE or ETBE

Despite the fact that methanol and ethanol have low cetane numbers, they are used in *compression ignition* (diesel) engines as neat fuels (90-95% alcohol). Tests have been carried out in order to study the possibility of using a blend (15%) of methanol and ethanol in diesel oil (Bechtold, 1986) which has been described earlier in this report. A blend of ethanol is in the process of being tested in Sweden.

Both methanol and ethanol can be used as sources for fuel cells and in that case there will be no harmful emissions. When comparing the use of the two alcohols methanol and ethanol, it is obvious that there are some important differences in that:

- methanol is more corrosive and aggressive than ethanol to metals and other materials in the fuel system and the engine. According to representatives from two manufacturers of engines and vehicles, Detroit Diesel and Ford, and one owner of methanol fueled buses, the Metropolitan Bus Authority (MBA) in Los Angeles, there have been problems not only with the piping in the fuel system of the vehicles but also with alloys in the engines. Therefore ethanol is preferred as these problems have not occurred since methanol was replaced by ethanol. All buses authorized by MBA are now converted to be fueled with ethanol

  On the other hand the problem with the material in the fuel system and the engine when using methanol would certainly be solved if there was a strong incentive among the engine and/or vehicle manufacturer to do so. A such incentive could be that the bus and truck owners should pronounce a stronger demand to purchase methanol fueled vehicles;

- methanol and mixtures of methanol must be handled with more care than ethanol when servicing and maintaining the vehicles due to its toxicity. The Urban Mass Transport Administration (UMTA) in the USA has therefore prepared a special manual, "A Training Manual for Methanol Fuel Use In Transit Operations", in which it is stated, amongst other things, that gloves "should be worn when working with liquid methanol in order to avoid skin contact";

- methanol has a lower energy content than ethanol and therefore a larger fuel tank volume has to be used in order to have the same driving range as when using ethanol;

- according to a vehicle operator survey carried out by the National Renewable Energy Laboratory (NREL), USA there is a preference for the use of ethanol when summing up the responses from both the fleet managers and the drivers of vehicles using alternative fuels (NREL, 1996);

- in the case of an accident during the transportation of the fuel and there is a spill of fuel the damage will be much more serious if the spill is methanol than if the spill is ethanol especially if the fuel reaches the ground water, because of the poisonous character of methanol;

- if one of the two alcohols is going to be used as a blending component in diesel oil the opinion is that ethanol will be a better choice because it is less aggressive to the materials in the fuel system and other parts of the engine. The idea with the mixed fuel, i.e. alcohol in diesel oil, is that the fuel should be used without any special adaptation of the engine;

- if there will be a tax reduction for biofuels it may be difficult and costly to distinguish between the part of the fuel which is made from a fossil source (natural gas) and the part which is made from biomass in he case methanol.

Concerning the comparison of emissions from methanol fueled vehicles contra ethanol fueled vehicles, there is no large difference. The only comments in this report are that;

- methanol fueled vehicles emits more formaldehyde than ethanol fueled vehicles. On the other hand ethanol fueled vehicles emits more acetaldehyde. Formaldehyde is regarded as more harmful to man than acetaldehyde.

In an international perspective the use of methanol has been preferred among vehicle owners. The reason for this is regarded to be the cost of the fuel. Both in the US and in Japan, where methanol is used, methanol is manufactured from natural gas, which makes the current cost of methanol much lower than the cost of ethanol.

When considering whether methanol or ethanol is preferred as a fuel for automotive use, the situation in the actual country should be taken into account.

The situation in Sweden is that;

- the alternative fuels and at least methanol and ethanol, if used, should be manufactured from renewable sources. The Swedish Government has a commitment that Sweden up to year 2000 shall reduce the emission of carbon dioxide (CO_2) to the level of 1990 which means that the use of fossil fuels must be limited and the use of biofuels must increase during the years ahead.

- if biomasses (mostly salix and logging residues) are to be used as sources for the manufacture of methanol or ethanol and other biofuels the potential of increasing the use of biomass in Sweden is such that fuels made from biomass up to year 2015 could replace all the automotive use of fossil fuels (Johansson, 1996). It is an open question whether all these biomasses can be collected and transported to the fuel production plant at reasonable efficiency and cost.

Within the program for biofuels (KFB, 1994) several studies have been carried out concerning the cost of methanol and ethanol when manufactured from cellulosic feedstocks and these studies have shown that ethanol cannot compete with methanol concerning the cost of the fuel (Östman, 1996; Ecotraffic, 1992; Ecotraffic, 1995; Ecotraffic, 1996). One advantage of methanol is that this fuel, manufactured from natural gas, will be available on the market at a reasonable price if there is a shortage of methanol manufactured from biomass. On the other hand it has been shown that the development of new methods of production of ethanol may reduce the production costs to a level comparable to the cost of methanol produced from biomass (von Sivers and Zacchi, 1996; Wimmersted, 1996). To quote Wimmerstedt concerning enzymic hydrolysis ”...a technical break-through for this technique has been achieved in the USA...”

Dr Wallander, a representative from the Swedish National Board for Industrial and Technical Development (NUTEK), has also pointed out that the costs for the production of both methanol and ethanol are strongly linked to the method used. He refers to a IEA report "Alternative Motor Fuels" which reports a study of four processes for production of ethanol and four processes for production of methanol, all of them based on biomasses. The conclusion of the study is that the costs for the production of ethanol is assumed to be 13 - 33 USD/GJ[12] and for methanol 13 - 29 USD/GJ[13]. However, neither ethanol or methanol will reach down to the level of the cost for production of methanol from natural gas.

In the perspective that one of the ideas in Sweden of using an alcohol as an automotive fuel is that the fuel must be manufactured from a renewable feedstock and that the price different between ethanol and methanol may even out, it seems to be logical for Sweden to keep using ethanol instead of methanol especially as there is an opinion among most of the people involved in the trial of an introduction of alternative fuels in Sweden and also the authorities that ethanol should be used instead of methanol. Today it is not possible to make a fair judgment about the cost of methanol and ethanol. Therefore it must be left to the future to decide which one of the two finally shall be chosen for the Swedish market i.e. economically or environmentally economically chosen.

In order to decrease the cost of the alcohol fuel for heavy duty vehicles the engines used in Sweden should be modified or redesigned for the use of some other fuel ignition aid than an ignition improver. Today the additional cost of adding an ignition improver to the fuel is about 1 SEK per liter. In other countries, USA, Japan etc., glow plugs or spark plugs are used, (USA, 1986; Japan, 1995).

Despite the problems associated with the deterioration of the glow plugs or spark plugs, it will be advantageous, from the point of view of costs, to use such ignition aids instead of an ignition improver in the fuel. According to the experiences in Japan the spark plugs will last for at least 20 000 km driving. Here it is assumed that the cost for the changing the spark plugs will be less than the additional cost of the fuel caused by the use of an ignition improver.

---

13 Approx. 90-200 SEK/GJ if $1 = 7 SEK. (1 GJ = 10^9 J. 1 litre ethanol = 21.1 MJ)

13 Approx. 90- 230 SEK/GJ. (1 litre methanol = 15.8 MJ)

1. REFERENCES

Applied Catalysis (1995). A Substitute for Diesel Fuel. Applied Catalysis A: General, Volume 132 No. 2.

Aronow, et. al., (1977) Effect of Carbon Monoxide On Exercise Performance In Chronic Obstructive pulmonary Disease, Am. J. Med., 1977.

ASPEN (1995). Report concerning Alkylate + ethanol. Report in Swedish under preparation

Auto/Oil Air Quality Improvement Research Program (1992) Emissions and Air Quality Modeling Results from Methanol/Gasoline Blends in Prototype Flexible/Variable Fuel Vehicles, Technical Bulletin No. 7.

Auto/Oil Air Quality Improvement Research Program (1992b) Emissions of Three Dedicated-Methanol Vehicles, Technical Bulletin No. 10.

Auto/Oil (1996). Air Quality Improvement Research Program. Dynamometer Study of Off-Cycle Exhaust Emissions. Technical Bulletin No. 19.

AQMD (1994). Rules and Regulations: Rule 1003 - Reduced-Emission Fleet Vehicles/Alterative Fuels. Sacramento Metropolitan AQMD, 1994.

Barenescu et al., (1988). Conversion of a Navistar DT-466 Diesel Engine to Methanol Operation. VIII International Symposium on Alcohol Fuels. New Energy and Industrial Technology Development Organization. Proceeding.

Bechtold, R.L. (1986). Status of Alcohol Fuels Utilization. Technology for Highway Transportation. A 1986 Perspective. Volume II - Compression Ignition Engines. ORNL/Sub/85-22007/3.

Bertilsson, B-I and Gustavsson, L. (1987). Experiences of Heavy-Duty Alcohol-Fuelled Diesel-Ignition Engines. SAE-paper871672.

