EXHAUST EMISSIONS FROM NATURAL GAS VEHICLES

Issues related to engine performance, exhaust emissions and environmental impacts

A report prepared for the IANGV Technical Committee

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ABSTRACT

Natural gas is one of the most promising fuel alternatives for the future. Independent of vehicle category, natural gas will help to bring down harmful emissions. There are already excellent natural gas vehicles on the market. However, some technical improvements are still needed, especially in the heavy-duty sector.

This report or "Position Paper", which has been prepared within the IANGV Technical Committee, is a status report on engine technology, exhaust emissions, energy efficiency and environmental impacts in general from a technical point of view. The report does not cover commercial aspects, and it does not deal with refuelling or fuel storage related issues.

The report, which was completed in early 2000 covers, among other things, fuel properties, engine technology for gaseous fuels, emission legislation and examples on gas fuelled vehicles and their performance. The report itself has a global perspective on NGVs, although, for obvious reasons, the North American and the European situations have been given much attention. Also Japanese technology is discussed.

The report highlights the progress in fuel system development, OBD requirements for gas fuelled vehicles, new test methods for emission testing and examples of the performance of the latest natural gas vehicles. It also discusses the progress in conventional technologies and the areas for improvement so that natural gas vehicles will stay environmentally competitive with conventional technologies. The newest data included in the report is from late 1999.

PREFACE

The IANGV Technical Committee is chaired by the eminent Mr. Jouke van der Weide of TNO, Holland. During a meeting of the Technical Committee in Cologne, Germany in May 1998, it was decided that the Technical Committee should form two new Task Forces on highly topical themes, one on general emissions related issues and one on OBD (On-Board-Diagnostics). Dr. Nils-Olof Nylund of VTT, Finland was nominated head of the Emissions Task Force and Dr. Alex Lawson of GFI Control Systems, Inc., Canada, head of the OBD Task Force.

It was then also decided that the two new Task Forces should prepare two separate reports on their individual topics. However, at the following Technical Committee meeting, held in Sydney, Australia in April 1999, a decision was made to combine the two documents. The rationale for this was that the OBD issue very much is an emissions issue.

The report at hand is a "Position Paper" or "Status Report" on emission related issues. This technical report concentrates on fuel properties, engine technology, fuel and OBD systems, emissions and energy efficiency. In a way it is a more detailed emissions complement to the general 1997 IANGV Position Paper on Natural Gas Vehicles prepared by John Stephenson.

The main part of the report text was prepared by Dr. Nylund. Dr. Lawson contributed the OBD part and information on North American emission regulations. Mr. Walter Knecht of Iveco Motorenforschung AG, Switzerland, kindly contributed data on heavy-duty gas engines. Mr. Jouke van der Weide contributed both material and valuable comments on the text. Dr. Hien Ly of AGL Infrastructure Management and Services, Australia, also gave his valuable review of the text.

The IANGV wishes to extend its gratitude to all the people who have contributed to this latest IANGV report.

Jeff Seisler
President, IANGV

SUMMARY

This report or "Position Paper", which has been prepared within the IANGV Technical Committee, is a status report on engine technology, exhaust emissions, energy efficiency and environmental impacts in general from a technical point of view. The report does not cover commercial aspects, and it does not deal with refueling or fuel storage related issues.

The report aims to look at natural gas vehicle technology in an international perspective. However, due to the availability of information and the experience of the authors, the report relies heavily on European and to some extent North-American information. Examples on Japanese CNG vehicles are, however, also included.

In the 1990s environmental issues have had a great impact on most human activities in the developed countries. Exhaust emission requirements are becoming more and more stringent. In the pre-catalyst age, switching from gasoline to a gaseous fuel often led to reduced exhaust emissions. Today, however, the engine management and the catalyst efficiency are decisive factors from the regulated emissions point of view, whereas the fuel itself plays a minor role.

The conventional diesel engine is very energy efficient and reliable. For these reasons, the direct injection diesel engine is currently almost the only power unit used in heavy-duty vehicles. The conventional diesel engine is, however, facing difficulties in meeting increasingly stringent emission regulations. By substituting the conventional diesel by an advanced engine capable of burning alternative fuels such as alcohols or gaseous fuels, exhaust emissions and exhaust toxicity can be lowered substantially.

