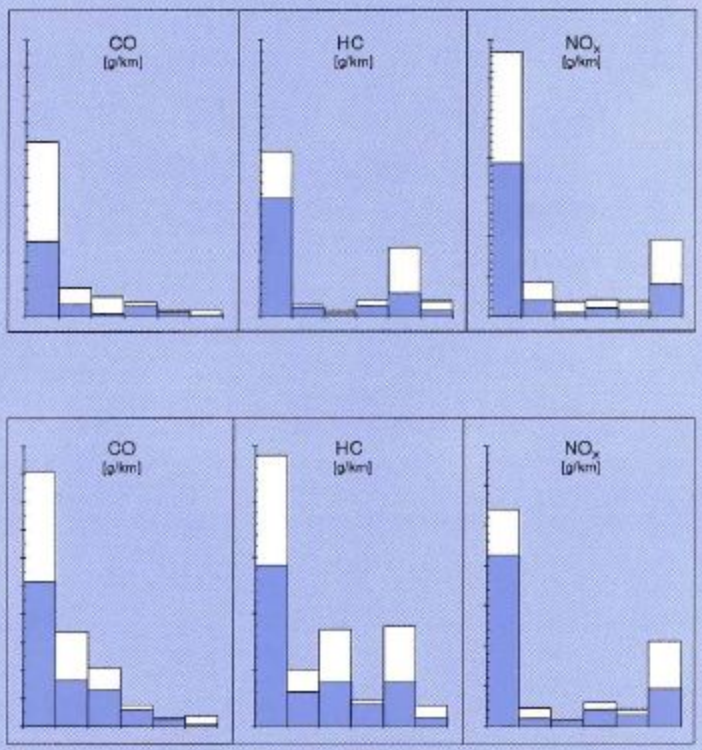
VTT PUBLICATIONS

271

# Performance evaluation of alternative fuel/engine concepts 1990–1995

## Final report including addendum of diesel vehicles




TECHNICAL RESEARCH CENTRE OF FINLAND
ESPOO 1996

IEA International Energy Agency

Alternative Motor Fuels
Annex V

VTT PUBLICATIONS 271

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## Final report including addendum of diesel vehicles

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VTT Energy

TECHNICAL RESEARCH CENTRE OF FINLAND
ESPOO 1996

ISBN 951–38–4929–5
ISSN 1235–0621


JULKAISIJA – UTGIVARE – PUBLISHER

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Technical editing Leena Ukskoski

VTT OFFSETPAINO, ESPOO 1996

Nylund, Nils-Olof, Ikonen, Markku, Kytö, Matti, Lappi, Maija, Westerholm, Mårten & Laurikko, Juhani. Performance evaluation of alternative fuel/engine concepts. 1990–1995. Final report including addendum of diesel vehicles. Espoo 1996, Technical Research Centre of Finland, VTT Publications 271. 120 p. + app. 16 p.

**UDC** 662.6/.8:621.436:53.083

**Keywords** fuels, substitutes, utilization, energy, performance, evaluation, motors, diesel engines, vehicles, tests, emissions, exhaust gases, measurement

## ABSTRACT

Annex V, "Performance evaluation of alternative fuel/engine concepts" within the IEA Agreement on Alternative Motor Fuels, is the first subtask to generate new experimental data. The objective of the task is to generate information on the true emission potential of alternative fuel concepts in severe operating conditions and to evaluate new emission measurement methods. The work was carried out in three phases, Part One: Engine Tests (1990-1993), Part Two: Light-Duty Vehicle Tests (1993-1994) and Part Three: Addendum of Diesel Vehicles (1995). The work was carried out at VTT (Technical Research Centre of Finland) as a cost shared operation. Participants were Belgium (Parts Two and Three), Canada (Parts One and Two), Finland, Italy (Part One), Japan, the Netherlands, Sweden and USA. The United Kingdom also joined at the end of the Annex.

### PART ONE: ENGINE TESTS

Three engines, one using gasoline, one using gaseous fuels and one using M85, were tested for regulated and unregulated exhaust emissions within the temperature range from +20 to -7 °C. Some tests were also carried out at -20 °C. All engines were equipped with a closed-loop fuel system and a three-way catalyst (TWC). The tests were conducted as engine tests. Test duration was 30 minutes. The engines were connected to a normal CVS type exhaust sampling system. The overall emission of regulated components was determined by diluted bag sampling. In addition, exhaust gas compositions before and after the catalyst were monitored continuously with a dual-bench analyzer system.

All engines gave roughly the same level of regulated pollutants at +20 °C. In the cases of LPG and CNG the emissions of CO and HC were more or less unaffected by test temperature. Lowering the test temperature from +20 to -7 °C increased the CO and HC emissions of the gasoline engine by a factor of 3 to 5. On M85 lowering of the test temperature from +20 to -7 °C increased the CO emission by a factor of 12 and the HC emission by a factor of 5. The specific CO emission expressed as g/kWh for the M85 engine was thus 5 to 20 times higher than for the engine fueled with LPG and CNG at -7 °C. Cold starting was also difficult with alcohol fuel.

The unregulated emissions were measured over the first part of the test cycle (15 minutes). For the gasoline engine the combined emission of the harmful unregulated components measured varied from 1 to 9 g/kWh depending on the test temperature. Among these unregulated emissions, the dominating components were aromatic hydrocarbons. The gaseous fuels gave by far the lowest emission of harmful components, appr. 0.3 g/kWh for LPG and only 0.025 g/kWh for CNG independent of test temperature. The emission level of harmful unregulated components varied from 3 to 22 g/kWh for the M85 engine, with unburned methanol being the dominating component in this group. Thus, the differences in unregulated emissions are even greater than the differences in regulated emissions with the different fuels.

The tests proved that both fuel and test temperature have a major impact on regulated and unregulated emissions. CNG gave by far the lowest total emissions, and the emissions were almost independent of temperature. LPG also gave very good results. The gasoline engine performed reasonably well, but for this fuel the temperature has a relatively strong influence on both regulated and unregulated emissions. The gasoline engine was the only engine to start and operate without any problems at -20 °C.

The M85 engine had low emissions of regulated emission components at +20 °C. The emission level of formaldehyde and methanol, however, was high. Furthermore, the emission performance deteriorated dramatically at ±0 °C. These results indicate very clearly that low-temperature emission performance should be included in the evaluation work on alternative fuels.

## PART TWO: VEHICLE TESTS

In Part Two, which was a direct continuation of Part One, eleven light duty vehicles were run on a chassis dynamometer and both regulated and unregulated emission components were measured. The fuels included were hydrocarbon gasoline, oxygenated gasolines, ethanol blend (E85), methanol blends (M0, M50, M85), LPG and CNG. Test temperatures were +22, +7, ±0, -7 and for gasoline also -20 °C. The number of combinations of vehicles/fuels/temperatures tested was 112, and including duplications the total number of US FTP75 type emission tests conducted was about 140. Included were 4 gasoline vehicles, 4 FFV's and 3 vehicles on gaseous fuels. The alternative fuel vehicles included both prototype and commercial vehicles.

The most efficient way to reduce emissions from vehicles equipped with Otto type engines is to introduce three way catalyst technology. In normal ambient temperatures TWC technology will reduce emissions some 80...90 %. The emission reductions that can be achieved by switching to an alternative fuel are in general smaller than those found when going from a non-catalyst vehicle to a TWC vehicle. The differences between all fuel alternatives using TWC technology are rather limited. The emissions of CO are clearly reduced with alternative fuels, especially with gaseous fuels. Natural gas gives the highest total HC emissions, but most of this is non-toxic methane. Three of the four flexible fuel vehicles (FFV's) tested in Part Two also performed rather well at -7 °C, and gave in general lower emission results than gasoline. One prototype vehicle equipped with an electrically heated catalyst gave extremely low emissions at normal ambient temperature. However, this vehicle did not start at -7 °C on M85.

Also, in the case of unregulated emissions the biggest improvements in emissions can be achieved by switching over to catalyst technology. However, the emissions of 1,3-butadiene and benzene are reduced at all temperatures using alternative fuels instead of gasoline. The formaldehyde emission values of the FFV's at +22 °C were on average below the LEV limit values set by California. The formaldehyde emissions of the FFV's were some two times higher compared to the gasoline vehicles at +22 °C, and the difference increased with falling temperature. The emissions of unburned methanol were moderate to very high, ranging from 30 to 1600 mg/km depending on vehicle and temperature.

As in Part One, the engines on gaseous fuels gave by far the lowest overall emissions, both regulated and unregulated. The vehicles tested had up-to-date gaseous fuel injection systems, and the emissions were almost independent of temperature. The total HC emissions of the CNG vehicles were high, but 90 % of the total HC value was methane.

It was anticipated when starting Annex V that alcohol fueled vehicles would have very high low-temperature CO and HC emissions. Such a conclusion could also be drawn from the results of Part One, Engine Tests. However, the FFV's tested for Part Two showed equal or even better regulated emission performance compared to gasoline vehicles at all temperatures.

In addition to formaldehyde, unburned methanol is a problem with M85 particularly at low temperatures. A value of 1600 mg/km must be considered unacceptable. The emission of both formaldehyde and unburned methanol can be controlled with proper engine management and catalyst technology. To measure only CO emissions at -7 °C does not give a true picture of the emissions of FFV's at low temperature, formaldehyde and methanol should also be included.

Today's advanced gasoline vehicles must be considered rather clean. M85 can give lower emissions in warm conditions, but the emission of unburned methanol must be controlled. Natural gas and LPG are inherently clean fuels, which, using up-to-date engine technology, give low emissions in all conditions.

## PART THREE: ADDENDUM OF DIESEL VEHICLES

In Part Three the same kind of test procedure as in part two was performed for three light-duty diesel vehicles. All three test vehicles had a different engine configuration, even though they all shared the same 1.9-liter engine block. The test matrix consisted of three fuels which were conventional diesel fuel, reformulated sulphur-free diesel fuel and a blend of rapeseed methyl ester/reformulated diesel. The temperatures used were +22, ±0, and -7 °C. Also -20 °C was used for the reformulated fuel. Both regulated and unregulated gaseous emission components were measured like in Part Two using modern analyzing technology.