Biniek, "Air Pollution Impacts On Agriculture And Forestry", Congressional Research Service, Library of Congress, May 1982

Björkman E. and Egebäck K-E. (1987). Etanol som drivmedel (Ethanol as an automotive fuel) Naturvårdrverket Rapport 3304 (The Swedish Environment Protection Board, Report 3304) in Swedish.

Brolin L., Hagelberg M. and Norström A. (1994) "Biogas as Automotive Fuel", (in Swedish), Report Vattenfall Energisystem, Stockholm.

Building markets for low-emission technologies (1995) s28

California Energy Commission (1986). Methanol-Fueled Transit Bus Demonstration. Phase 1 Technical Analysis. Acurex Project 6629, Contract No. 500-82-001.

Carroll, J.N., Ullman, T.L. and Winsor, R.E. (1990). Emission Comparison of DDC 6V-92TA on Alcohol Fuels. SAE paper 902234.

CDTECH (1993). Catalytic Distillation Technologies. Folder from CDTECH with a decription of the Technology for manufacturing oxygenates.

Chevron U.S.A. (1989). California Fuel Methanol Cost Study. Executive Summary, Volume 1.

Cipolat, D., Jaworek, H.H. and Rallis C.J. (1991). Methanol/Dimethyl Ether Fuelling of a Compression Ignition Engine. Proceeding, ISAF IX Nov. 12 - 15.

Clemmens, W.B. and Martin, C.M. (1990). Methanol Decomposition Through Rich Oxidation in a Self-Ignited Catalytic Reactor. SAE paper 900582, Warrendale.

Cui and Ji (1988). Investigation on Methanol-Fueled Engine with Glow Plug Initiated Combustion. VIII International Symposium on Alcohol Fuels. New Energy and Industrial Technology Development Orgnization. Proceeding.

Decker G., Heinrich H., Kröll M. and Loeck H. (1993) Field Experience and Progress of Volkswagen's Multi Fuel Vehicles. Tenth International Symposium on Alcohol Fuels, Vol. 1, 41-52.

Department of Energy, DOE (1991) Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity, DeLuchi, Center for Transportation Research, Argonne National Laboratory, for the US Department of Energy, November 1991.

Department of Energy, DOE (1995b). Next Steps: DOE Transition Study, Nov. 1995

Dockery, et. al., "An Association Between Air Pollution And Mortality In Six U.S. Cities", The New England Journal of Medicine, December 9, 1993.

Eberhard, G.A. Ansari, M. and Hoekman, S.K. (1990). Emissions and Fuel Economy Tests of a Methanol Bus with a 1988 DDC Engine. SAE paper 900342, Warrendale.

(EEC, 1985) EEC Council Directive according to Allion, 1991.

Ecotraffic (1992). Brandberg, Å., Ekelund, M., Johansson, A. and Roth, A. Life of Fuels. ISBN 91-88370-09-7.

Ecotraffic (1995). Brandberg, Å. Methanol som alternativt drivmedel (Methanol as an automotive fuel). Sammanställning för Alternativbränsleutredningen, ET/2096.

Ecotraffic (1996). Brandberg, Å. and Sävbark, B. Distribution av motoralkoholer (Distribution of automotive alcohols). Kommunikationsforskningsberedningen, Meddelande 1996:23.

Egebäck K-E. and Bertilsson B-M. (1983) Chemical and biological characterization of exhaust emissions from vehicles fueled with gasoline, alcohol, LPG, and diesel. National Swedish Protection Board, SNV Report 1635, Studsvik

Egebäck K-E., Tejle G. and Laveskog A. (1984) Investigation of Regulated and Unregulated Pollutants from different Fuel/Engine Concepts and Temperatures, (in Swedish) National Swedish Protection Board, SNV Report 1812, Studsvik.

Egebäck K-E. and Westerholm R. (1988) Regulated and Unregulated Pollutants from Vehicles Fueled with Alcohols. Proceedings. VIII International Symposium on Alcohol Fuels. Tokyo, Japan, 1988.

Egebäck K-E. (1994) Inblandning av alkohol i bensin (Mixtures of alcohol in gasoline). Litteraturstudie. KFB-report 1994:23. ISBN 91-883370. ISSN 0282-8014, 1994.

Egebäck, K-E. and Pettersson, E. 1996). Research on a Scania 11 liter Ethanol Fueled Bus Engine. TULEA 1996:13 ISSN 0347 - 0081.

Fahlander S. and Walde N. (1981) Ethanol fuels with ignition improver for turbocharged diesel engines. Proceedings 4:th International Alcohol Fuel Technology Symposium, Brazil.

Ferris, (1978) Health Effects of Exposure To Low Levels of Regulated Air Pollutants, A Critical Review", Journal of The Air Pollution Control Association, May 1978.

Elam N., Ekström C., Östman A. and Rensfelt E. (1994) Project Bioenergy (in Swedish), Report from Vattenfall Utveckling AB. 1994/1, Stockholm

Fleisch T., McCarty C., Basu A., Udovich C., Charbonneau P., Slodowske W. Mikkelsen S-E. and McCandless J. (1995). A New Clean Diesel Technology: Demonstration of ULEV Emissions on a Navistar Diesel Engine Fueled with Dimethyl Ether. SAE paper 950061, Warrendale.

Fleisch T. and Meurer, P. (1995). DME The Diesel Fuel for the 21th Century? Presented at AVL Conference Engine and Environment 1995.

Ford (1995). Personal communication with representative for Ford.

Fuel (1991). Oil, Auto and Government join ranks for cleaner fuel. What will 2000 bring. FuelReformation voll No. 1, September/October 1991.

Furey R. (1985). Volatility Characteristics of Gasoline-Alcohol and Gasoline-Fuel Blends, SAE paper 852116, Warrendale.

Gabele P. and Black F. (1993) Emissions and Fuel Economy of Federal Alternatively Fueled Fleet Vehicles, Tenth International Symposium on Alcohol Fuels, Vol. 1, 63-72.

Galvin M. (1988). Aspirated Ether Ignition System for Methanol Fuelled Diesel Engines. VIII International Symposium on Alternative Fuels, 1988, pages 601-612.

Goldemberg and Macedo, (1994) Brazilian alcohol program: an overview, Energy for Sustainable Development, May 1994.

Gong R. and Waring P. (1993). Improvement of Ether "Chemical Spark" Ignition in Methanol Diesel Engine. Tenth International Symposium on Alcohol Fuels. The Road to Commercialization. Proceedings: Volume II, 1993.

Grägg K. and Egebäck K-E. (1989). Karakterisering av avgaser fron etanoldriven buss resp. lastbil (Characterization of exhausts from a bus and a truck fueled with ethanol). PM for the Swedish Environmental Protection Board.

Gustavson E. (1994) Alternative automotive fuels: Access and costs, (in Swedish) VTI meddelande No. 752, Swedish Road and Transport Institute, Linköping

Hansen J., Voss B., Joensen F. and Sigurðardottir I. (1995). Large Scale manufacture of Dimethyl Ether - a New Alternative Diesel Fuel from Natural Gas. SAE paper 950063, Warrendale.

Havenith C. (1988). Experience with the Deutz Glow Plug Assisted Methanol Engine for Transit Bus Operation. VIII International Symposium on Alcohol Fuels. New Energy and Industial Technology Development Organization, Japan, 1988.

Hikino K. and Suzuki T. (1988). Improvement of Heavy Duty Spark-Assisted Methanol Engine for City Bus. VIII International Symposium on Alcohol Fuels. New Energy and Industrial Technology Development Organization, Japan, 1988.

Hira, A.U. et al., (1988). A State-of-Knowledge Review of the Emissions Effects of Methanol Vehicles.
VIII International Symposium on Alcohol Fuels. New Energy and Industial Technology Development Organization, Japan, 1988.

Höchsmann, G. and Gruden, D., (1988). VIII International Symposium on Alcohol Fuels. New Energy and Industrial Technology Development Organization, Japan, 1988.

Ishizuki, Y., (1988). Development of Komatsu Small Bore Methanol Engine. VIII International Symposium on Alcohol Fuels. New Energy and Industrial Technology Development Organization, Japan, 1988.

Inernational Energy Agency, IEA (1986). Alcohols and alcohol blends as motor fuels. "Sate-of-the-Art" report. Vol II A, Chapters 1-7 and Vol II B, Chapters 8-14. Prepared by The Swedish Motor Fuel Technology Co. (SDAB). STU Information no 580-1986. ISBN 91-7850-213-6. ISSN 0347-8645.

Jackson M., Unnasch S., Sullivan C. and Renner R. (1985). Transient Bus Operation with Methanol Fuel. SAE paper 850216, Warrendale.

Jaye, J., Miller, S. and Bennethum, J., (1988). Development of the Detroit Diesel Corporaation Methanol Engine. VIII International Symposium on Alcohol Fuels. New Energy and Industrial Technology Development Organization, Japan, 1988.