In many applications, natural gas can contribute to the reduction of toxic and reactive automotive emissions. The vehicle population and general energy use is growing fast in developing countries. As natural gas is a clean burning fuel, this fuel is a good option in vehicles which do not have sophisticated exhaust gas aftertreatment systems.

However, there is also the aspect of general energy use and greenhouse gas emissions. International agreements like the Kyoto agreement have been signed to stop the growth of greenhouse gas emissions. In gasoline fuelled cars substantial carbon dioxide reductions can be achieved by switching to natural gas, and as the technology for heavy-duty engines improves, we might see a reduction potential in this sector, too. Methane can be collected from waste treatment facilities, and thus there is a possibility to run natural gas vehicles also on renewable fuel.

Natural gas is well suited as an Otto engine fuel, as methane has high knock resistance. Gaseous fuels easily form a homogeneous mixture with air. This, and the simplicity of the fuel molecule, is advantageous for soot-free complete combustion. In general, for both light- and heavy-duty applications, the decisive factor for regulated emissions is the engine and exhaust gas aftertreatment technology used on the vehicle.

Fuel chemistry, on the other hand, is clearly linked to exhaust gas toxicity, and in this respect the simple chemical structure of methane gives a clear advantage over conventional fuels. Research organisations like TNO and VTT have studied unregulated emissions from different fuel alternatives.

In general, three main features or components determine the emission performance of a gas engine, i.e. combustion system, fuel system and catalyst technology. A division of spark-ignition automotive gas engines into three categories according to the air-fuel ratio can be made:

- stoichiometric engines
- lean-burn engines
- engines optimised for low consumption but not low emissions

Previously, most automotive gas engines were tuned slightly lean for low fuel consumption. This, however, resulted in very high emissions of nitrogen oxides, and therefore such concepts can no longer be used on new vehicles in countries with stringent exhaust gas legislation.

There are basically two ways to control emissions. One is to use a three-way catalyst. A stoichiometric engine equipped with a closed-loop fuel system and a TWC gives very low exhaust emissions. This system is used for most current light-duty and also some heavy-duty applications. The second one is to use lean-burn combustion, and in this case the formation of nitrogen oxides is controlled in the combustion process itself. Carbon monoxide and hydrocarbons are often controlled using an oxidation catalyst. Lean-burn combustion is a common alternative in heavy-duty engines.

It is very important in both stoichiometric and lean-burn engines to have precise fuel control to ensure proper dynamic emission performance. One vision of the future is that gas engines will have sequential multi-point fuel injection, and that they will have closed-loop control both for stoichiometric and lean-burn operation. The advanced light-duty CNG vehicles of today, with their sequential multi-point fuel injection systems are capable of meeting the EPA Tier 2 emission standards.

On-board diagnostic systems, which can detect malfunctions of the engine management and the exhaust control system, are required in the US for light-duty vehicles, and will soon be introduced also in Europe. The problem is that systems originally designed for gasoline operation will not work properly on alternative fuels.

Current regulations in the US require alternative fuel vehicles to be compliant with OBD II regulations. The Malfunction Indicator Light cannot be disabled, since this would be considered tampering with the original emission control system.

However, until 2004, manufacturers of alternative fuel systems may request approval of a monitoring strategy where specific monitoring requirements are disabled. This means that selected monitors which would otherwise set a false MIL and codes, can be disabled when operating on the alternative fuel.

Similar regulations are emerging in Europe with EOBD systems, and it appears likely that manufacturers can apply for a derogation of EOBD monitoring systems because monitoring may not be reliable on alternative fuels.

It seems that the OBD systems will become so complex that only a close working relationship with the OEM will allow suppliers of alternative fuel conversion systems to achieve full OBD capability. This would eliminate traditional aftermarket conversions on markets with strict emission regulations.

In Europe, new emission regulations for both light-duty and heavy-duty vehicles have been decided upon recently. The European regulations for light-duty vehicles do not differentiate between total hydrocarbons and non-methane hydrocarbons, a problem for natural gas vehicles.