Additional measurements performed for Part Three were the total particulate mass determination and also PAH analysis from both the semivolatile and the particulate phases. The semivolatile and particulate phase emissions were measured from one of the three vehicles. One gasoline TWC vehicle and one FFV vehicle were used as reference for these measurements.

The results showed, that the CO and total HC emissions from a modern diesel engine are comparable to TWC gasoline engine at normal temperature. When the temperature is lowered, diesel vehicles gives lower CO and HC emissions than TWC gasoline vehicles. The most problematic emission components from diesel vehicles are $NO_x$, particulates and aldehydes.

# PREFACE

The implementation of alternative and reformulated fuels is a way to reduce exhaust emissions. Most of the data on exhaust emissions from alternative fuels, however, has been generated in mild environmental conditions.

The objective of IEA Alternative Motor Fuels Annex V, "Performance evaluation of alternative fuel/engine concepts," is to generate data on the emission potential of different alternative fuels in severe operating conditions. In most cases, emissions will increase dramatically with falling temperature. Annex V is the first Annex within the IEA agreement on "Alternative Motor Fuels" to generate new experimental data.

In the first part of Annex V, "Engine tests", three engines on different fuels were tested for exhaust emissions within the temperature range of +20 to -20 °C. The differences in emissions between the different concepts at low temperatures were considerable. New emission measurement technologies were used to measure unregulated pollutants on-line.

Part Two, "Cold start and unregulated emissions from light-duty vehicles", was a direct continuation of the previous work. The testing was carried out on a chassis dynamometer using the FTP 75 test cycle. Eleven different vehicles, both commercial and prototype vehicles, were run on different fuels at different temperatures to evaluate both regulated and unregulated emissions. Over 100 vehicle/fuel/temperature combinations were investigated. Fuels included were different types of gasolines, methanol and ethanol at different concentrations in gasoline, LPG and CNG. The second phase verified the results on the first one, ie. there are significant differences in both low-temperature performance and unregulated pollutants for the different fuels.

In Part Three, "Addendum of Diesel Vehicles", the same methodology as in Part Two was used. Three diesel vehicle configurations were measured using three fuels at 3...4 temperatures.

The tests were carried out at Technical Research Centre of Finland (VTT). Finland was also the Operating Country for this task. In Finland both the Ministry of Trade and Industry and Neste Oy supported the task financially. Other participants in this task were Belgium (Parts Two and Three), Canada (Parts One and Two), Italy (Part One), Japan, the Netherlands, Sweden and USA.

The people at VTT responsible for the work would like to thank all representatives of the other participating parties for their strong support to the execution of the task. A special aknowledgement goes to Dr. Ralph McGill of Oak Ridge National Laboratory, who arranged the methanol test engine for VTT for Part One. Oak Ridge National Laboratory also reviewed this report carefully. We also want to thank TNO in Holland for the two retrofitted vehicles on gaseous fuels tested in Part Two, which they prepared and shipped to VTT.

Technical Research Centre of Finland
Espoo, Finland
February 1996

# CONTENTS

## PART TWO: VEHICLE TESTS



## PART THREE: ADDENDUM OF DIESEL VEHICLES



## APPENDICES

# BACKGROUND

# 1. ACTIVITIES WITHIN IEA

The "Implementing Agreement for a Programme of Research, Development and Demonstration on Alcohol and Alcohols Blends as Motor Fuels" under the "Working Party on Energy End-Use Technologies" was signed in 1984. It was stated that the work within this agreement should consist of cooperative research, development, demonstrations and exchanges of information regarding alcohol and alcohol blends as motor fuels. In 1990 the name of the agreement was changed into "Alternative Motor Fuels", so that other alternatives like gaseous fuels could be included. The work within the agreement is carried out in subprojects, so-called "Annexes". The Annexes of the agreement are listed in Table 1 (status September 1994). Additional Annexes are under discussion.

This report is the final report of Annex V (Performance Evaluation of Alternative Fuel/Engine Concepts) The Annex consists of two parts, which are Part One: Engine tests and Part Two: Vehicle tests ("Cold start and unregulated emissions from light-duty vehicles"). Annex V is the first Annex with the agreement on Alternative Motor Fuels to generate new experimental data.

Table 1. Annexes of IEA Alternative Motor Fuels.

| No | Title | Duration | Status | Participants |
|---|---|---|---|---|
| 1 | Alcohols as Motor Fuels | 84-86 | comp-leted | CDN, NZ, S, USA, J |
| 2 | Technology Information Exchange | 86-92 | comp-leted | CDN, FIN, I, J, NZ, S, USA |
| 3 | Alcohol Diesel Field Trials | 87-91 | comp-leted | CDN, I, J, S, USA |
| 4 | Production of Alcohols | 87-92 | comp-leted | CDN, I, J, NZ, S, USA |
| 5 | Performance Evaluation of Alternative Fuel/Engine Concepts | 90-94 | comp-leted | B*), CDN, FIN, I**), J, NL, S, USA |
| 6 | Natural Gas as Motor Fuel | 90-92 | comp-leted | CDN, FIN, I, J, S, USA |
| 7 | Comparison of Relative Environmental Impacts of Alternative and Conven-tional Motor Fuels | 92-95 | active | B, CDN, FIN, I, J, NL, S, USA |
| 8 | Heavy-duty vehicles and engines using alternative motor fuels | 94-98 | active | B, CDN, FIN, NL, S, UK, USA |

*) Part Two **) Part One

## 2. GENERAL ALTERNATIVE FUEL SITUATION

Environmental issues and the desire to make the fuel supply system less dependent on crude oil have lead to widespread research and development programs on alternative fuels. Alcohols, methanol and ethanol are viable fuel options. In particular, M85 fuel, containing 85 % methanol and 15 % hydrocarbons, is undergoing wide field testing involving numerous FFV-vehicles (fuel-flexible vehicles) in the USA.

Vehicles using gaseous fuels (natural gas and LPG) have a long history all around the world. The main reason for using gaseous fuels has been low fuel price and therefore low operating costs. Also these fuels have environmental benefits compared to conventional liquid fuels, and the technology for low-emission gas fueled vehicles is emerging.

It is generally claimed that alternative fuels will reduce both regulated (carbon monoxide CO, total hydrocarbons HC, nitrogen oxides $NO_x$, particulates) and unregulated exhaust emissions. It is relatively well demonstrated that CO, HC and $NO_x$ emissions can be reduced with alcohol fuels in spark-ignition engines. On gaseous fuels reductions of CO and HC emissions can be expected in spark-ignition engines without a closed-loop fuel system and a three-way-catalyst (TWC). In cars equipped with TWC-technology the benefits in switching from gasoline to gaseous fuels are, however, relatively limited. This is due to the fact that fuel systems for gaseous fuels have not yet reached the same level of technical sophistication as the gasoline injection systems.

The group of compounds called 'unregulated' contains both toxic and reactive components. The first unregulated component to become regulated is formaldehyde in the Californian emission regulations (0.015 g/mile) /1/. The five most important air toxics components from mobile sources listed by US Environmental Protection Agency EPA are /2/:

* benzene ($C_6H_6$)
* 1,3-butadiene ($C_4H_6$)
* polycyclic organic matter (POM)
* formaldehyde (HCHO)
* acetaldehyde ($CH_3CHO$)

Benzene is considered to cause around 50 % of the motor vehicle induced cancer cases, and 1,3-butadiene around 30 % /3/.

The most reactive ozone precursors are light olefines and substituted benzenes /4/. 1,3-butadiene has the highest reactivity. Also formaldehyde has high reactivity.

In general, alternative fuels should reduce toxic and reactive emissions, because most of the alternative fuels are explicitly defined, chemically simple compounds. They do not contain aromatic hydrocarbons (with the possible exception of M85 type fuels), and should burn with significantly lower soot formation. The emission of partially and unburned fuel should be less harmful to people and less reactive compared to conventional liquid fuels.

With alcohol, however, the emission of unburned alcohol and aldehydes can be a problem and efficient catalyst technology is needed to control these emissions. Natural gas produces mainly unreacted methane ($CH_4$). Table 2 gives an example on emission rates (mg/mile) for selected emission components for different methanol fuels.

Table 2. Selected component emission rates (mg/mile) for methanol fuels /5/.

| Component/fuel | M0 | M15 | M50 | M85 | M100 |
|---|---|---|---|---|---|
| methane | 36.2 | 15.6 | 20.4 | 13.6 | 2.4 |
| ethylene | 13.9 | 14.7 | 12.0 | 5.0 | 0.7 |
| propylene | 10.7 | 10.0 | 7.8 | 2.5 | 0.8 |
| isobutylene | 8.5 | 7.5 | 6.1 | 1.6 | 0.3 |
| formaldehyde | 7.2 | 11.1 | 16.8 | 36.7 | 40.2 |
| benzene | 9.6 | 8.3 | 7.9 | 2.0 | 0.9 |
| 1,3-butadiene | 0.9 | 1.3 | 1.0 | 0.4 | 0.3 |
| iso-octane | 21.0 | 19.2 | 16.3 | 3.4 | 0 |
| methanol | 1.2 | 38.2 | 106 | 215 | 761 |
| pentane | 6.7 | 6.7 | 4.5 | 1.2 | 0 |
| isopentane | 8.0 | 19.9 | 6.5 | 2.2 | 0 |
| toluene | 33.6 | 28.8 | 24.9 | 5.0 | 0 |
| total HC | 229 | 210 | 172 | 50.6 | 9.4 |
| organic carbon | 233 | 232 | 226 | 161 | 358 |

The Auto/Oil Air Quality Research Program (AQIRP) has published data for 10 prototype FFV/VFV vehicles /6/. Although these vehicles were prototypes, and might differ considerably from coming production models, the results give valuable information on the effect of the fuel on the emissions. Compared to gasoline, the $NO_x$ emissions were increased 23 % and CO and HC emissions were reduced by 31 and 40 % respectively with M85. The total emissions of toxic components were lower with M85, although the emission of formaldehyde increased considerably. All vehicles were equipped with a close-loop controlled TWC.

Since Annex V was initiated (1989), the situation regarding alternative fuels has changed considerably. Several manufacturers have launched FFV's on the market for the US, and there are also some dedicated light-duty CNG-vehicles available. The technology for using gaseous fuels in light-duty vehicles has improved considerably, and now there are several advanced fuel systems available (gaseous fuel injection).