Johansson, B. (1996). Biomass-based energy carriers in the transportation. (In Swedish). KFB-Report 1995:11. ISBN 91-88370-94-1.

Johns, R.A., Henham, A.W.E. and Newhamn, S., (1988). Optimization of Ignition and Injection Timings in a Spark-Assisted Alcohol Fuelled Diesel. VIII International Symposium on Alcohol Fuels. New Energy and Industrial Technology Development Organization, Japan, 1988.

Kapus P. and Ofner H. (1995). Development of Fuel Injection Equipment and Combustion System for DI Diesels Operated on Dimethyl Ether. SAE paper 950062, Warrendale.

Kapus P. and Cartellieri W. (1995). ULEV Potential of a DI/TCI Diesel passenger Car Engine Operated on Dimethyl Ether. SAE paper 952754, Warrendale.

Karbowski G. and Pellagrin V. (1991) Methanol Transit Bus: Research and Development to Operational Reality.SAE paper 911632, Warrendale.

Karbowski G. and Davies R. (1995) The Los Angeles County Metropolitan Transportation Authority, Los Angeles. Personal communication.

Karpuk, M.E., Cowley, S.W. and Ratcliff, M.., (1988). Design and Testing of a Dissociated Methanol Vehicle. VIII International Symposium on Alcohol Fuels. New Energy and Industial Technology Development Organization, Japan, 1988.

Kapus, P. and Cartelleri, W. (1995). ULEW Potentialof a DI/TCI Diesel Passenger Car Engine Operated on Dimethyl Ether. SAE paper 972754.

Kapus, P. And Ofner, H. (1995). Development of Fuel Injection Equipment and Combustion System for DI Diesels Operated on Dimethyl Ether. SAE paper 9950062.

Kasamatsu, I. (1996). Report of the 2nd Fleet Test of Methanol Fueled Vehicles. Organization for the Commercialization of Low-Emission Vehicles; Tokyo, Japan.

Kasamatsu, I. (1996). Personal communication.

Kato, S. and Onishi, S., (1988). Stratified Charge Methanol Engine by Impingement of Fuel Jet (OSAKA). VIII International Symposium on Alcohol Fuels. New Energy and Industrial Technology Development Organization, Japan, 1988.

Katohno, R., Matsaue, J. and Terada, F., (1988). VIII International Symposium on Alcohol Fuels. New Energy and Industrial Technology Development Organization, Japan, 1988.

Kawaguchi A., Sato Y., Yanagihara X. and Ishiguro T. (1992). A Study of Soot Formation Processes in a Dual Fueled Compression Ignition Engine. SAE paper 922304, Warrendale.

KFB (1994)

KFB (1996). Several reports about a mixture between ethanol (15 %) and dieseloil (85 %) presented or under prepatation to be presented before the end of June 1997 (all in Swedish): Berg , R., 93-126-742. "Blandbränsle: Diesel - emulgator - etanol. Etapp 1; Aspen Petroleum, Meddelande 1996:18. "Diesohol - Blandbränsle diesel/etanol". Lägesrapport 1996-08-22. (This two reports are presented);Lunds University of Technology (Marforio, K.). Presentation of an investigation on an engine fuelled with a mixture between ethanol and diesel oil; Luleå University of Technology (Haupt, D.). Presentation of an investigation on engines fuelled with dieseloil, ethanol and a mixture between ethanol and dieseloil; Stockholms University (Westerholm, R.). Presentation of a characterisation of unregulated emissions (especiallly PAC) in the exhaust from the engine used in the engine used at Luleå University of Technology - a coporative investigation. (Reports from these three investigations are under preparation).

Konberger, K. (1995). DME can make diesels smokeless and quiet. High Speed Diesels & Drives. Alternative Fuels

Kroeger, C. (1986) A Neat Methanol Direct Injection Combustion System for Heavy Duty Applications. SAE paper 861169, Warrendale.

Laveskog, A. (1990). Emission at regulated and non regulated test cycles. Report: MTC, Rev. 1 Motortestcenter, Sweden. (In English).

Laveskog. A (1995). Emissions of unregulated compounds from five different gasoline qualities. A report for The Swedish Environmental Protection Agency, Aspen Petroleum and OK Petroleum AB.

Liang P. and Winsor R. (1990). Ignition Enhancement of the DDC Methanol Engine - Results.

Lipari F. and Keski-Hynnila D. (1986). Aldehyde and Unburned Fuel Emissions from Methanol-Fueled Heavy Duty Diesel Engines. SAE paper 860307, Warrendale.

Lewis R. (1995) American Methanol Institute, Washington, Personal communication.

Marietta M. (1994). Comparison of Relative Environmental Impacts of Alternative and Conventional Motor Fuels. Draft Final Report Annex VII. IEA International Energy Agency.

Mauderly J. et al., (1994) Pulmonary Toxicity of Inhaled Diesel Exhaust and Carbon Black in Chronically Exposed Rats, Health Effects Institute Research Report Number 68, October 1994.

Mitchell W., Litzinger T. and Lee W. (1992). Effects of In-Cylinder Catalysts on Combustion and Emissions of a D.I. Diesel Engine Fueled on Neat Methanol. SAE paper 920688, Warrendale.

Modetz H.., McCormack M. and Ward P. (1993) Maintaining Fuel Quality: California's Methanol Experience. Tenth International Symposium on Alcohol Fuels. The Road to Commercialization. Proceedings: Volume I, 1993.

Moore, (1980) Exposure to Lead In Childhood: The Persisting Effects, Moore, Nature Vol. 283, 24 January 1980

Mostardi, et al, The University Of Akron Study on Air Pollution and Human Health Effects, Archives of Environmental Health, September/October 1981.

Murayama, T., Miyamoto, N., Chikahisa, T and Ogawa, H., (1988). Potential and Problem in Alcohol Fuel Combustion Techniques in Diesel Engines. VIII International Symposium on Alcohol Fuels. New Energy and Industrial Technology Development Organization, Japan, 1988.

Murayama T., Chikahisa T., Guo J. and Miyano M. (1992). A Study of a Compression Ignition Methanol Engine with Converted Dimethyl Ether as an Ignition Improver. SAE paper 922212, Warrendale.

MTA (1995). Personal kommunikation.

Nagakura, K. and Fukudome, J., (1988). A Study on Ethanol Stratified Charge Combustion Engine. VIII International Symposium on Alcohol Fuels. New Energy and Industrial Technology Development Organization, Japan, 1988.

Needleman, et al., (1979) Deficits In Psychological And Classroom Performance Of Children With Elevated Dentine Lead Levels, The New England Journal Of Medicine, Vol. 300, Number 13, March 29, 1979.

Needleman, (1980) Lead Exposure And Human Health: Recent Data On An Ancient Problem, Needleman, Technology Review, March/April 1980

Needleman (1980). Lead Exposure and Human Health: Recent Data on an Ancient Problem. Needleman, Technology Review, March/April 1980.

Nishida, A. (1990). The Present State of the Methanol Diesel Engine for Two-Ton Trucks. National Symposium on Methanol-Fueled Vehicles, Proceedings, 1990.

NREL, 1996). Light-Duty Vehicle Operator Survey: Summary of January 1996 Data Collection Period.

Nylund, N-O. and Eklund, T.H., (1988). Experiences from an Ethanol Fueled Otto-Cycle Engine. VIII International Symposium on Alcohol Fuels. New Energy and Industrial Technology Development Organization, Japan, 1988.

New York Times (1996) '95 the Hottest Year on Record As the Global Trend Keeps Up, The New York Times, January 4, 1996.

Olsson L., Ekman L., Rosén Å., Westerholm R., Almén Jacob and Rannug U. (1992) Chemical and Biological Characterization of Exhaust Emissions from Flexible Fuel Vehicles Equipped with a Heated Pre-Catalyst System. Society of Automotive Engineers, SAE Paper 920291, Warrendale.

Orehek, et al., "Effect of Short-Term, Low-Level Nitrogen Dioxide Exposure on Bronchial Sensitivity of Asthmatic Patients", The Journal of Clinical Investigations, Volume 57, February 1976.

Parry, R., Miller, S. and Walker, L. (1993). "Detroit Diesel Corporation Alcohol Engines and Field Experience". Tenth International Symposium on Alcohol Fuels. The Road to Commercialization. Proceedings: Volume I, 1993.

Parry R. (1995). Personal communications.

Pettersson L. and Sjöström, K., (1988) The Onboard Decomposed Methanol Engine - An Experimental Evaluation. VIII International Symposium on Alcohol Fuels. New Energy and Industrial Technology Development Organization, Japan, 1988.

Pettersson, L.J., Wahlberg, A.M. and Järås S.G. (1997) Evaluation and characterization of catalysts for alternative fuelled vehicles. A study of the influence of catalyst composition on activity and by-product formation. Royal Institute of Technology (KTH), Department of Chemical Engineering and Technology, Chemical Technology., Stockholm, Sweden.