The new heavy-duty regulations now recognise both natural gas and LPG engines, and a dynamic emission test will be required for these engine categories. Diesel engines without exhaust gas aftertreatment can meet the Euro 3 requirements (starting 2000), but the Euro 4 requirements for the year 2005 will definitely require aftertreatment devices for diesels. Especially the particulate emission limit, 0.02 g/kWh, is very strict. This might be a chance for natural gas engines, as the best gas engines of today can already meet the requirements for 2005 and 2008.

The US emission regulations form a jungle with numerous vehicle and fuel classes. A new Super Low Emission Vehicle class is present in California regulations for medium-duty vehicles, and is proposed for light-duty vehicles. New emission regulations for heavy-duty vehicles are proposed for the year 2004. The NMHC + NO_x value is 2.4 or 2.5 g/hph.

The regulated measurement of total particulate mass does not specify chemical composition of the particulate matter nor particulate size distribution. The health effects of ultra-fine particulates have been much discussed lately. New instrumentation to measure on-line particulate size distribution has been developed. In the future we will probably have regulations that specify more than just total particulate mass.

Today gas fuelled vehicles have reached a certain technical maturity. Natural gas vehicles are supplied by Original Equipment Manufacturers both for light- and heavy-duty applications. In 1998 there were 43 OEMs around the world producing over-the-road natural gas vehicles, 11 heavy-duty engine manufacturers producing natural gas engines and also a number of manufacturers producing a variety of off-road natural gas vehicles.

Included on the list of manufacturers supplying natural gas light-duty vehicles are BMW, Daimler-Chrysler, Fiat, Ford, Honda, Mitsubishi, Nissan, Toyota and Volvo.

The performance of an engine running on natural gas very much depends on the sophistication of the engine, and whether the engine is dedicated for natural gas or not. Normally power loss of some 10 % due to reduced fuel mixture energy density can be expected when switching from gasoline to natural gas in light-duty vehicles. In most cases there is power enough for satisfactory performance even when running on natural gas

Depending on the vehicle, one could estimate that a CNG vehicle consumes 0-10 % more energy than a gasoline vehicle. The overall emissions of greenhouse gases, however, are clearly lower when running on natural gas.

In less sophisticated engines, a fuel switch from gasoline to natural gas can lead to considerable emission reductions both relatively and absolutely.

With current technology the California ULEV limits are rather easily met using CNG both in the passenger car and light/medium-duty truck category. Methane is helpful in achieving very low NMHC and NMOG values, as methane normally accounts for more than 90 % of the hydrocarbons in the exhaust stream. With gasoline, the cold start enrichment makes a major contribution to the hydrocarbon emissions, and therefore it is more difficult (but not impossible) to meet the proposed SULEV NMOG limits on gasoline.

Some MY 2000 dedicated CNG vehicles are or will be SULEV certified. Included on this list are at least the Honda Civic passenger car, the Dodge Ram van, the Dodge Ram wagon, the Ford F-150 pick-up truck and the Ford 6.8 L F-350 & F-450.

Huge reductions in emissions have taken place due to improved vehicle technology. It is easy to understand that no major absolute emission reductions can be expected in advanced vehicles just by switching fuels. Compared to vehicles without catalytic aftertreatment, the SULEV vehicles come very close to "zero" emissions. However, regardless of the absolute emission level, natural gas can reduce both exhaust gas reactivity and toxicity.

Gaseous fuels are advantageous over gasoline regarding cold starts. Most of the dedicated engines perform very well at moderately low temperatures. Some bi-fuel vehicles, however, are designed in such a way that they always start up on gasoline, thus offering little emission benefit at lower ambient temperatures. Advanced bi-fuel vehicles with integrated computer systems, on the other hand, start well on CNG, and can provide just as low emissions as dedicated vehicles operating on CNG, retaining fuel flexibility in a market still limited in CNG refuelling infrastructure.

The supply of high-displacement gasoline engines is rather limited, with the exception of the North American market. Therefore gas engines for heavy-duty applications are mostly based on converted diesel engines. The biggest problems with heavy-duty automotive gas engines based on converted diesel engines are related to the control the thermal loads of the engine and to the control of the NO_x emissions. From engine durability point-of-view, lean-burn combustion is generally the preferred alternative, whereas stoichiometric combustion in combination with a TWC gives lower emissions and better driveability.