Reformulated gasoline is now on the market in the US and in Europe. Proposals on tax exemptions for biofuels and biocomponents within the European Community can lead to the widespread use of ethanol and ethanol derived gasoline components. The use of ethanol as a gasoline component (E10) is widespread in the US.

Also emission regulations have changed. The limit values are becoming more stringent both in the US and in Europe. In US, an additional low temperature test (-7 °C = 20 °F) has been introduced in 1994 to reduce cold condition carbon monoxide emissions. In the US, the use of oxygenated gasoline is mandatory in wintertime in some parts of the country beginning 1992. This aims at the reduction of carbon monoxide emissions. Reformulated gasoline will be introduced in some areas to reduce ozone formation beginning 1995.

The latest overviews of alcohol fuel technology and field experience were presented at the Tenth International Symposium on Alcohol Fuels in Colorado Springs, Colorado November 1993 /7/.

## 3. EXHAUST EMISSION MEASUREMENTS

The most commonly used emission test procedure for light-duty vehicles is the US Federal Test Procedure (US FTP) /8/. The test is performed with a vehicle on a chassis dynamometer. The exhaust is diluted in a CVS (Constant Volume Sampler) device. The test consists of three phases (cold transient, hot stabilized and hot transient). For each phase a diluted exhaust sample is collected in a Tedlar bag. After the test has been completed, each sample bag is analyzed, and a composite result of the three phases is calculated. The standardized test temperature is 68...86 F, which corresponds to 20 . . . 30 °C.

The standardized emission tests were originally designed to evaluate different vehicle concepts using a specified reference fuel. However, the tests can also be used to study fuel effects on emissions. In this case, it should be recognized that there are some limitations in the calibration and calculation procedures developed for pure hydrocarbon fuels.

The FTP test procedure offers the opportunity to study regulated gaseous emissions for each of the three phases separately. In addition, it is relatively simple to perform on-line measurement of CO, HC and $NO_x$.

Measurements of unregulated components and the speciation of hydrocarbons are normally done from bag samples using gas chromatography (GC). Alcohols are collected in water-filled impingers and analyzed by GC. Aldehydes are collected in DNPH-liquid impingers or -adsorption cartridges, and analyzed using high pressure liquid chromatography (HPLC) /9/.

All these techniques need a relatively long sampling time, and they are therefore not suited for transient measurements. During the last two years new Fourier Transformation Infrared (FTIR)-analyzers have emerged, which make it possible to measure several unregulated components on-line /10/. Another example on an on-line measurement system is the continuous formaldehyde measurement system based on second order derivative spectrophotometry developed by Mori et.al. /11/.

Heavier, semivolatile polyaromatic compounds (PAC) need a special sampling system, in which the sample is collected in polyurethane foam (PUF) /9/. Biological and mutagenic effects of the exhaust can be studied with the AMES-tests based on *Salmonella* bacteria. These tests can be carried out both on the semivolatile and the particulate phase of the exhaust. Even spark-ignited engines can emit significant amounts of particulates especially in cold conditions running on extremely rich mixtures.

For alternative fuels there is a lot of data available on the emissions of both regulated and unregulated components at normal ambient temperatures. However, for low temperature conditions, there is little data on regulated emissions and even less data on the emission of unregulated components. We have not been able to find any published data from on-line measurements of unregulated components at low temperatures with alternative fuels.

# 4. THE EFFECT OF COLD START ON EMISSIONS

## 4.1 Theoretical considerations

The key factor in the cold starting process is the ratio between air and fuel in the gaseous phase. This is because combustion can be initiated only when fuel is evaporated. The overall supplied air/fuel ratio is of secondary importance, since much of the liquid fuel will not evaporate in a cold engine.

According to Quader /12/, the equivalence ratio in terms of evaporated fuel and air needed to start an engine is almost independent of the ambient temperature. In tests that were carried out with a single-cylinder engine in the temperature range of -29...+21 °C, the supply equivalence ratio (inverse of lambda-value) varied between 5.6 and 1.1. The calculated equivalence ratio for vaporized gasoline, on the other hand, varied only between 0.85 and 1.1 (Figure 1). The cold start will be successful when enough fuel is vaporized in one way or another (if the spark plugs are not fouled). Increasing the cranking speed of the engine alone will facilitate the fuel evaporation and the startup. When using gasoline, the supply equivalence ratio can be leaned out soon after start, and a slightly rich mixture is enough to keep the engine running.

Quader has also carried out cold start tests with propane. The engine could be started with a slightly lean mixture (equivalence ratio 0.7) independent of the test temperature (Figure 2). As the ratio between vaporized fuel and air needed to start the engine is independent of temperature both with gasoline and propane, this should also be true for other fuels.

Diesel engine behaves differently. In the diesel process, the combustion process always takes place with excess air in the combustion chamber. This means that with the diesel engine there is no enrichment needed like in spark ignited engines when the engine is cold. However, when cold, the amount of fuel sprayed into the engine is somewhat greater than when the engine is warm. This leads only to slight increase in emissions (mostly hydrocarbons and white smoke).

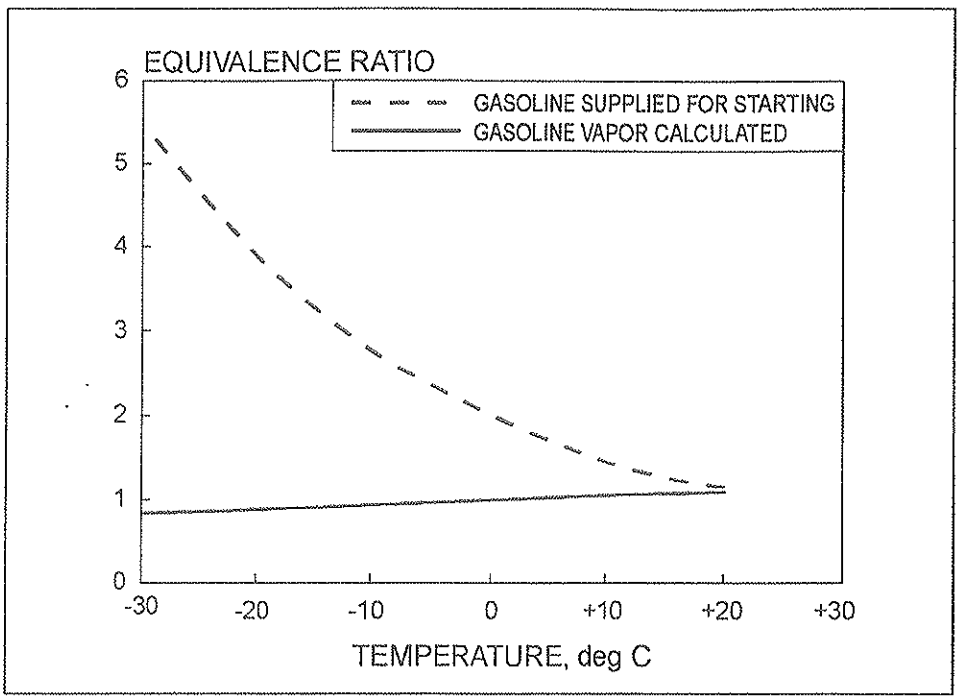



Figure 1. Supply fuel/air ratio and calculated vaporized fuel/air ratio needed to start a single-cylinder test engine on gasoline as function of ambient temperature /12/.

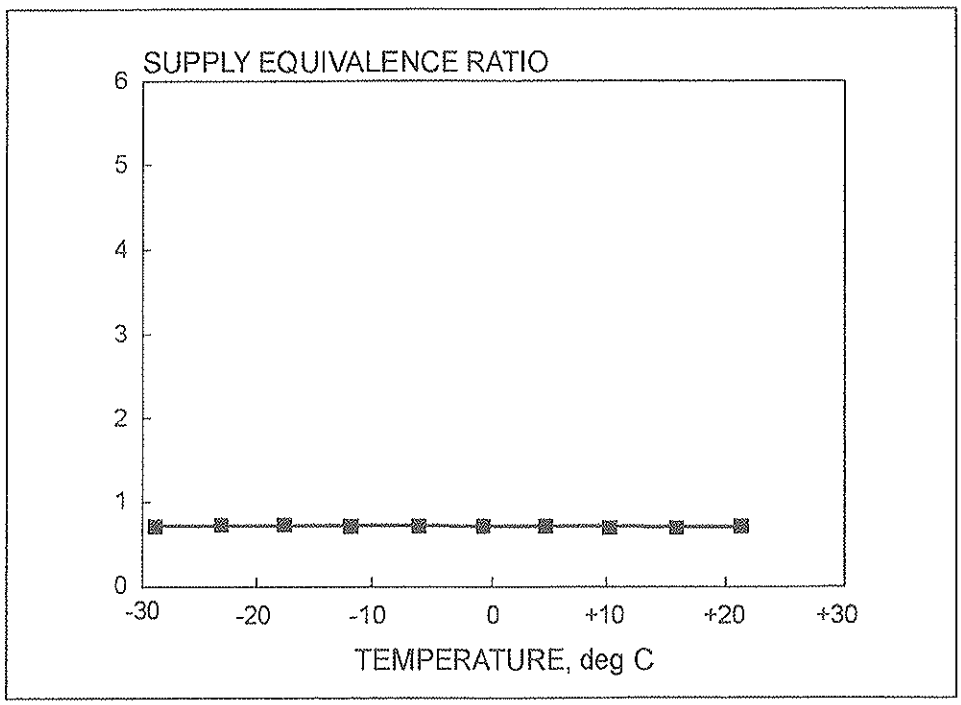



Figure 2. Supply fuel/air ratio needed for start with propane as a function of ambient temperature /12/.