Pocock S. et al., (1994) Environmental Lead and Children's Intelligence: A Systematic Review of the Epidemiological Evidence", BMJ 1994, November 5; 309: 1189-97.

Pope, C.A., Dockery, D.W. and Schwartz, J. (1995). Review of Epidemiologic Evidence of Health Effects of Particulate Air Pollution. Inhalation Toxicology 7 (1): 1-18.

Public Information Office (1995). Newest Fuel Cells Show Great Potential For Energy Industry. News Release from Jet Propulsion Laboratory, Pasadena, California.

Rannug U. (1983) Data from short term tests on motor vehicle exhausts. Environ. Health Perspec. Vol. 47, 161-169.

Rouhi A. (1995). Amoco, Haldor Topsoe Develop Dimethyl Ether as Alternative Diesel Fuel. C&EN Washington, 1995. Science/Technology, May 1995. C&EN.

Rydén and Egebäck (1997). Field test with 53 FFV (Flexible Fuel Vehicles); written in Swedish. Title: "Flottförsök med 53 FFV (Flexible Fuel Vehicles". Report for The Swedish Transport and Communications Research Board (under preparation).

Saito, T., Takemura, N., Daiso, Y. And Yoshida, Y., (1988). Improvement of efficiency and Emissions at Light Load in a Spark-Assisted Methanol Engine. VIII International Symposium on Alcohol Fuels. New Energy and Industrial Technology Development Organization, Japan, 1988.

The Economist/Science/Technology March (1995). Fuel. The lawnmower's tale.

Science (1995) Its Official: First Glimmer of Greenhouse Warming Seen, Science, 8 December 1995.

SCRTD (1992). Alternative Fuel Section Status Report, July - September, 1992. Southern California Rapid Transit District, Equipment Maintenance Department, 1992.

Schwartz, (1991) Air Pollution and Daily Mortality in Philadelphia, presented at the 1991 meeting of the American Lung Association, Anaheim, CA, May 1991.

Seko, T., Hori, M., Kim, E., and Niwa, K., (1988). Comparison of Various Methanol Combustion Systems For Heavy-duty Application. VIII International Symposium on Alcohol Fuels. New Energy and Industrial Technology Development Organization, Japan, 1988.

Seko, T., Tsuchiya, K. and Kim, E. (1993). Performances and Exhaust Emissions of Methanol City Bus Engines in MITI/PEC/JARI's Fleet Test. Tenth International Symposium on Alcohol Fuels. The Road to Commercialization. Proceedings: Volume I, 1993.

Seko T., Tsuchiya K, Hamada H., and Tsuchida H. (1995). Performance of Lean NO_X Catalyst Applied to a Heavy-Duty Methanol Engine Exhaust. SAE paper 952494, Warrendale.

Shino, S. and Nakashima, N., (1988). Development of a Spark-assisted Heavy Duty Methanol Engine. VIII International Symposium on Alcohol Fuels. New Energy and Industrial Technology Development Organization, Japan, 1988.

Sigsby, (1982). Automotive Emissions of Ethylene Dibromide. SAE paper 820786.

Silbergeld E. (1982) Lead Poisoning, Dr. Ellen Silbergeld, Toxic Substance Control Newsletter, Autumn 1982.

SIS-STG, (1991a). Standards in Sweden according to SS 15 54 21. Swedish Commission for Standards.

SIS-STG, (1991B). Standards in Sweden according to SS-EN 228. Swedish Commission for Standards.

Small A. and Kazimi C. (1995) On The Costs of Air Pollution From Motor Vehicles, Department of Economics, UC Arvin, forthcoming in The Journal of Transport Economics, January 1995.

SNV, (1993). Improved environmental quality of gasoline. Proposal for Environmental Classes (in Swedish). Swedish Environmental Protection Agency.

Sorensen, S. and Mikkelsen, S-E. (1995). Performance and emissions of a O.273 Liter Direct Injection Diesel Engine Fuelled With Neat Dimethyl Ether. SAE paper 950064, Warrendale.

Stadsluften (Ambient air in the City), (1990) Swedish Environmental Protection Board, SNV-Report. Stockholm

STU, Swedish National Board for Technical Development (1986). Alcohols and alcohol blends as motor fuel. Vol II "State-of-the-Art" Report, page 8:71.

STU (1987). Project M 100 - A test With Methanol-Fueled Vehicles in Sweden. Prepared by SDAB. STU Information no. 640-11987.ISBN 91-7850-213-6. ISSN 0347-8645.

Swedish Environmental Protection Agency (NV), (1993) Environmental classes of gasoline

Takada, Y., Sasaki, M. And Machida, M., (1988). Durability of Heavy-Duty Direct Injection Methanol Engine. VIII International Symposium on Alcohol Fuels. New Energy and Industrial Technology Development Organization, Japan, 1988.

Tsunemoto, H., Yamada, T., Ishitani, H., Takatuki, T. And Iizuka, H., (1988). Cold Startability of a Spark Assisted Alcohol Diesel Engine. VIII International Symposium on Alcohol Fuels. New Energy and Industrial

Technology Development Organization, Japan, 1988.

Toepel R., Bennethum J. and Heruth R. (1983) Development of Detroit Diesel Allison 6V-92TA Methanol Fueled Coach Engine, SAE paper 831744, Warrendale.

Ullman T., Hare C. and Baines T. (1986) Emissions from Two Methanol-Powered Buses. SAE paper 860305, Warrendale.

UMTA (1988). Training Manual For Methanol Fuel Use In Transit Operations. Technical Assistance - An UMTA Program. UMTA-IT-06-0322-88-2, 1988.

Unnasch and Jackson, 1986).Preliminary Wear and Durability Results for Heavy-Duty Methanol Engines.

UOP (1990).

UOP (1991). The clean Air Act and the Refining Industry. Understanding the Issues. Meeting the Challenges.

U.S. Environmental Protection Agency (1977) Air Quality Criteria For Lead, Office of Research and Development, U.S. Environmental Protection Agency, Washington, D.C.,

U.S. Environmental Protection Agency (1978) Air Quality Criteria For Ozone and Other Photochemical Oxidants, Washington, D.C.

U.S. Environmental Protection Agency, (1980) Air Quality Criteria For Nitrogen Oxides, Draft, June 1980, Washington, D.C.

US Environmental Protection Agency (1991). Fuels and Fuel Additives Program - Notice of Proposed Rulemaking: Proposed Regulatory Text.

US Environmental Protection Agency (1991a). Outline of Supplemental Proposed Rules and Guidance for Reformulated Gasoline, Antidumping and Oxygenated Gasoline.

US Environ Protection Agency (1992). Fuel and Fuel Additives Registration Regulations: Proposed Rule, Federal Register, Part II, 40 CFR Part 79.

U.S. Environmental Protection Agency (1993) EPA 400-F-92-011 January 1993, Fact Sheet OMS-9. http://www.epa.gov/OMSWWW/09-altfu.htm

U.S. Environmental Protection Agency (1995) Excerpted from Draft PM Criteria Document, April 1995, Washington, D.C.

von Sivers, M. And Zacci, G. (1996). Ethanol from lignocellulosics: A Review of the Economy. Bioresource Technology 56 (1996) pp. 131 - 140.

VTT (1996). Performance evaluation of alternative fuel/engine concepts 1990-1995. Final report including addendum of diesel vehicles. VTT publications 271. ISBN 951-38-4929-5.

Walsh M. (1989). The Global importance of Motor Vehicles in the Climate Modification Problem. International Environment Reporter, May 1989.

Walsh, M. (1996). International Experiences Concerning Emissions and Biofuels.

Westerholm R. (1981) Report in Swedish. Department of Analytical Chemistry, Arrhenius Laboratory, Stockholm University, Stockholm, Sweden.

Westerholm R., Petersson K-A. and Walde N. (1984) A Study of Organic Emission from a Turbocharged Diesel Engine Running on 12 Per Cent Hexyl Nitrate Dissolved in Ethanol. SAE paper 840367, Warrendale.

Westerholm R., Christensen A. and Rosén Å. (1996). Regulated and Unregulated Exhaust Emissions from Two Three-Way Catalyst Equipped Gasoline Fuelled Vehicles. Atmospheric Environment pp. 3529 - 3536.

Wiens J., Sullivan C. and Jackson M. (1993). California's Methanol Truck Demonstration. Tenth International Symposium on Alcohol Fuels. The Road to Commercialization, Proceedings: Vol. I.

Winneke, (1983) Comments at Conference, Lead In Petrol, Winneke, May 1983

Williams, Larson, Katofsky and Chen (1995). Methanol and hydrogen from biomass for transportation, Energy for Sustainable Development.

Wuebben P., Unnasch S., Pellegrin V., Quigg D. and Urban B. (1990). Transit Bus Operation with 6V-92TAC Engine Operating on Ignition-Improved Methanol. SAE paper 902161, Warrendale.