Major emission reductions can be expected, at least with present technology, going from diesel to gaseous fuel. The combustion of a homogeneous lean mixture in a gas engine results in lower NO_x emissions than diesel combustion, and with stoichiometric combustion there is the option to use TWC technology for ultra low emissions.

Independent of the combustion system, the fuel related particulate emissions from the burning of gaseous fuels are extremely low, the particulate emission originating almost solely from the lubricating oil. A gas engine which is not emission optimised, can have a much higher NO_x emission than a conventional diesel engine. The reported NO_x emission of current heavy-duty gas engines varies from some 0.5 to 3.5 g/kWh.

In Europe, there has been much discussion on the real-life emission performance of gas fuelled buses. This discussion originates from the fact that some gas engines, although they give very good emissions in steady-state emission testing, do not perform so very well in real transient driving conditions. The situation for Europe will change soon, as the new transient ETC test cycle will be required for gas engines starting with the new Euro 3 emission regulations. Some of the best available gas engines can already beat the diesel regarding NO_x emissions by a factor of more than 10 in real-life service. Key technologies for low emissions in transient driving conditions are multi-point fuel injection and closed-loop control systems. In the US, transient testing has been used already for a number of years.

The maximum efficiency of a spark-ignited gas engine is some 10-15 % lower (relative) compared to a good diesel engine. In real service, the energy consumption difference is higher, both due to reduced efficiency at partial loads and to increased vehicle weight. A qualified estimate is that the energy consumption of a heavy-duty vehicle will, in most applications, increase 20-35 % when switching from diesel to natural gas. Operational conditions and duty cycles have a major impact on the energy consumption.

The reduction of harmful exhaust emissions and greenhouse gases will continue to direct the technical development of fuels, engines, aftertreatment systems and complete vehicles. Natural gas will surely play a role in achieving these goals.

The best gasoline vehicles of today are extremely clean. In order to achieve corresponding emission levels, simple retrofit systems for gaseous fuels are not good enough. On markets with stringent emission legislation, future gas vehicles will most probably be sold through OEM networks.

Although the OBD requirement will be a big challenge for the alternative fuel vehicle sector, in the case of light-duty vehicles the engine technology itself is not the biggest obstacle for NGVs in achieving a significant market position. The best vehicles, both dedicated and bi-fuel vehicles, perform very well, they have enough power and they are extremely clean. In order to make the light-duty NGVs a success, more emphasis should perhaps be given to the design of the vehicle so that the fuel storage will not hamper the practicality of the vehicle. There are already examples on neatly designed CNG vehicles with fuel storage that does not take up any available passenger or luggage space. Another requirement is that the fuel should be readily available.

For fleet-operated heavy-duty vehicles the refuelling issue is easier to handle. However, in the case of heavy-duty vehicles the engine technology still needs some improvements. The ultimate goal is to have diesel-like efficiency and reliability.

Future diesel engines equipped with De-NO_x systems and/or particulate traps will be rather clean but much more complicated than the engines of today. The improved diesel engine might be a threat to the gas engine for emission performance. As some of the current gas engines already meet all foreseeable emission regulations, it can also mean that the heavy-duty gas engine becomes even more competitive than it is today.

In both light-duty and heavy-duty gas vehicles there is a trend towards more and more sophisticated fuel systems; ultimately to adaptive sequential multi-point fuel injection systems or even direct-injection systems. Accurate fuel metering is one of the most critical items for good emission performance, and for TWC systems, the strategy and software for controlling air/fuel ratio is critical to achieving high catalyst efficiencies.

There are very promising technologies available for natural gas vehicle applications. Most of the technical issues have been solved or will be solved in the near future. The task to get NGVs really going is really not a technical issue, but rather more a marketing issue. Work to building up adequate refuelling networks is also needed.