## 4.2 Vehicle tests

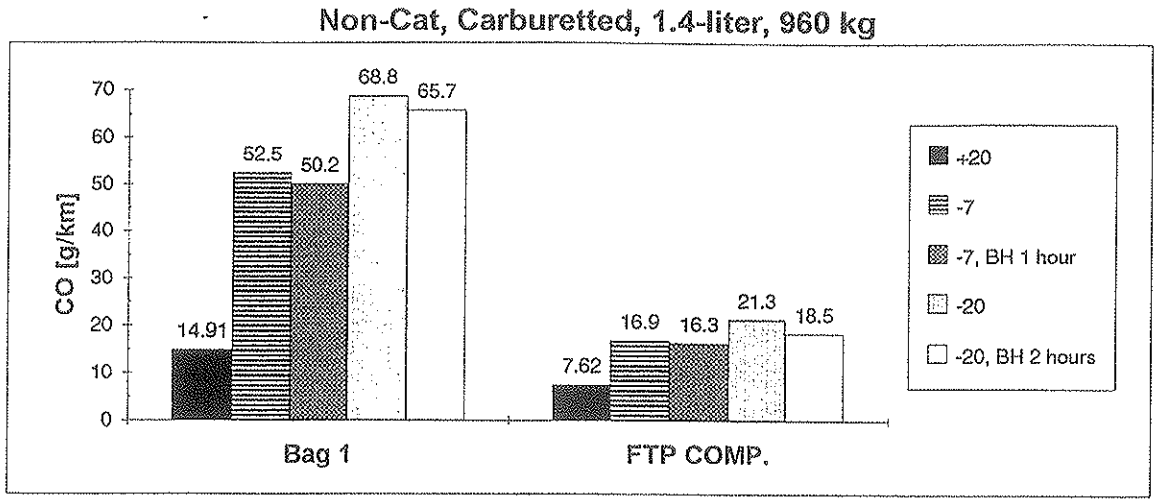
At the Technical Research Centre of Finland (VTT) several emission tests at low ambient temperature have been carried out with different gasoline fueled cars. With gasoline, temperature has a strong influence on emissions (Figures 3 & 4). For a TWC-equipped car the composite FTP result for both CO and HC will typically increase by a factor of 5...10 when the test temperature is lowered from +20 to -20 °C.

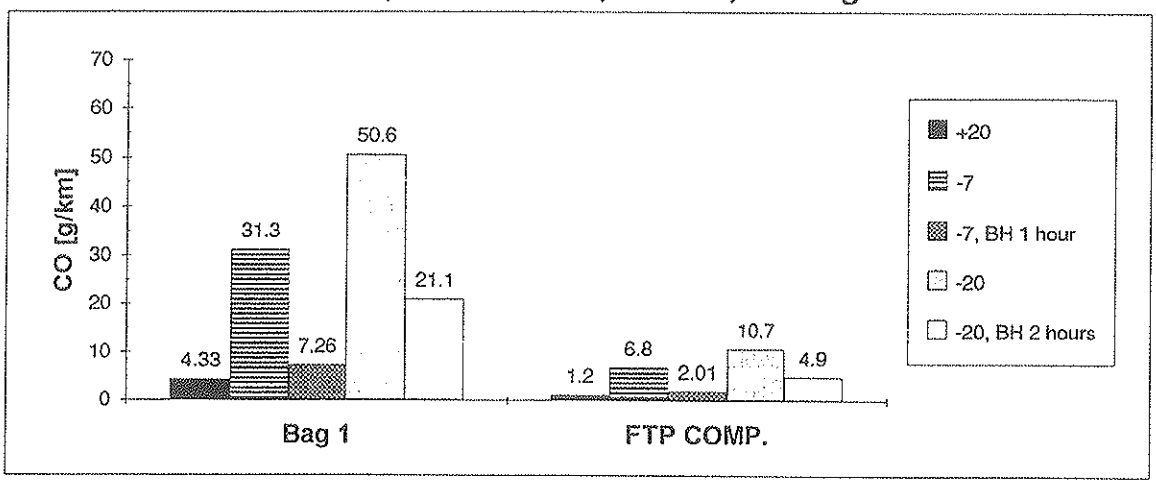
The relative impact of temperature on emissions is considerably smaller with a carburetted car. In this case CO and HC emissions increase only by a factor of 2...3. For a non-catalyst car, the absolute emission level is, however, much higher than for TWC-equipped cars. For both car categories, the test temperature influences mainly the emissions of phase 1 on the FTP-test (the first 505 seconds) /13/.

Tests at VTT have demonstrated that generally the enrichment strategy, not the warming-up and the temperature of the catalyst, determines the low-temperature emissions of a TWC-equipped car. Figure 5 shows CO emission (in g/km) for the first phase of the FTP-test and light-off time of the catalyst for 17 TWC-equipped cars (model year 1993) at 0 °C.

Overfueling, which is used to start the engine and to secure stable running at cold conditions, increases all products of incomplete combustion and components of unburned fuel in the exhaust. Furthermore, in a catalyst equipped car, the catalyst can in some cases during the cold start and warm-up phase cause formation of unwanted secondary components like nitrous oxide ($N_2O$), ammonia ($NH_3$) and aromatic compounds.

Quader has demonstrated /12/, that no enrichment for cold start is needed for a gaseous fuel like propane. This means that CO and HC emissions should not increase very much with falling temperature with natural gas and propane. Here the time needed for the catalyst to reach its working temperature might be the most important factor influencing the emissions.



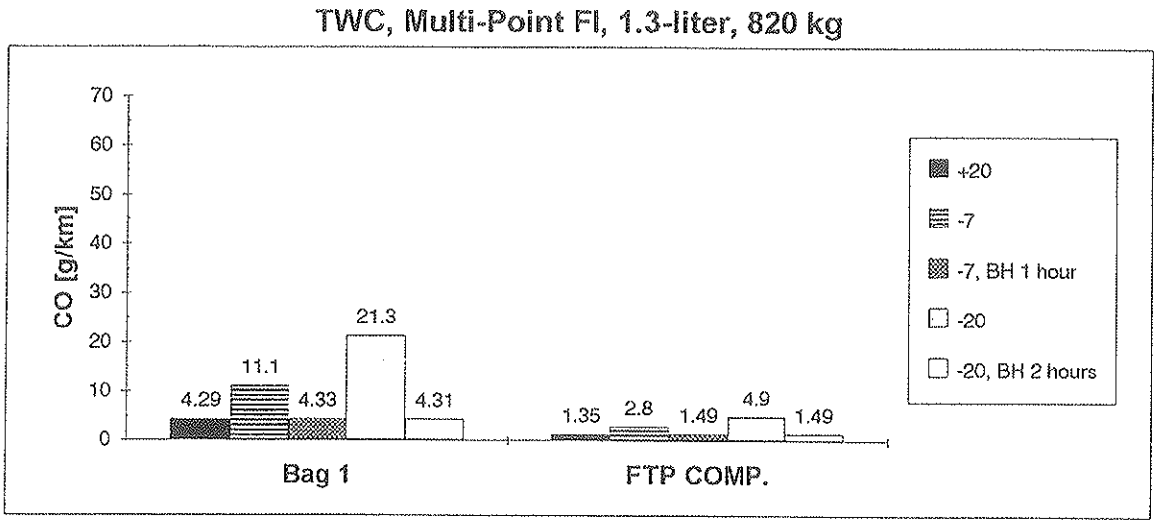




Figure 3. Cold-start FTP75 CO emissions at different ambient temperatures (with and without block heater) /13/.

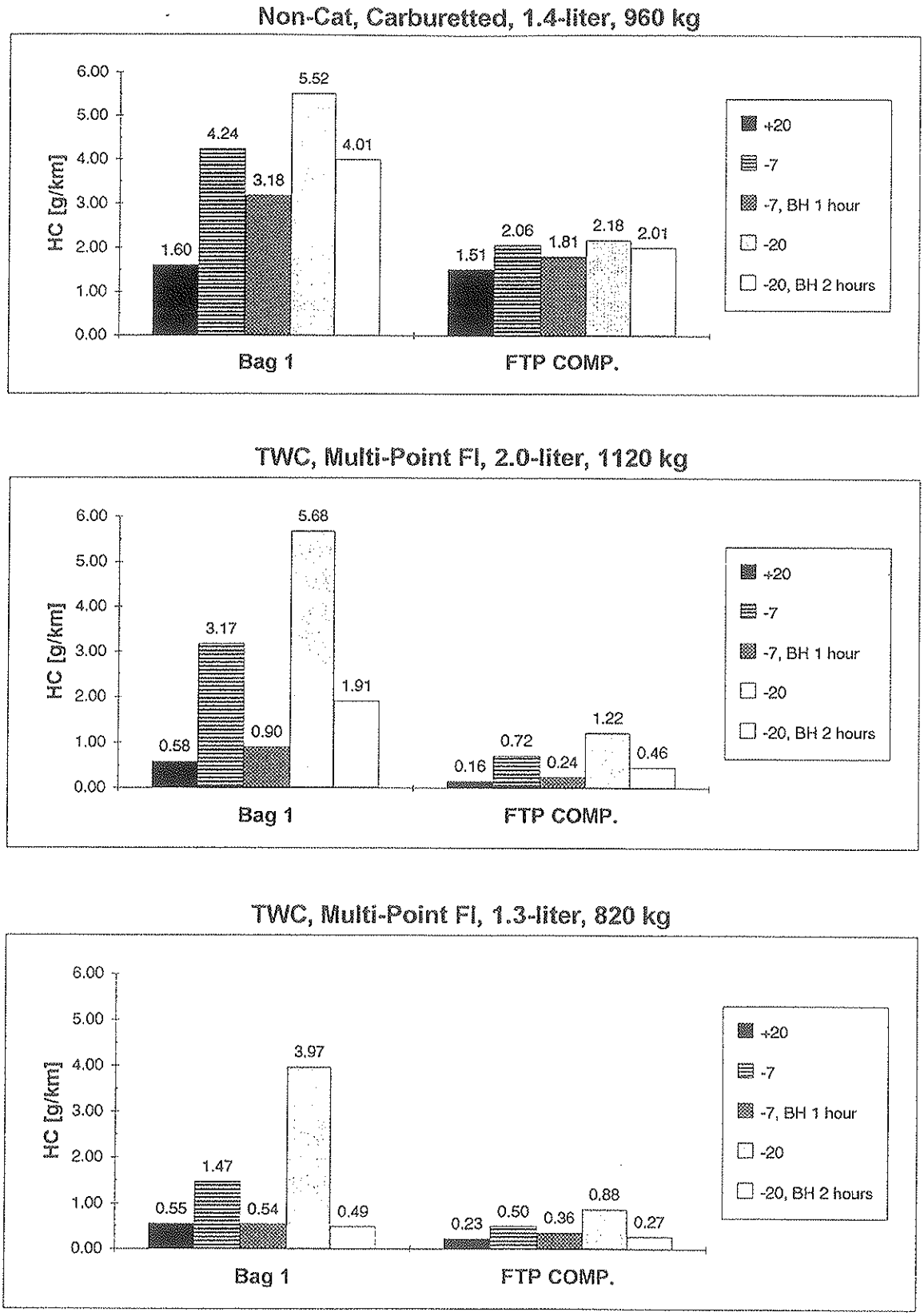



Figure 4. Cold-start FTP75 HC emissions at different ambient temperatures (with and without block heater) /13/.