Wuebben P. (1993) The Implications of the Clean Fuel Bus Success. Presented at: World Methanol Conference, Atlanta, Georgia, November 29- December 1, 1983.

Wuebben P., George, S., Watkins, L. and Bonny, A. (1995). The permitting and Commercialization of Landfill Gas Based Methanol Production Facilities. Presented at the Seventeenth Symposium on Biotechnology for Fuels and Chemicals.

Yamamoto, T., Noda, A., Sakamoto, T. and Sato. Y. (1996) Aluminia Catalysts for Reduction of NO_X from Methanol Fueled Diesel Engine. SAE paper 960137.

Yanagihara, H., Sato, Y., Sami, H. and Tsukahara, K., (1988). A New Approach to Methanol Combustion in Direct Injection Diesel Engine. VIII International Symposium on Alcohol Fuels. New Energy and Industrial Technology Development Organization, Japan, 1988.

Yule, (1980) The Relationship Between Blood Lead Concentrations, Intelligence and Attainment in a School Population: a Pilot Study", Yule, Lansdown, Millar and Urbanowicz, Devel., Med. Child. Neurol. 1981, 23, 567-576.

Yui, H. and Nakashima, N., (1988).Performance and Exhaust Gas Characteristics of a Glow Plug Assisted Methanol Diesel Engine. VIII International Symposium on Alcohol Fuels. New Energy and Industrial Technology Development Organization, Japan, 1988.

Zelenka P. and Kapus P. (1992). Development and Vehicle Application of a Multi-Fuel DI-Alcohol Engine. To be presented at the XXIV. FISITA Congress, IMechE, London.

Östman, A. (1996). Produktionskostnader för etanol, metanol och biogas (Production costs for ethanol, methanol and biogas). (Ingår i biodrivmedelsprogrammets systemstudie). Kommunikationsforskningsberedningens Meddelande 1996:29.

Appendix A: Status of Technology For Reducing Emissions From Vehicles

Great progress has been made during the last decade in the development of control technologies which are capable of dramatic reductions in the gasoline fueled vehicle emissions which cause or contribute to many of the above adverse effects. However, in order to utilize the best of these technologies, the catalytic converter, it is necessary to fuel vehicles exclusively on unleaded gasoline since lead tends to "poison" existing converter systems. The following section reviews the technologies available for reducing gasoline vehicle emissions and the important role that catalysts have come to play.

Before emission controls were mandated, fumes from the engine crankcase were vented directly into the atmosphere. Crankcase emission controls involved closing the crankcase vent port, and were introduced on new automobiles in the early 1960s. Control of these emissions is no longer considered a significant technical issue.

Evaporative emissions of hydrocarbons result from distillation of fuel in the carburetor float bowl and evaporation of fuel in the gas tank. The control of these emissions generally requires feeding the HC vapors back into the engine to be burned along with the rest of the fuel. When the engine is not in operation, vapors are stored, either in the engine crankcase or in charcoal canisters, which absorb these emissions to be burned off when the engine is started.

By far the most difficult emission control problem is the one related to vehicle exhaust emissions. Fortunately, much progress has been made during the last decade in the development of control technologies which are capable of dramatic reductions in the exhaust pollutants. These involve the physics of combustion, changes in engine design, and exhaust treatment devices.

1. Combustion and Emissions

Emissions of hydrocarbons, which include thousands of different chemical compounds, are largely the result of incomplete combustion of the fuel. The amounts emitted are related to the air/fuel mixture inducted, the peak temperatures and pressures in each cylinder, whether lead is added to the gasoline, and such hard to define factors as combustion chamber geometry.

The oxides of nitrogen are generally formed during conditions of high temperature and pressure and excess air (to supply oxygen). Peak temperatures and pressures are affected by a number of engine design and operating variables and so are the concentrations of nitrogen oxides in the exhaust.

Carbon monoxide also results from incomplete combustion of the carbon contained in the fuel and its concentration is generally governed by complex stoichiometry and equilibrium considerations. The only major engine design or operating variable which seems to affect its concentration is the air/fuel mixture: the leaner the mixture or the more air per unit of fuel, the lower the carbon monoxide emission rate.

Finally, lead compounds (and their associated scavengers) are exhausted by an automobile almost directly in proportion to the amount of fuel used by a vehicle and the concentration of lead in it.

2. Engine Design Parameters

Certain engine design parameters are capable of inducing significant changes in emissions. Most notable among these are air/fuel ratio and mixture preparation, ignition timing, and combustion chamber design and compression ratio.

3. *Air/Fuel Ratio and Mixture Preparation*

The air/fuel ratio has a significant effect on all three major pollutants (CO, HC and NO_X) from gasoline engines. In fact, CO emissions are almost totally dependent on air/fuel ratio whereas HC and NO_X emissions rates can be strongly influenced depending on other engine design parameters. CO emissions can be dramatically reduced by increasing air/fuel ratio to the lean side of stoichiometric. HC emissions can also be reduced significantly with increasing air/fuel ratio, until flame speed becomes so slow that pockets of unburned fuel are exhausted before full combustion occurs or, in the extreme, misfire occurs. Conversely, NO_X emissions increase as air/fuel mixtures are enleaned up to the point of maximum or peak thermal efficiency; beyond this point, further enleanment can result in lower NO_X emission rates.

4. *Ignition Timing*

Ignition timing is the second most important engine control variable affecting "engine out" HC and NO_X from modern engines. When timing is optimized for fuel economy and performance, HC and NO_X emissions are also relatively high (actual values depending of course on other engine design variables). As ignition timing is delayed (retarded), peak combustion temperatures tend to be reduced thereby lowering NO_X and peak thermal efficiency. By allowing combustion to continue after the exhaust port is opened (thereby resulting in higher exhaust temperatures), oxidation of unburned hydrocarbons is greater and overall hydrocarbon emissions are reduced.

5. *Compression Ratio and Combustion Chambers*

According to the fundamental laws of thermodynamics, increases in compression ratio lead to improved thermal efficiency and concomitantly increased specific power and reduced specific fuel consumption. In actual applications, increases in compression ratios tend to be limited by available fuel octane quality; over time, a balance has been struck between increased fuel octane values (through refining modifications and fuel modifications, such as the addition of tetraethyl lead to gasoline) and higher vehicle compression ratios.

Compression ratios can be linked to combustion chamber shapes and in combination these parameters can have a significant impact on emissions. Higher surface to volume ratios will increase the available quench zone and lead to higher hydrocarbon emissions; conversely, more compact shapes such as the hemispherical or bent roof chambers reduce heat loss, thus increasing maximum temperatures. This tends to increase the formation of NO_X while reducing HC. Further, combustion chamber material and size and spark plug location can influence emissions. In general, because of its higher thermal conductivity, aluminum engine heads lead to lower combustion temperatures and therefore to lower NO_X rates, but at the expense of increased HC emissions. Since the length of the flame path has a strong influence on engine detonation and therefore fuel octane requirement, larger combustion chambers which can lower HC emissions tend to be used only with lower compression ratios.

6. *Emission Control Technologies*

Tighter emission standards have required more specific attention to the treatment of vehicle exhaust emissions. Commonly used technologies to control exhaust emissions include recirculation of exhaust gases, electronic control of engine performance, exhaust after-treatment devices, and advanced combustion techniques.

With the current state of the art, engine modification alone cannot reduce emissions to the same extent as with a three-way catalyst. Compared to a carburetted engine, an electronically controlled engine equipped with a 3-way catalyst can reduce CO emissions from a mean rate of 7.5 g per km to 1.5 g per km; HC emissions from 1.5 g per km to 0.25 g per km; and NO_X from 2.0 g per km to 0.25 g per km. Electronic fuel injection and ignition systems (EFI) without a catalytic converter are effective in reducing CO and HC emissions but have only a minor effect on NO_X emissions.[14]

---

[14] ECMT [1990]. Transport Policy and the Environment. European Conference of Ministers of Transport. OECD, Paris.

7. *Exhaust Gas Recirculation (EGR)*

Recirculating a portion of the exhaust gas back into the incoming air/fuel mixture is frequently used as a technique for lowering NO_X. The dilution of the incoming charge reduces peak cycle temperature by slowing flame speed and absorbing some heat of combustion.

Charge dilution of homogeneous-charge engines by excess air and/or by exhaust gas recirculation (EGR) has been used for many years. The use of excess air alone results in relatively small NO_X reductions, in the order of 35-40%. When EGR is incorporated, substantially higher NO_X reductions have been demonstrated. Excessive dilution, however, can result in increased HC emissions, driveability problems or fuel economy losses.