LIST OF SYMBOLS AND ABBREVIATIONS

SYMBOLS

λ	relative air-fuel ratio

ABBREVIATIONS AND CODES

A	Low C_3 content LPG reference fuel
AAMA	American Automobile Manufacturers' Association
ACEA	Association des Constructeurs Européens d'Automobile
ASTR	All States Trading Region
B	High C_3 content LPG reference fuel
BAT	Best Available Technology
BLPI	Berner Low-Pressure Impactor
BMEP	Brake Mean Effective Pressure
BTDC	Before Top Dead Centre (crank position)
BTX	Benzene, Toluene, Xylene
CA	Crank Angle
CAA	Clean Air Act
CARB	California Air Resources Board
CATP	Committee for Adaptation and Technical Progress
CFF	Clean Fuel Fleet
CFFV	Clean Fuel Fleet Vehicle
CFV	Clean Fuel Vehicle
CH_4	Methane
C_3H_8	Propane
C_4H_{10}	Butane
CLD	Chemiluminescent Detector
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CRT	Continuously Regenerating Trap
CVS	Constant Volume Sampler
De-NO_x	System for Nitrogen Oxide reduction in lean conditions
DF	Deterioration Factor
DI	Direct Injection
DME	Di-Methyl Ether
DNPH	Di-Nitro-Phenyl-Hydrazine
EC	European Community
ECE	Economic Commission for Europe, ECE test method
EEV	Environmentally Enhanced Vehicle
EGR	Exhaust Gas Recirculation
ELPI	Electric Low-Pressure Impactor
ELR	European Load Response Test

EMA	Engine Manufacturers' Association
ENGVA	European Natural Gas Vehicle Association
EOBD	European On-Board Diagnostics
EPA	Environmental Protection Agency
ESC	European Steady State Cycle
EU	European Union
EUDC	Extra Urban Driving Cycle
EURO	European Union test method/limit value
ETC	European Transient Cycle
EZEV	Equivalent Zero Emission Vehicle
FI	Fuel Injection
FID	Flame Ionisation Detector
FTIR	Fourier Transformation Infra-Red
FTP	(US) Federal Test Procedure
G_{20}, G_{23}, G_{25}	European reference natural gases for emission testing
GC	Gas Chromatograph
GFI	Gaseous Fuel Injection
GFP	Gaseous Fuel Prepared
GWP	Global Warming Potential
HC	Hydrocarbons
HD	Heavy-Duty
HDT	Heavy-Duty Transient
hph	horse power hour
HPLC	High Performance Liquid Chromatography
HWFET	Highway Fuel Economy Test
IANGV	International Association for Natural Gas Vehicles
IC	Intercooler, Intercooled
IDI	Indirect Injection (Diesel)
IEA	International Energy Agency
I & M	Inspection and Maintenance
JAMA	Japan Automobile Manufacturers' Association
JARI	Japan Automobile Research Institute
kWh	kilowatt hour
LB	Lean-Burn
LCA	Life Cycle Analysis
LEV	Low Emission Vehicle
LNG	Liquefied Natural Gas
LNT	Lean NO_x Trap
LPG	Liquefied Petroleum Gas
LT	Long term
M85	Methanol fuel containing 85 % methanol
MeOH	Methanol
MIL	Malfunction Indicator Light
MPFI	Multi Point Fuel Injection
mpg	miles per gallon (fuel economy)

MVEG	Motor Vehicle Emissions Group
MY	Model Year
N_2	Molecular nitrogen
NA	Naturally Aspirated
NGV	Natural Gas Vehicle
NLEV	National Low Emissions Vehicle Program
NMHC	Non-Methane Hydrocarbons
NMOG	Non-Methane Organic Gases
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxides
NSCR	Non-Selective Catalyst Reduction (i.e. TWC)
NTP	Normal Temperature and Pressure
NTR	North East Trading Region
OC	Oxidation Catalyst
OEM	Original Equipment Manufacturer
OBD	On-Board Diagnostics
OTAG	Ozone Transport Assessment Group
PAH	Polyaromatic Hydrocarbons
PCV	Positive Crankcase Ventilation
PIXE	Particle Induced X-Ray Emission
PM	Particulate Matter
Pt	Platinum
PUF	Polyurethane Foam
RFD	Reformulated Diesel Fuel
Rh	Rhodium
SCR	Selective Catalyst Reduction
SI	Spark Ignition
SM	Stoichiometric
SMPS	Scanning Mobility Particulate Sizer
SULEV	Super Ultra Low Emission Vehicle
TC	Turbocharger, Turbocharged
THC	Total Hydrocarbons
THT	Tetrahydrotiofen
TLEV	Transitional Low Emission Vehicle
TNO	TNO Road-Vehicles Research Institute (Holland)
TWC	Three-Way Catalyst
UBA	Umweltbundesamt (Federal Environmental Agency, Germany)
ULEV	Ultra Low Emission Vehicle
ULS	Ultra Low Sulphur (diesel fuel)
US	United States, US test method
VITO	Vlaamse Instelling voor Technologisch Onderzoek (Belgian Research Institute)
VTT	Technical Research Centre of Finland
XAD	Polymer resin for semivolatiles sampling (trade mark)
ZEV	Zero Emission Vehicle