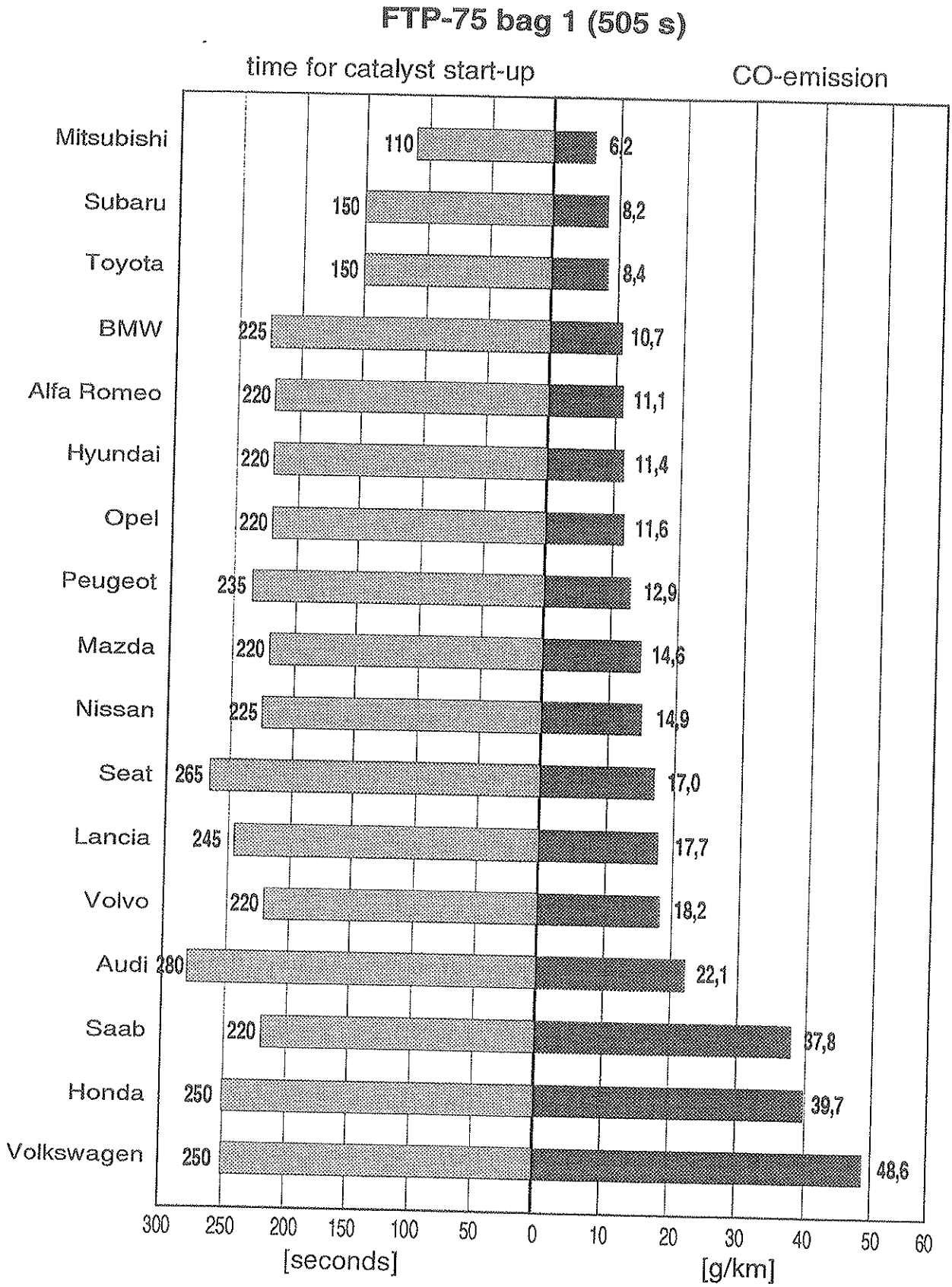



Figure 5. FTP75 bag 1 CO emissions and time for catalyst light-off for different vehicles at 0 °C.

## 4.3 Alcohol fuels

The starting problems associated with neat alcohol fuels are well documented. Alcohols are troublesome due to high boiling points, low vapor pressure, high heat of vaporization and high fuel flow (high fuel/air ratio with stoichiometric mixture). Figure 6 shows the vapor pressures and starting limits for gasoline, ethanol and methanol. Without any special measures to facilitate cold starts, the starting limit will be around +15 °C for ethanol and around +5 °C for methanol /14/.

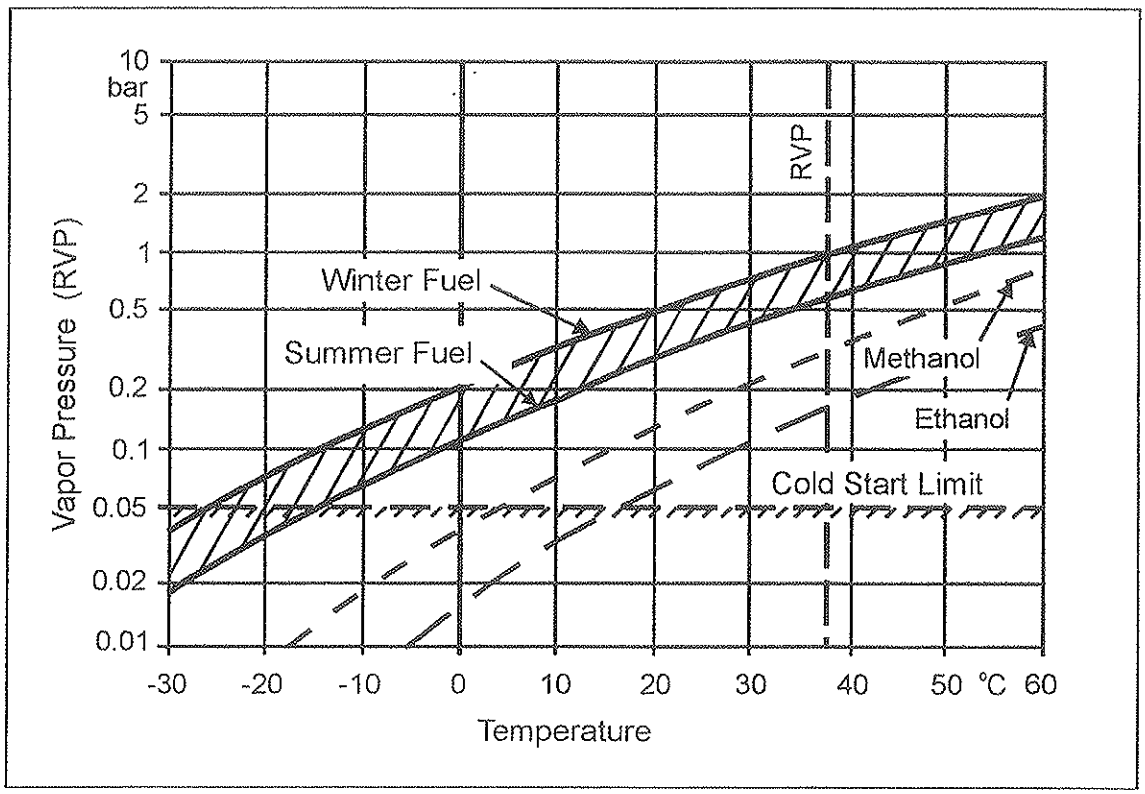



Figure 6. Vapor pressure and starting temperatures for gasoline, ethanol and methanol /14/.

Several measures can be taken to promote the cold-start performance of alcohol engines /15/:

a) fuel modifications

* addition of different hydrocarbons to the alcohol to increase the vapor pressure (typically 15 % by volume)

b) engine modifications

* the use of a separate starting fuel
* the use of different kinds of heaters
  (intake air, fuel or air/fuel mixture)
* improved ignition systems
* improved fuel atomization
* special combustion systems
  (stratified charge, exhaust gas recirculation etc.)

Figure 7 shows the starting limits for M100 fuel with different technologies and a typical cold starting range for M85- M90 fuels /16/.

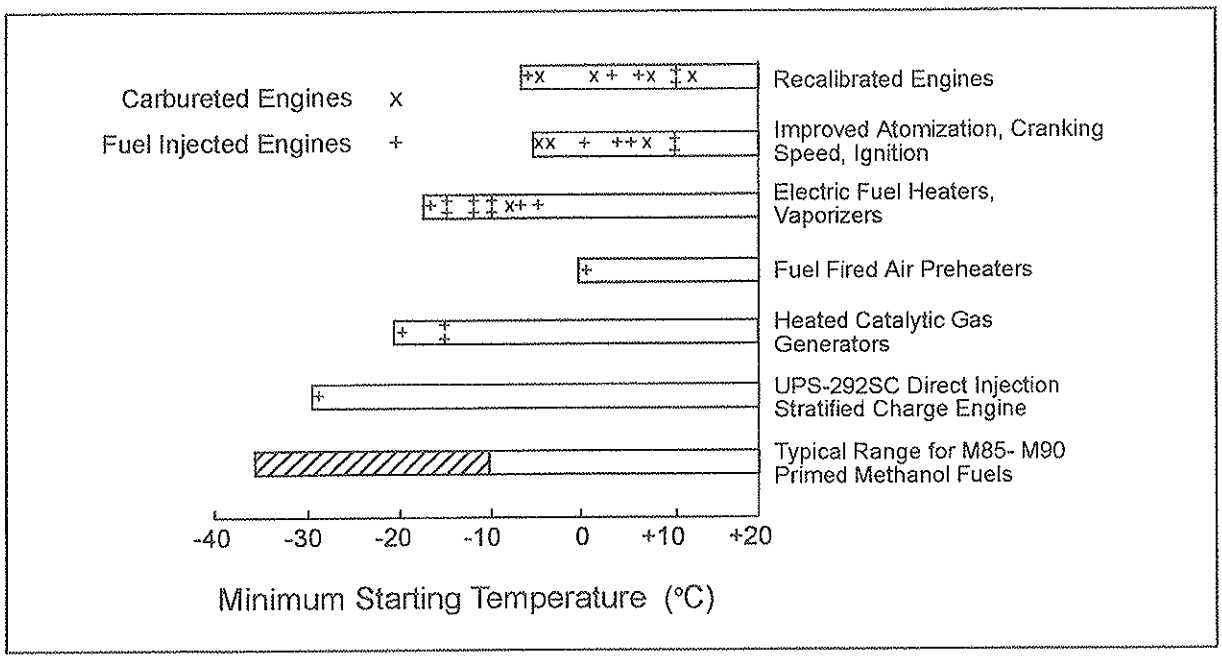



Figure 7. Starting limits for M100 fuel with different technologies and a typical cold starting range for M85 - M90 fuels /16/.