Fuel consumption can be modified when EGR is utilized. Brake specific fuel consumption and exhaust temperature decrease with increasing EGR because dilution with EGR decreases pumping work and heat transfer, and increases the ratio of specific heats of the burned gases. Improvements in mixture preparation, induction systems, and ignition systems can increase dilution tolerance. The latest technique for improving dilution tolerance is to increase the burn rate or flame speed of the air-fuel charge. Dilution can then be increased until the burn rate again becomes limiting. Several techniques have been used to increase burn rate including increased "swirl" and "squish", shorter flame paths, and multiple ignition sources.

8. *Electronics*

With so many interrelated engine design and operating variables playing an increasingly important role in the modern engine, the control system has become increasingly important. Modifications in spark timing must be closely coordinated with air/fuel ratio changes and amount of EGR lest significant fuel economy or performance penalties result from emissions reductions or NO_X emissions increase as CO goes down. In addition, controls which can be more selective depending on engine load or speed have been found beneficial in preventing adverse impacts.

To meet these requirements, electronics have begun to replace more traditional mechanical controls. The conventional combination of carburetor and distributed ignition systems can now be replaced by electronic fuel injection (EFI) and ignition to provide more precise control.[1] Furthermore, electronic control of ignition timing has been shown to optimize timing under all engine conditions and has the added advantage of reduced maintenance and improved durability compared with mechanical systems. When both ignition timing and EGR are electronically controlled, it has been demonstrated that NO_X emissions can be reduced with no fuel economy penalty and in some cases with an improvement.

9. *Exhaust After-Treatment Devices*

The use of catalytic converters and thermal reactors, generically known as exhaust after-treatment devices, becomes necessary in order to achieve a quantum reduction in exhaust emissions, beyond those feasible with engine design modifications. The catalyst comprises a ceramic support, a washcoat (usually aluminum oxide) to provide a very large surface area, and a surface layer of precious metals (platinum, rhodium, and palladium are most commonly used) to perform the catalytic function. The catalyst is housed in a metal container forming part of the vehicle exhaust system. For effective operation, the catalyst temperature must exceed the light-off value (about 300° C), which takes one to three minutes to achieve in typical urban driving conditions.[2] The cost of a

---

[1] ECMT [1990]. Transport Policy and the Environment. European Conference of Ministers of Transport. OECD, Paris.

[2] ECMT [1990]. Transport Policy and the Environment. European Conference of Ministers of Transport. OECD, Paris.

catalytic converter and its accompanying equipment ranges from US$250 to US$750 per automobile (1981 prices) equivalent to a 4 - 20% increase in the cost of the vehicle.[3] Small inexpensive vehicles bear the brunt of the cost increase in relative terms. These devices can reduce HC emissions by an average of 87%, CO by 85% and NO_X by 62% over the life of a vehicle.[4]

Oxidation Catalysts: Quite simply, an oxidation catalyst is a device which is placed on the tailpipe of a car and which, if the chemistry and thermodynamics are properly maintained, will oxidize almost all the HC and CO in the exhaust stream to carbon dioxide and water vapor. Starting with the 1975 model year automobile, catalysts have been placed on upwards of 80% of all new cars sold in the United States. In 1981, they were placed on 100% of the new cars. A major impediment to the use of catalysts is lead in gasoline. Existing, proven catalyst systems are poisoned by the lead in vehicle exhaust. One of the unique advantages of catalysts is their ability to selectively eliminate some of the more harmful compounds in vehicle exhaust such as aldehydes, reactive hydrocarbons, and polynuclear hydrocarbons.

Three-way Catalysts: So called because of their ability to lower HC, CO and NO_X levels simultaneously, they were first introduced in the United States in 1977 by Volvo and subsequently became widely used when the U.S. NO_X standard was made more stringent (1.0 grams per mile) in 1981. For three-way catalysts to work effectively, it is necessary to control air/fuel mixtures much more precisely than is needed for oxidation catalyst systems. As a result, three-way systems have indirectly fostered improved air/fuel management systems such as advanced carburetors, throttle body fuel injection, and electronic controls. Three-way catalyst systems also are sensitive to the use of leaded gasoline. An occasional tankful of leaded gasoline will have a small but lasting effect on the level of emitted pollutants.

10. Technological Advances on the Horizon

The technology to reduce vehicle emissions continues to evolve and develop. Lower trace lead levels in unleaded gasoline and more advanced emission control components, particularly more durable catalysts, better air fuel management systems, and electronics will be key elements of future control. California (USA), still plagued by severe smog conditions in Los Angeles, continues its worldwide leadership in extending the pollution control requirements.

The level of tailpipe hydrocarbon emissions from modern vehicles is primarily a function of the engine-out emissions and the overall conversion efficiency of the catalyst, both of which are highly dependent on proper function of the fuel and ignition systems. A fairly comprehensive system has evolved. A significant portion of the HC and CO emissions are generated during cold-start, when the fuel system is operating in a rich mode and the catalyst has not yet reached its light off temperature. There are many technological improvements, which are currently becoming widespread or are on the horizon, that make more stringent control of HC and CO feasible. These advances are expected to not only reduce the emission levels that can be achieved in the certification of new vehicles, but also to reduce the deterioration of vehicle emissions in customer service.

First is the trend toward increased use of fuel injection. Fuel injection has several distinct advantages over carburetion as a fuel control system -- more precise control of fuel metering, better compatibility with digital electronics, better fuel economy, and better cold-start function. Fuel metering precision is important in maintaining a stoichiometric air/fuel ratio for efficient three-way catalyst operation. Efficient catalyst operation, in turn, can reduce the need for dual-bed catalysts, air injection, and EGR. Better driveability from fuel injection has been a motivating force for the trend to convert engines from carburetion to fuel injection. In fact, it has

---

[3] OECD [1988a]. <u>Transport and Environment</u>, Paris.

[4] French, H.F. [1990]. "You are what you breathe." <u>World Watch</u>, Vol. 3, No. 3, Washington, D.C.

been projected that the percentage of new California light-duty vehicles with fuel-injection will reach 95% by the early 1990's, with 70% being multi-point. Because of the inherently better fuel control provided by fuel-injection systems, this trend is highly consistent with more stringent emissions standards.

Fuel injection's compatibility with onboard electronic controls enhances fuel metering precision, and also gives manufacturers the ability to integrate fuel control and emissions control systems into an overall engine management system. This permits early detection and diagnosis of malfunctions, automatic compensation for altitude, and to some degree, adjustments for normal wear. Carburetor choke valves, long considered a target for maladjustment and tampering, are replaced by more reliable cold-start enrichment systems in fuel-injected vehicles.

Closed-loop feedback systems are critical to maintain good fuel control, although when they fail emissions can increase significantly. In fact, the CARB in-use surveillance data show that failure of components in the closed-loop system frequently has been associated with high emissions. The CARB's new requirement for onboard diagnostics will enable the system to alert the driver when something is wrong with the emission control system and will help the mechanic to identify the malfunctioning component.

Second, improvements to the fuel control and ignition systems, such as increasing the ability to maintain a stoichiometric air/fuel ratio under all operating conditions and minimizing the occurrence of spark plug misfire, will result in better overall catalyst conversion efficiency and less opportunity for catastrophic failure. These improvements, therefore, have a twofold effect: 1) limiting the extra engine-out emissions that would be generated by malfunctions, and 2) helping to keep the catalyst in good working condition.

Finally, there are alternative catalyst configurations that could and likely will be used in the future to meet lower emission standards. It is likely that dual-bed catalysts will be phased out over time, but a warm-up catalyst (preceding the TWC) could be used for cold-start hydrocarbon control. To avert thermal damage and lower the catalyst deterioration rate, this small catalyst could be bypassed at all times other than during cold-start. Warm-up air injection could also be used with a single-bed TWC for cold-start hydrocarbon control. As hydrocarbon standards are lowered, preheated catalysts will likely become a more important element of the pollution control system of many cars.

11. The 1990 Clean Air Act Amendments

The 1990 Clean Air Act Amendments contain numerous provisions to reduce air pollution emissions from motor vehicles. These include incentives to remove older polluting vehicles from the road; tightening new-vehicle emission standards for nitrogen oxides, volatile organic compounds, and carbon monoxide; developing and using cleaner fuels with lower volatility and fewer toxic components; enhancing inspection and maintenance (I&M) programs, including inspections of anti-tampering emission-control equipment; and extending the useful life for pollution-control equipment to ten years or 100,000 miles rather than the current five years or 50,000 miles. The potential overall impacts of tighter standards, enhanced inspection and maintenance, and extended useful life are especially significant because they help ensure that the benefits of clean-air technology will persist for the vehicle's full life.

In addition to more stringent standards for cars, trucks and buses, the Amendments will require substantial modification to conventional fuels, provide greater opportunity for the introduction of alternative fuels (but without mandating them) and extend the manufacturers responsibility for compliance with auto standards in use to 10 years or 100,000 miles.

Highlights of the 1990 Clean Air Act Amendments as they relate to vehicle emissions are summarized below.