1 OVERVIEW

Since the 1980s environmental issues have had a great impact on most human activities in the developed countries. Exhaust emission requirements are becoming more and more stringent. For gasoline-fuelled light-duty vehicles, many countries in the world have since the 1980s implemented regulations that in practice are met only by using three-way catalyst technology. In favourable conditions a three-way catalyst in conjunction with a closed-loop fuel system is capable of reducing the regulated exhaust emissions (carbon monoxide CO, unburned hydrocarbons HC, and nitrogen oxides NO_X) by more than 90 % compared to pre-catalyst vehicles /1,2/. Honda has presented a prototype gasoline vehicle, which is capable of achieving 1/10 of the US ULEV emission levels. The vehicle will go into closed-loop operation only 15 seconds after start, and this means that this vehicle is extremely clean although it runs on gasoline /3/.

Figure 1.1 shows the development of the European emission regulations for light-duty vehicles /4/.

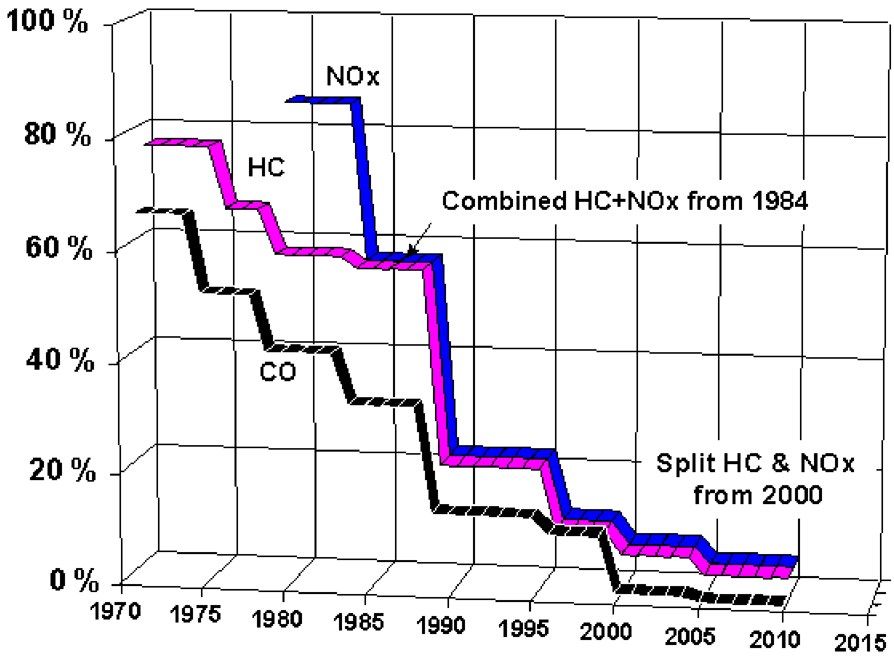

Figure 1.1. The development of European light-duty vehicle emission regulations /4/.

In the pre-catalyst age, switching from gasoline to a gaseous fuel often meant reduced exhaust emissions. Today, however, the engine management and the catalyst efficiency are totally decisive from the emissions point of view, whereas the fuel itself plays a minor role. This is especially true for the regulated emissions. If an advanced catalyst equipped gasoline vehicle is retrofitted to gaseous fuel without a comparable level of sophistication, it is probable that the emissions will increase rather than decrease.

On many markets, requirements for on-board diagnostic (OBD) systems are emerging /5/. This will in practice mean that in the future the alternative fuel systems have to work seamlessly together with the vehicle's own engine management system. If alternative fuel technology relies on exemptions, it will probably be on the wrong route. To secure the future, the alternative fuel technology has, after a certain lead time, to be as good and advanced as the conventional fuel technology.