Cold starting with M85 fuel can be possible down to -30 °C using a combination of a high volatility primer, intake air/mixture/coolant heater, efficient ignition system and good fuel atomization. The problems are not yet fully solved, and further research is going on. Good results have been achieved using for example an Ultrasonic Partial Oxidation Combustor for fuel atomization /17/.

Good startability and fast warm-up combined with a good, possibly preheated catalyst are the keys to control emissions of unburned alcohol and formaldehyde. It is, however, difficult to see that alcohol fuels could easily be emissionwise competitive with gasoline or gaseous fuels at very low ambient temperatures.

# EXPERIMENTAL PART

# 5. OBJECTIVES AND GENERAL REMARKS

The objectives of IEA Alternative Motor Fuels Annex V, Performance Evaluation of Alternative Fuel/Engine Concepts, are:

* to generate comparable information on the true emission potential of alternative fuel concepts in severe operating conditions

* to determine and improve the applicability of alternative fuel concepts in severe operating conditions

* to collect data on, test, and apply new emission measurement technology

Listed in the original plans for Annex V were the following sub-tasks:

1. exhaust emission performance of current engine/fuel concepts (engine tests)

2. testing and development of different cold-start systems for alcohol engines

3. exhaust emission performance of enhanced engine/fuel concepts (vehicle tests in laboratory conditions and on the road)

The Executive Committee of the Agreement, however, considered the second phase to be too close to product development and the generation of proprietary information to be carried out under IEA sponsorship. Therefore the final program was made up of two phases, Part One: Engine Tests and Part Two: Cold start and unregulated emissions from light-duty vehicles.

In Part One of Annex V three engines were run in a climatic test chamber at VTT. It was decided to start the work with engine tests for several reasons. Performing the tests with separate engines instead of complete vehicles increases the accuracy of the measurements and facilitates instrumentation. It was also a way of keeping the total costs down for phase one. On the other hand, the installation of test engines is time consuming, so the number of engines to be tested had to be limited. One problem of Part One was obtaining relevant test engines. However, even in this phase, significant differences in the emission performance for gasoline, methanol and gaseous fuels could be demonstrated.

When Part Two, which was carried out as chassis dynamometer tests, started in 1993, the situation had changed somewhat. The fact that several manufacturers had launched FFV's and made vehicles for gaseous fuels commercially available, made obtaining test objects much easier compared to getting engines for Part One of the Annex. Carrying out the tests as vehicle tests on a chassis dynamometer made the testing itself easier, and made it possible to run many vehicles. Altogether 11 different light-duty vehicles were tested in Part Two.

Special thanks for help in obtaining test vehicles goes to TNO of Holland. TNO prepared and provided for VTT a retrofitted LPG vehicle and a vehicle with retrofitted LPG and CNG fuel systems. This vehicle was extremely interesting, since three types or fuels (also gasoline) could be tested with the same vehicle. Both of these vehicles represented the newest technology with gas injection systems. Making these vehicles available for VTT was TNO's task sharing contribution to Annex V.

Included in this final report of Annex V is the work carried out both in Part One and Part Two. In addition to this final report the following reports have been prepared within Annex V:

* Cold Start and Cold Start Emissions of Alcohol Fueled Light-Duty Engines. Literature Review. Technical Research Centre of Finland. Espoo June 3 1992. 21 p. /15/.

* Performance Evaluation of Alternative Fuel/Engine Concepts. Current Status of Part One (Engine Tests). Technical Research Centre of Finland. Espoo June 3rd 1992. 7 p. + app. /18/.

* Performance Evaluation of Alternative Fuel/Engine Concepts. Final Report of Part One (Engine Tests). Technical Research Centre of Finland. Espoo March 1993. 61 p. + app. /19/.

* Performance Evaluation of Alternative Fuel/Engine Concepts. Part Two: Cold Start and Unregulated Emissions from Light-Duty Vehicles. Interim Report. Technical Research Centre of Finland. Espoo February 1994. 34 p. + app. /20/.

# PART ONE: ENGINE TESTS

# 6. TEST ENGINES

## 6.1 General

Three engines (one gasoline engine, one retrofitted gas engine and one alcohol engine) were installed on an engine dynamometer and tested for exhaust emissions at different ambient temperatures in a climatic test chamber. Each engine was run on two different fuel qualities.

## 6.2 Gasoline engine

The gasoline engine was a MY 1989 16-valve 2.0 litre engine equipped with a TWC. The engine has a multi-point fuel injection system by Bosch (LH Jetronic), and it performs reasonably well at low temperatures. The maximum power output of this engine is 94 kW. This particular engine had formerly been used as a test engine only at VTT.

## 6.3 Gas engine

VTT bought a 1.6 litre engine from a wrecked MY 1990 vehicle. The driving distance of the car was appr. 40.000 km. The engine was inspected and serviced, and was found to be in very good condition. Maximum power output of this engine on gasoline is 60 kW.

The engine was modified for gaseous fuels at VTT using retrofitting systems but maintaining the original compression ratio. An IMPCO fuel system with closed-loop control system was used for both propane and natural gas. The original carburettor was replaced by an IMPCO mixer. The same secondary pressure regulator/evaporator was used for both fuels. LPG was supplied from 11 kg propane vessels stored in the climatic chamber. The natural gas was stored in 40 litre cylinders at 200 bar pressure. Pressure was reduced in two steps, from cylinder pressure to 6 bar in a coolant heated reduction valve, and from 6 bar to (near) atmospheric pressure in secondary pressure regulator (coolant flow disconnected to the secondary regulator). A TWC (OEM spare part) was installed in the exhaust system.

## 6.4 M85 engine

This engine originated from a wrecked test vehicle at Argonne National Laboratory in the US. The car had been driven appr. 110.000 km on M85 fuel. The engine was delivered to VTT through Oak Ridge National Laboratory in the US with support from US Department of Energy.

This 5.0 litre V8 engine with sequential electronic fuel injection was originally converted to dedicated M85 fuel use by a US company in cooperation with the engine manufacturer. The modifications included, among other things:

*high-compression pistons (11.2:1)
*low heat range spark plugs
*methanol-compatible fuel tank, fuel pump, fuel lines and hoses
*reprogrammed PROM
*high capacity fuel injectors
*cold start below -12 °C prevented if block heater is not used

The engine has a quite complicated exhaust treatment system including dual bed converters and an secondary air injection system. The engine was checked and rebuilt at VTT.

Technical data for all three test engines is presented in Table 3.

Table 3. Technical data for the test engines.

| engine | gasoline | gas | M85 |
|---|---|---|---|
| number of cylinders | 4 | 4 | 8 |
| displacement ($cm^3$) | 1990 | 1580 | 4940 |
| bore (mm) | 90 | 86 | 102 |
| stroke(mm) | 78 | 67 | 76 |
| compression ratio (-) | 10.1:1 | 9.2:1 | 11.2:1 |
| maximum power (kW) | 94 | 60 [1] | n/a |
| rated speed (r/min) | 6000 | 6000 [1] | n/a |
| fuel system | MPFI | IMPCO | MPFI |
| exhaust aftertreatment | TWC | TWC [3] | dual bed converters, secondary air injection |

[1] for gasoline version
[2] with gaseous fuels only (OEM spare part)

## 7. TEST FUELS AND LUBRICANTS

All engines were tested on two different fuel qualities:

| | |
|---|---|
| gasoline: | * hydrocarbon gasoline |
| | * oxygenated gasoline |
| gas: | * propane |
| | * natural gas (methane) |
| M85: | * M85 with 15 % unleaded gasoline |
| | * M85 with 15 % isopentane |

The oxygenated gasoline contained 13 % ETBE and 2 % ethanol giving an oxygen content of 2.7 % (wt). Two vapor pressure levels were used depending on test temperature, 65 kPa at +20 °C and 85 kPa Reid at lower temperatures. The propane used for the tests was olefin-free propane. Propane concentration is >95 mole-%, olefin concentration <1 mole-% and concentration of $C_4$ and higher hydrocarbons <5 mole-%. Concentration of 1,3-butadiene is < 0,1 mole-%. The natural gas used in Finland has a very high concentration of methane, more than 98 %.

The M85 fuel was primed with both commercial grade unleaded gasoline and pure isopentane. The distillation temperatures and the RVP-values of the two blends are given in Table 4.

Table 4. Distillation temperatures and RVP for the M85-blends.

| | M85 (15 % gasoline) | M85 (15 % isopentane) |
|---|---|---|
| start of distillation [°C] | 46.5 | 31.5 |
| 5 % | 58.5 | 46.5 |
| 10 % | 60.5 | 58.5 |
| 20 % | 62.5 | 61.5 |
| 30 % | 63.5 | 63.5 |
| 40 % | 64.0 | 64.5 |
| 50 % | 64.5 | 64.5 |
| 60 % | 64.5 | 64.5 |
| 70 % | 64.5 | 64.5 |
| 80 % | 64.5 | 64.5 |
| 90 % | 65.0 | 64.5 |
| 95 % | 65.5 | 64.5 |
| end of distillation [°C] | 175.0 | 123.0 |
| RVP (ASTM D 4953-1) | 59 kPa | 106 kPa |

Fully synthetic commercial lubricants (SAE 5W-50) were used in the gasoline and gas engine. A specially formulated methanol engine oil was used in the M85 engine (Shell LA 02466, SAE 10W-30).