1. Light Duty Vehicles

(1) Tier 1

The Tier 1 tailpipe standards for light-duty vehicles are summarized in Tables A and B.

TABLE A
EMISSION STANDARDS FOR LIGHT-DUTY VEHICLES (PASSENGER CARS) AND LIGHT-DUTY TRUCKS OF UP TO 6000 LBS. GVWR

Column A	Column B							
	(5 yrs/50/000 mi)				(10 yrs/100,000 mi)			
Vehicle Type	NMHC	CO	NO_X	Part.	NMHC	CO	NO_X	Part.
<u>Non-Diesel</u>								
LDT's (0-3,750 lbs. LVW) and light-duty vehicles	0.25	3.4	0.4	-	0.31	4.2	0.6	-
LDT's (3,751-5,750 lbs. LVW)	0.32	4.4	0.7	-	0.40	5.5	0.97	-
Diesel								
LDTS (0-3,750 lbs. LVW and light-duty vehicles	0.25	3.4	1.0	0.08	0.31	4.2	1.25	0.10
LDT's (3,751-5,750	0.32	4.4	-	0.08	0.40	5.0	0.97	0.10

TABLE B
EMISSION STANDARDS FOR LIGHT-DUTY TRUCKS OF MORE THAN 6,000 LBS. GVWR

Column A (5 yrs/50,000 mi) Column B (11 yrs/120,000 mi)

LDT Test weight	<u>NMHC</u>	<u>CO</u>	<u>NO_X</u>		<u>NMHC</u>	<u>CO</u>	<u>NO_X</u>	<u>PM</u>		
3,751-5,750 lbs	0.32		4.4	0.7*		0.46		6.4	0.98	0.10
Over 5,750 lbs	0.39		5.0	1.1*		0.56		7.3	1.53	0.12

Standards are expressed in grams per mile (gpm).
*Not applicable to diesel-fueled LDT's.

For purposes of certification, the standards in Table A will be phased in over a three year period (applicable to 40 percent of MY 1994 vehicles, 80 percent of MY 1995 vehicles, and 100 percent of MY 1996 vehicles, as illustrated in Table C). In use, starting in 1994, the standards will start to be phased in -- 40% the first year, 80% the second and 100% the third year (1996) for NO_X. For HC, in the first year, 40% will be required to meet the <u>intermediate</u> in use standard (0.32 grams per mile NMHC) with the remainder achieving the current standard. This will rise to 80% in the second year. By the third year only 60 % will meet the intermediate standard with the other 40% meeting the <u>final</u> (0.25 NMHC) standard. In the fourth year, 80% will be required to meet the 0.25 level, rising to 100% by 1998.

Starting in 1996, new in use standards are starting to be phased in for 100,000 miles (75,000 miles for Recall testing) which allow for 25 percent higher emissions levels between 50,000 and 100,000 miles for HC and CO, and 50% higher for NO_X. Diesel vehicles are also allowed to comply with a relaxed 1.0 gpm NO_X standard. Light trucks under 3750 loaded vehicle weight (LVW) will be required to achieve the same standards as cars.

TABLE C
IMPLEMENTATION SCHEDULE FOR TIER 1 STANDARDS FOR LIGHT-DUTY VEHICLES (PASSENGER CARS) AND LIGHT-DUTY TRUCKS OF UP TO 6000 LBS. GVWR

Model Year		
Certification	In Use	Percentage of Manufacturers Sales Volume
1994	1996	40%
1995	1997	80%
1996	1998	100%

—

IMPLEMENTATION SCHEDULE FOR STANDARDS FOR LIGHT-DUTY TRUCKS OF MORE THAN 6,000 LBS. GVWR

Model Year		Percentage of Manufacturers Sales Volume
Certification	In Use	
1996	1998	50%
1997	1999	100%

(2) Cold Temperature CO Standards

During late 1992, EPA issued a final rule implementing cold temperature standards for passenger cars and light-duty trucks. The emission standards are 10.0 gpm for passenger cars and light duty trucks with 3750 lbs or less LVW and 12.5 gpm for light-duty trucks over 3750 lbs. LVW. The standards are based on testing at 20 degrees F and are applicable for 50,000 miles. The standards are being phased in according to the following schedule:

TABLE D
PHASE-IN SCHEDULE FOR COLD START STANDARDS

Model Year	Percentage of Manufacturer's Sales Volume
1994	40%
1995	80%
1996 and after	100%

2. *Heavy Duty Vehicles and Engines*

EPA has issued its final rule implementing several provisions of the Clean Air Act related to buses and heavy-duty engines (HDE's). First, for model year 1993, EPA expanded the applicability of the 0.10 gram per brake horsepower-hour (g/bhp-hr) particulate matter (PM) standard currently required of urban bus engines to a broader group of HDE's used in other types of buses. Second, for model year 1994 and 1995 HDE's used in urban buses, EPA promulgated a PM standard of 0.07 g/BHP-hr. (For model year 1996 and later HDE's used in urban buses, the certification and SEA standard is lowered to 0.05 g/BHP-hr, the in-use standard remains at 0.07 g/bhp-hr.) Third, EPA retained the current heavy-duty transient test procedure for emissions testing of urban bus engines. Fourth, in addition to the bus requirements, the final rule also promulgated an oxides of nitrogen (NO_X) standard of 4.0 g/BHP-hr for all 1998 and later model year HDE's. Finally, for the two new emission standards promulgated in this action (1994 urban bus PM standard and 1998 HDE NO_X standard), the useful life was extended from eight years to ten years.

Beyond the vehicles themselves, EPA has issued a rule limiting the sulfur content of diesel fuel to 0.05 percent by weight (Wt. %) after October 1, 1993. This decision not only directly lowers particulate (sulfur) emissions, but also paves the way for the use of catalytic control technology for diesel particulate since it reduces the concern over excessive sulfate emissions. The rule also allows vehicle manufacturers to certify their engines for compliance with the 1991 to 1993 emission limits with fuel of 0.10 sulphur content.

3. Off Road Vehicles Or Engines

EPA completed a study of non-road engine emissions in 1991 as required by the 1990 Clean Air Act Amendments. The Act requires EPA to adopt regulations for non road engines if it determines that non road engines' emissions make a significant contribution to ozone or CO nonattainment problems in more than one area.

(1) Preempted Engines

Under the Clean Air Act Amendments of 1990, EPA must define the class of off-road engines preempted from regulation by California. EPA expects to issue by fall a final rule defining the preempted class of engines. The rule is expected to be based on a compromise definition of the preempted class worked out between CARB and the industry. Once the preemption definition is finalized, EPA plans to reopen the comment period on California's request to enforce its emission standards for small utility engines.

(2) Small Engine Standards

EPA and interested parties have tentatively agreed to a plan under which EPA will propose Phase I federal emission standards for gasoline-powered engines at and under 25 HP based on the level of the California Phase I standards effective either January 1, 1996 or possibly January 1, 1997. EPA hopes to propose the Phase I standards by April 30, 1994. The Phase II standards will be developed as part of a formal negotiated rulemaking process which should commence this Fall.

(3) Diesel Engines

On May 17, 1993 EPA proposed its determination that non road engines are a significant contributor to ozone non-attainment. This determination is required by the Clean Air Act before EPA may regulate non road sources. EPA also proposed a smoke (opacity) standard and a 6.9 g/BHP-hr NO_X standard for diesel powered off-road engines to take effect as follows:
50-99 HP (January 1998);
100-174 HP (January 1997);
175-750 HP (January 1996) and
751 HP and above (January 2000).

EPA believes current test procedures do not properly evaluate particulate emissions from non road engines. EPA is working with industry to evaluate alternative test procedures and may propose Phase II standards at a later date.

4. California's Unique Requirements

Under the US system, California has been allowed to adopt its own vehicle emission standards. The program which has evolved has consistently been the most stringent in the world. Highlights of the program as it relates to greenhouse gas emissions are summarized below.

1. Light Duty Vehicle Exhaust Emissions

In 1990, the CARB Board adopted vehicle emissions standards to apply throughout the 1990's and into the next century; these are generally referred to as the Low Emission Vehicle (LEV) program. Specifically, a portion of new vehicles starting in 1994 would have to meet a hydrocarbon standard of 0.125 gpm when fueled with conventional gasoline (so called "transitional low emission vehicles" or TLEV's) or "low emission vehicles"

(LEV's) emitting only 0.075 gpm HC or "ultra low emission vehicles" (ULEV's) which emit no more than 0.04 gpm HC and 0.02 gpm NO_X. These standards are summarized in Table E, below. Table F shows the different standards which could apply if the vehicles are powered by alternative fuels. In addition, "Zero Emission Vehicles" (ZEV's) must be introduced and comprise at least 2% of sales by the year 1998 and 10% by 2003. In the aggregate, the vehicle combination must comply with average emissions levels as listed in Table F.