The conventional diesel engine is very energy efficient and reliable. For these reasons, the direct injection diesel engine is currently almost the only power unit used in heavy-duty vehicles. The conventional diesel engine is, however, facing difficulties in meeting increasingly stringent emission regulations. There is no technology available for the diesel engine that could cut emissions of all major components to the same extent as the three-way catalyst does for gasoline engines. The most important pollutants of the diesel engine are particulates, nitrogen oxides and hydrocarbons.

As the gasoline vehicle population is getting cleaner, the relative share and importance of heavy-duty diesel vehicle emissions are increasing. This is especially true in urban conditions. Diesel emissions can be reduced by engine /6/, fuel system /7/ and fuel modifications /8,9/ and by using exhaust aftertreatment /10,11/. In Europe, the limit values for the regulated emissions were cut by more than 50 % from 1985 to 1995 /12/.

In the Nordic countries, high quality, practically sulphur-free reformulated diesel fuel is already widely used /13/. The European Union has agreed to introduce practically sulphur free diesel for the whole Community by the year 2005 /14/. Reformulated diesel can, to some extent, reduce the regulated emissions of both old and new engines. More importantly, however, reformulated diesel fuel reduces the toxicity of diesel exhaust substantially /8/. The practically sulphur-free fuel also makes it possible to apply exhaust aftertreatment, the most common option being an oxidising catalyst.

For some special applications, i.e. city buses, refuse and delivery trucks, alternatives other than the conventional diesel engine are under consideration /15/. Over the last 20 years the main driving force behind the promotion of alternative motor fuels has shifted from oil substitution to improving urban air quality.

By substituting the conventional diesel by an advanced engine capable of burning alternative fuels such as alcohols or gaseous fuels, exhaust emissions and exhaust toxicity can be lowered substantially. In this sector the gaseous fuels are clear market leaders compared to other alternatives.

Gaseous fuels like methane, propane and butane are inherently clean-burning fuels, which in favourable conditions give a soot-free combustion and less harmful exhaust components than conventional liquid hydrocarbon fuels /16/. However, to achieve low overall exhaust emissions, advanced engine technologies and control systems have to be applied /17/. Engines which work well in steady-state (i.e. ECE R49) emission testing do not necessarily perform so well in real life service /18/.

Most heavy-duty gas engines are diesel engines converted to spark-ignition Otto cycle engines. Low engine efficiency and for some gas engines also low power output is a problem. In normal service, gas engines can consume 25-35 % more energy than their diesel counterparts. In order to overcome the efficiency deficit, engine manufacturers are working towards lean-burn combustion, higher specific power output and some special turbocharging and fuel injection systems /19/. New engine technologies and electronics like variable valve timing, skip-fire etc. can help to enhance the performance of gas engines /20/.

In many applications, natural gas can contribute to the reduction of toxic automotive emissions. However, there is also the aspect of general energy use and greenhouse gas emissions. International agreements like the Kyoto agreement have been signed to stop the growth of greenhouse gas emissions. The general perception is that the gas resources are more extensive than the known oil resources. From the viewpoint of sustainable development the societies should seek for energy solutions which combine energy diversification, low greenhouse gas emissions and also low toxicity.

In these respects natural gas is an attractive alternative also in the transportation sector. In gasoline fuelled cars substantial carbon dioxide reductions can be achieved by switching to natural gas, and as the technology for heavy-duty engines improves, we might see a reduction potential in this sector, too. The vehicle population and general energy use is growing fast in developing countries. As natural gas is a clean burning fuel, this fuel is a good option in vehicles which do not have sophisticated exhaust gas aftertreatment systems.

Figure 1.2 shows two energy demand scenarios, "sustained growth" and "dematerialization". In both cases, natural gas is projected to cover a substantial part of the energy demand in the time frame 2000-2060.