# 8. TEST PROGRAMME

## 8.1 General

All tests were run with the engines connected to engine dynamometers. The tests were run in two phases, preliminary tests in April-May 1992 and the final tests between October 1992 and February 1993.

The preliminary tests were carried out to give an idea of the general performance of the engines. In the preliminary tests exhaust emission measurements were mainly limited to regulated emissions. The results of the preliminary tests were documented in a report dated June 3rd 1992 /18/.

A new type of exhaust analyzer, which makes on-line measurement of unregulated emissions possible, was delivered to VTT in May 1992. It is based on the Fourier Transformation Infrared (FTIR) technique. The final tests were carried out using this new instrument. For all engines the final tests were carried out using a normal CVS-type exhaust sampler.

## 8.2 Test temperatures

Test temperatures for the gasoline and the gas engine on LPG were +20, ±0, -7 and -20 °C. The lambda-control of the IMPCO system did not work properly on CNG at -20 °C. This resulted in extremely rich mixtures and excessive CO emission. Therefore, -20 °C was excluded from the final test matrix with CNG. The M85 engine was tested at +20, ±0 and -7 °C. As already stated, the engine management system would not allow cold-starts below -12 °C.

VTT 's experience has shown, that exhaust emission performance can deteriorate considerably at or below ±0 °C (as shown in Fig. 5). This temperature can be experienced all over Europe.

US EPA is introducing a low temperature test to control cold-start CO emissions beginning in 1994 /21/. This test is carried out at 20 F equivalent to -7 °C. This is why this temperature was included in the test program. The lowest test temperature was -20 °C, which represents conditions that can occur in Northern Europe, Northern Japan, Canada and the US.

The final test programme matrix is presented in Table 5.

Table 5. Test programme matrix.

| Engine, fuel | Final tests |
|---|---|
| gasoline | hydrocarbon gasoline<br>+20, ±0, -7, -20 °C<br>oxygenated gasoline<br>+20, ±0, -7, -20 °C |
| LPG/CNG | LPG/IMPCO<br>+20, ±0, -7, -20 °C<br>CNG/IMPCO<br>+20, ±0, -7 °C |
| M85 | M85 (gasoline)<br>+20, ±0, -7 °C<br>M85 (isopentane)<br>+20, ±0, -7 °C |
| Combinations | 21 |

## 8.3 Loading of the engines

Most of the tests were done with cyclic loading. A load cycle simulating urban driving (type ECE R15) consisting of four load steps was repeated six times to give a total test duration of 30 minutes. The share of idling was 20 %. The timing of the cycles was the same for all engines. The load steps (engine speed/load) varied from engine to engine in order to simulate the different loads under which the engines would operate in the vehicles.

The mean power output of the engines during the tests was (appr. values):

gas engine 4.0 kW, gasoline engine 5.0 kW, M85 engine 7.0 kW

Figure 8 shows the load cycles for the test engines. The first idling period was 90 seconds and the total duration of the test was 1890 seconds.

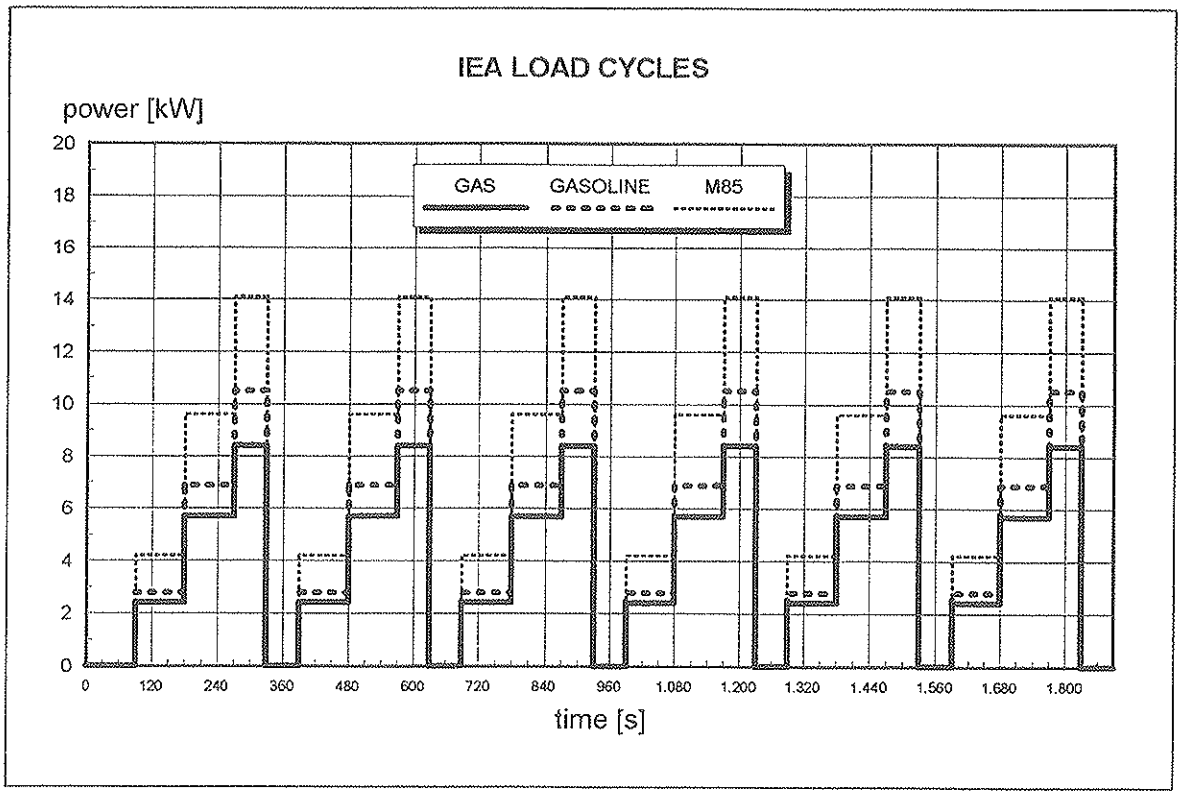



Figure 8. Load cycles of the test engines.

# 9. INSTRUMENTATION

## 9.1 General

Figure 9 gives the general lay-out of the test set-up. The test engines were installed in the climatic chamber. The engines were equipped with a normal cooling system including a radiator, which also was placed in the climatic chamber. The first part of the exhaust system including the catalyst (catalysts) was inside the climatic chamber. A separate fan was used to create an air flow toward the radiator and also to some extent, toward the exhaust system. The fuels, both liquid and gaseous, were kept inside the climatic chamber. Thus, both engines and fuels were cooled down overnight before testing. The batteries were kept warm, as this increased repeatability of the start procedure especially for the M85 engine.

The engines were connected to the engine dynamometer by propeller shafts and a mechanical clutch. The engine dynamometer was placed in the adjacent engine test room, which is kept at normal room temperature.

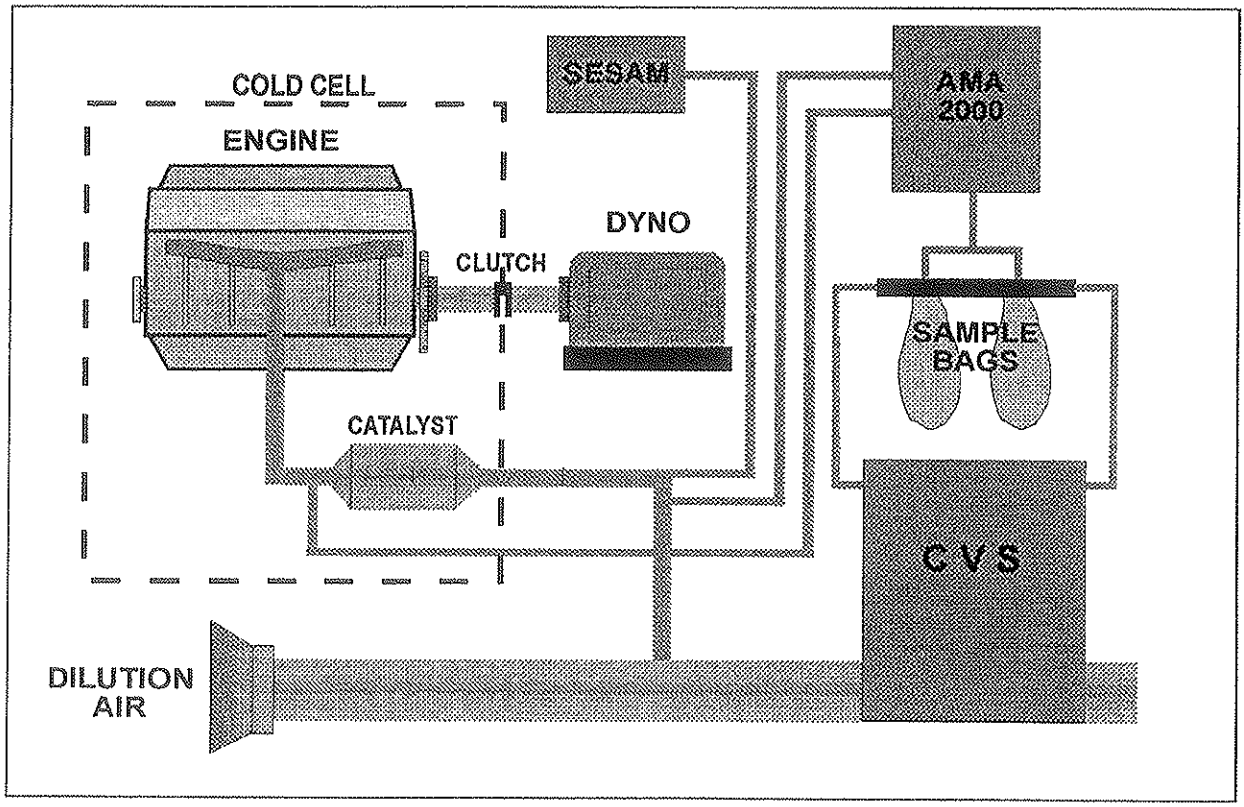



Figure 9. The general lay-out of the test set-up.