1. Exhaust emissions

Table E: 50,000 Mile Certification Standards (g/mi) for Passenger Cars Operating on Gasoline

CATEGORY	NMOG *	CO	NO_X
Adopted for 1993	0.25	3.4	0.4
TLEV	0.125	3.4	0.4
LEV	0.075	3.4	0.2
ULEV	0.040	1.7	0.2

* NMOG is substituted for conventional hydrocarbons because the constituents in the exhaust could change as fuels change in the future; these emissions will be reactivity adjusted for cleaner burning fuels.

Table F: NMOG Standards (g/mi) for Flexible- and Dual-Fueled Passenger Cars When Operating on an Alternate Fuel and Gasoline at 50,000 Miles.

CATEGORY	ALTERNATE FUEL*	GASOLINE
TLEV	0.125	0.25
LEV	0.075	0.125
ULEV	0.040	0.075

* Before reactivity adjustment.

Table G. Implementation Rates for Conventional Vehicles, TLEVs, LEV's, ULEV's, and ZEV's Used to Calculate Fleet Average Standards for Passenger Cars.

MODEL YEAR	**0.39**	**0.25**	**TLEV 0.125**	**LEV 0.075**	**ULEV 0.040**	**ZEV* 0.00**		**FLEET AVERAGE STANDARD**
1994		10%	80%	10%				0.250
1995			85	15				0.231
1996			80	20				0.225
1997			73		25%	2%		0.202
1998			48		48	2	2%	0.157
1999			23		73	2	2	0.113
2000					96	2	2	0.073
2001					90	5	5	0.070
2002					85	10	5	0.068
2003					75	15	10	0.062

* The percentage requirements for ZEV's are mandatory.

2. Evaporative Emission Control

To control the evaporative emissions from vehicles in use, both EPA and CARB have developed a sequence of events designed to test vehicles for compliance with evaporative emission regulations. The California Air Resources Board was first to adopt their new procedures but EPA tightened them even more earlier this year. Although both testing programs include the events of preconditioning, diurnal heat builds and exhaust, running loss, and hot soak tests, differences exist which complicate a comparison of the emission control differences that might result from the two programs. It appears likely, however, that the EPA and CARB procedures will eventually be closely matched.

California's evaporative HC test procedure reflects higher temperatures (105 degrees) and higher vehicle canister purge rates. This new procedure will be phased in starting in Model Year 1995 at 10% the first year, 40% the second, 80% the third and 100% the fourth (1998).

3. Medium Duty Vehicles

CARB also adopted new emission standards for medium-duty vehicles in June 1990. The regulation expands the definition of medium-duty vehicles to include vehicles weighing between 6000 lbs. and 14,000 lbs. GVWR, establishes a chassis test procedure for those vehicles (which should greatly facilitate in use Recall testing), and expands the useful life requirements to 120,000 miles.

The new emission standards are set out in Table H below. Manufacturers will be required to meet 50 percent certification compliance in 1995 and 100 percent compliance in 1996. Less stringent in-use compliance will be permitted through the 1997 model year with full 100 percent certification and in-use compliance required for the 1998 model year.

Table H

Test Weight	**50,000 Mile Standards** ---- **(g/mi)** ----		----	**120,000 Mile Standards** **(g/mi)** -----			
(lbs)	**NMHC***	**CO**	**NO_X**	**NMHC***	**CO**	**NO_X**	**PM**
0-3750	0.25	3.4	0.4	0.36	5.0	0.55	0.08
3751-5750	0.32	4.4	0.7	0.46	6.4	0.98	0.10
5751-8500	0.39	5.0	1.1	0.56	7.3	1.53	0.12
8501-10,000	0.46	5.5	1.3	0.66	8.1	1.81	0.15
10,001-14,000	0.60	7.0	2.0	0.86	10.3	2.77	0.18

* Non-methane Hydrocarbons

4. Off Road Vehicles or Engines

California has also taken the lead with regard to off road emissions.

(1) Diesel Engines above 175 HP

In 1992, the California Air Resources Board adopted emission standards for off-road diesel engines above 175 HP. New 1996 through 2000 model year engines must meet standards equivalent in stringency to the 1990 on road heavy duty diesel engine standards. Actual standards would be 6.9 grams per BHP-hr for NO_X and 0.4 particulate, based on an 8 mode steady state test largely culled from the ISO 8178 procedure. Beginning in the year 2001, the proposal is intended to be equivalent to 1991 on road heavy duty engine standards, 5.8 NO_X and 0.16 particulate. Beginning in 2000, CARB includes requirements for engines over 750 HP for the first time, requiring that they meet the 1996-1999 proposed levels.

CARB estimates that the 1996 standards will likely require modifications to fuel injection timing, fuel injectors, combustion chambers and jacket water aftercoolers. The 2000 standards will require further improvements in aftercooling, improved oil control, and possibly electronic fuel injection systems. CARB noted in its proposal that alternative fuels and particulate aftertreatment devices may be used but no 1991 on highway engine needed them to meet similar standards.

(2) Utility Engines

The CARB is being asked by utility engine manufacturers to reconsider the 1994 standards for utility engines because of technical concerns in meeting those standards and the uncertainty created by EPA's failure to define what engines are preempted from CARB regulations. CARB is planning to fund a demonstration project for a catalyst-equipped chainsaw.

(3) Recreation Vehicles

The CARB staff is also developing proposed standards for off-road recreational vehicles such as motorcycles and snowmobiles. The Board will likely consider at a public meeting later this year standards which could result in a phase out of two-cycle engines used on recreational equipment and will require zero emission (i.e., electric) golf carts.

(4) Miscellaneous Engines

The CARB staff is developing proposed regulations for a variety of off-road engines and vehicles. The types of sources to be regulated include mobile pumps, generators, compressors, mobile refrigerator units, airport service equipment, and forklifts. The staff is waiting to submit proposed rules until after EPA defines the class of engines which are preempted from regulation by California. The Board will likely consider standards in late 1993 or early 1994, depending on how fast EPA takes action on the preemption issue.

After extensive negotiations over a year period, CARB has presented EPA with a proposal regarding which nonroad engines would be preempted by Federal standards. The agreement concludes that equipment under 25 HP is generally not considered construction and farm equipment unless it is identified on a list of preempted engines, and equipment over 25 HP is generally presumed to be construction and farm equipment. Engines deemed to be farm and construction equipment include aerial devices, backhoes, balers, chainsaws of 45 cc and above, drills, and fertilizer spreaders. The following equipment is determined not to be farm and construction and would be subject to immediate regulation if EPA concurs -- forklifts of less than 50 HP not powered by diesel engines, off-highway recreational vehicles, refrigeration units of less than 50 HP and turf care equipment.

One of the key participants in the negotiations, the Equipment Manufacturers Association refused to go along with the agreement.

(5) Locomotives

The staff likely will present proposed standards to the Board in 1994. Recent studies have suggested that rail electrification may not be cost effective. As a result the staff is evaluating control strategies which include alternative fuels, SCR, EGR, and low NO_X diesel engines.

(6) Marine Vessels

The staff plans to propose standards near the end of 1993. The proposal will include standards for new marine engines and some type of market-based program to clean up existing engines. For new engines, SCR technology is being evaluated. For marine vessels, CARB may give individual air quality districts the option of requiring compliance with the CARB standards.

Inför avslutningen av biodrivmedelsprogrammet genomför KFB en *systemstudie*, som skall analysera de flesta aspekter på ett storskaligt införande av biobaserade drivmedel. Följande delstudier ingår:

- Sammanställning av emissionsdata och utvärdering av emissionsnivåer för fordon
- Kostnader för produktion av etanol, metanol och biogas
- Kostnader för fordon
- Kostnader för infrastruktur
- Energibalanser
- Ekonomiska jämviktsstudier
- Översikt över rapporter om biodrivmedel
- Analys av erfarenheter från introduktion av biodrivmedel
- Metanolstudie – internationella erfarenheter
- Värdering av hälsoeffekter
- Internationella erfarenheter av biogasfordon.

Denna publikation ingår i avrapporteringen från systemstudien.

Förteckningar över KFBs olika publikationsserier, bl a
- Rapporter
- Meddelanden
- KFB-Information
- Publikationer inom KFBs bio- och elprogram

kan erhållas från KFB.

KFB (The Swedish Transport and Communications Research Board) is a government agency with planning, initiating, coordinating and supporting functions in Swedish transport and communications research. KFB's activities encompass transportation, traffic, postal services and telecommunications, as well as the impact of transports and communications on the environment, traffic safety and regional development.

KFB is also responsible for information and documentation within its areas of responsibility.

Postal address: Box 5706, S-114 87 Stockholm, Sweden
Visiting address: Linnégatan 2, Stockholm
Phone: 08-459 17 00; Int: +46 8 459 17 00
Fax: 08-662 66 09; Int: +46 8 662 66 09
Internet Home page: www.kfb.se

KFB
SWEDISH TRANSPORT