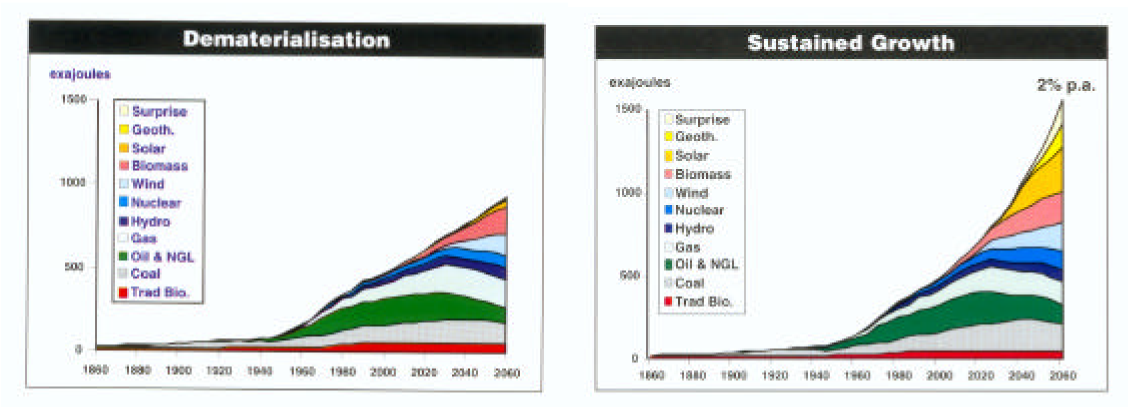

Figure 1.2. Energy scenarios by Shell International /21/.

This report aims at documenting the emission benefits, with emphasis on harmful and poisonous emissions, of natural gas as an automotive fuel. There are numerous benefits which originate from the simple chemical structure of methane, the main constituent of natural gas. The most important feature is that emissions from natural gas fuelled vehicles are less noxious than the exhaust emissions from gasoline and diesel vehicles. The unburned hydrocarbons in the exhaust of a natural gas fuelled vehicle consist mainly of methane, and therefore one can expect that natural gas exhaust would be less harmful to human health compared to gasoline or diesel exhaust.

Natural gas can be used as an automotive fuel as such. Normally the gas is stored under pressure as CNG (Compressed Natural Gas). Liquefied natural gas (LNG) and biogas are viable options to CNG. The use of LNG solves the problem of bulky fuel storage and restricted vehicle operating range. Biogas collected from waste treatment facilities can be purified and used as CNG. This means that natural gas vehicles can also be run on a fuel, which originates from renewable sources.

Natural gas can also serve as a feedstock for a number of different fuels, i.e. methanol, DME (di-methyl ether) and synthetic diesel fuel (Fischer-Tropsch diesel). Synthetic diesel fuel would, from an end-point of view, be the easiest way to use natural gas in transportation, as no modifications to the existing diesel vehicle fleet or to the existing refuelling infrastructure would be required.

DME, a gaseous fuel with similar physical properties to LPG (Liquefied Petroleum Gas), has good ignition properties, and can thus be used in diesel cycle engines. DME has clear emission advantages over conventional diesel fuels. DME, however, requires major modifications to the engine, fuel storage and distribution systems.

Hereafter, only the conventional use of natural gas as a transportation fuel, i.e. the direct use of natural gas as the fuel, will be covered. Focus will be on CNG applications, as from an engine point of view in current fuel systems both CNG and LNG are delivered to the engine in gaseous form. Some of the comments on on-board fuel storage are relevant to CNG only.

The technology of gas fuelled vehicles has still to be enhanced. The auto manufacturers have put in a lot of effort to develop and refine gasoline and diesel fuelled vehicles. Compared to this, the amount of work on natural gas fuelled vehicles is so far rather limited. As a result, at least in the past, most of the natural gas vehicles were not so very sophisticated. Most of the light-duty vehicles are actually bi-fuel solutions, which are not optimised for natural gas. However, some recent bi-fuel models with integrated computer systems are now optimised on natural gas as well as on gasoline, with excellent emissions on both fuels. This is an emerging trend for all OEMs offering bi-fuel vehicles.

The heavy-duty gas engines are mainly converted diesel engines, not engines designed especially for gas. Thus, at this stage, there is still room for technical improvements to enhance the emission performance, efficiency and also to some extent the reliability of natural gas fuelled engines and vehicles.

Ultimately, when the level of technical sophistication of gas engines is at the same level as for the conventional technologies, natural gas engines should have clear advantages from an environmental point of view over conventional fuels.