## 9.2 Engine dynamometer

The engine dynamometer used for the final tests was an eddy-current type Zöilner B-300 dynamometer. As the inertia of the dynamometer is relatively high, a mechanical, manually operated clutch had to be used between the test engine and the dynamometer to facilitate starting. The maximum power absorption capacity of this dynamometer is 260 kW, and maximum torque 1300 Nm. Thus, the dynamometer worked on very low loading. This, however, was no problem as the dynamometer is very stable and the control system worked very well.

The dynamometer and the throttle actuator (Barber-Coleman) were controlled by a Puma 4-system from AVL (Austria). Data logging was carried out both with the Puma 4-system and a separate data acquisition system including a Hewlett-Packard 3497A data acquisition unit.

## 9.3 Exhaust emissions

### 9.3.1 Regulated components

A US FTP-compatible emission measurement system by Pierburg (Germany) was used to measure regulated emission components in both the engine and the light-duty vehicle tests. The system consists of a PDP- (Positive Displacement Pump) type CVS-sampler (Pierburg 12,5 WT, maximum flow 12.5 $m^3$/min) and a versatile analytical bench (Pierburg AMA 2000). The analytical bench has two blocks, and is capable of continuous simultaneous measurements of exhaust gas composition before and after the catalyst.

During the engine tests, block 1 of the AMA 2000-system measured continuously the undiluted exhaust before the catalyst. In case of the M85 engine, however, it measured the exhaust of the cylinders on the right side of the engine block. Block 2 measured the undiluted exhaust after the catalyst (catalysts in case of the Ford engine). Both sample lines were heated to a temperature of 180...185 °C.

The $CO_2$ tracer measured $CO_2$ concentration in the diluted exhaust stream in the CVS-device, and this value was used to determine the dilution factor for instantaneous exhaust flow calculations.

CVS bag sampling was used to determine the total CO, HC and $NO_x$ emissions. The test was divided into two phases, bag 1 for 0-930 seconds, and bag 2 for 931-1890 seconds.

### 9.3.2 Unregulated components

The FTIR-instrument, SESAM II by SIEMENS, was used to measure certain unregulated exhaust components. The SESAM (System for Exhaust Gas Sampling And Measurement) also measures regulated components, so this makes it possible to make comparisons between the FTIR and conventional measuring techniques (AMA 2000).

VTT ordered the new instrument from SIEMENS AG (Germany) in the autumn 1991. The instrument was developed in cooperation between the American company NICOLET (the spectrometer and its associated software) and the German companies SIEMENS AG and VOLKSWAGEN AG (sample handling, control systems, etc.). VTT's instrument is of the second generation design carrying type designation SE 2. It was delivered to VTT in May 1992, and was, after a running-in phase, taken into service in the autumn of 1992.

The FTIR technique is based on the Michelson interferometer (Figure 10). The mirror in the instrument makes a sweep every second creating an interferogram. A powerful computer converts the interferogram by means of a Fourier transformation into a spectrum. From this spectrum components having IR-absorbance (and which are calibrated into the calculating method) can be detected by computation. The instrument is designed to measure undiluted exhaust and is equipped with a heated sampling line. The exhaust sample is treated only by filtering through a ceramic filter. After filtering it is led hot (185 °C) through the gas cell.

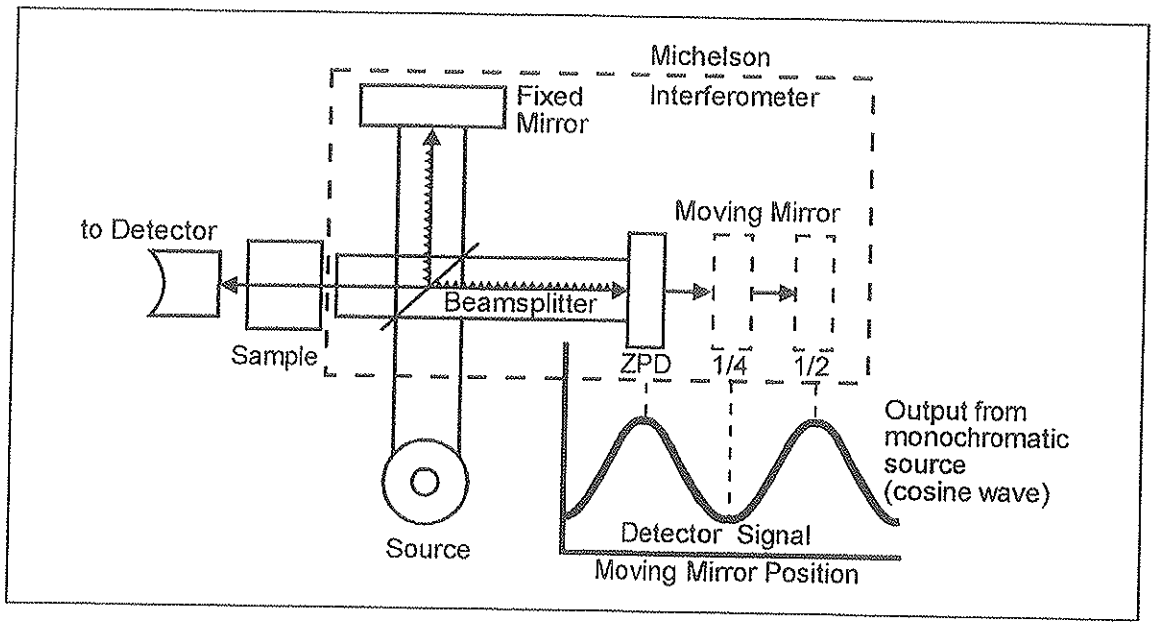



Figure 10. The principle of the Michelson interferometer /10/.

Exhaust gases originating from different fuels have their own calculation methods. In addition to the basic calculation methods supplied by SIEMENS (diesel, gasoline and methanol fuels), special methods have been developed for other fuels:

* reformulated gasolines with oxygenated species, like ethanol, MTBE and ETBE
* biodiesels, e.g. rapeseed oil based fuels
* reformulated diesel fuels
* methanol blends
* LPG
* CNG

The calculation procedure is very flexible allowing a calibration method to be created for practically any combustion gas for which the qualitative composition is known. The prerequisite for a reliable method is that all main components in the exhaust, both components to be measured and components which may cause interferences, are known and taken into account in the calibration. The components are calibrated over a wide range, making it possible to measure the majority of combustion effluents.

In general, the detection limit is well below 10 ppm for the most important components. Table 6 gives minimum detection limits for various exhaust components under ideal conditions and typical ranges for transient operation with different fuels.

Components like $NO_2$ (nitrogen dioxide), $NH_3$ (ammonia), $CH_4$ (methane), $C_2H_2$ (acetylene), $C_2H_4$ (ethylene), $C_4H_6$ (1,3-butadiene), formaldehyde (HCHO), methanol ($CH_3OH$), MTBE, ETBE and HCN (hydrogen cyanide) can be determined with high accuracy.

For spectrometric reasons, like reduced sensitivity, specificity or severe cross interferences caused mainly by $CO_2$ and water, higher detection limits are obtained for $N_2O$ (nitrous oxide), $C_2H_6$ (ethane), $C_3H_6$ (propylene), acetaldehyde, ethanol ($C_2H_5OH$), benzene ($C_6H_6$), total aromatics (AHC) and $SO_2$ (sulphur dioxide). Of these, acetaldehyde and benzene have been listed by the US EPA as priority pollutants.

Table 6. Detection limits for unregulated exhaust components.

| Component | Detection limits at steady-state conditions, all fuels (ppm) | Range of practical detection limits at 0-100 ppm concentration range, transient conditions (ppm) | | | |
|---|---|---|---|---|---|
| | | Gasoline HC/oxy | Methanol M85 | LPG | CNG |
| $NO_2$ | 5 | 2-6 | 2-5 | 2-20 | 2-7 |
| $N_2O$ | 7 | 5-17 | 4-80 | 3-13 | 4-10 |
| $NH_3$ | 5 | <5 | <5 | <5 | <5 |
| $CH_4$ | 3 | 1-7 | <3 | <3 | <3 |
| $C_2H_2$ | 6 | <6 | 3-8 | 3-16 | <6 |
| $C_2H_4$ | 7 | <7 | <7 | <7 | <7 |
| $C_2H_6$ | 6 | 3-30 | 2-27 | 2-13 | 2-6 |
| $C_3H_6$ | 12 | 5-11 | 5-8 | 3-10 | n.a. |
| $C_4H_6$ | 5-7 | <7 | n.a. | n.a. | n.a. |
| $C_6H_6$ | 20 | 17-23 | n.a. | n.a. | n.a. |
| AHC | 20 | 3-45 | 10 | n.a. | n.a. |
| HCHO | 7 | <7 | <7 | <7 | <7 |
| $CH_3CHO$ | 25 | 17-43 | 17-60 | n.a. | n.a. |
| $CH_3OH$ | 7 | <7 | <7 | <7 | <7 |
| $C_2H_5OH$ | 10 | 10-13 | - *) | n.a. | n.a. |
| MTBE | 6-11 | 6-11 | n.a. | n.a. | n.a. |
| ETBE | - | <5 | n.a. | n.a. | n.a. |
| $SO_2$ | 9 | 4-50 | n.a. | n.a. | n.a. |
| HCN | 7 | n.a. | n.a. | n.a. | n.a. |

n.a. concentrations below detection limits
*) large systematic error in the presence of methanol

The lower detection limits in Table 6 are more than adequate for all fuels in situations when the engine is operated in stabilized conditions and at constant load. In transient conditions, especially in connection with cold-start and warm-up at low ambient temperatures, the composition of the exhaust varies rapidly. This also means fast changes in the interactions and interferences between different exhaust components, and it can cause instability in the analysis. In these extreme conditions, the concentrations of certain exhaust components may give very high peak values, which exceed the calibration ranges.

Total aromatics (AHC) gives the sum of aromatic compounds in the gas phase (from benzene to higher gaseous aromatics). Since AHC is calibrated with toluene, the AHC is not an absolutely precise value for the aromatics. It is, however, well suited for comparisons of aromatic hydrocarbon emissions from related fuels. Due to the limited specificity of absorption bands for aromatics, the detection limit for benzene is fairly high - close to 20 volume-ppm.

In transient, non-stabilized conditions the detection limits for $SO_2$ and $N_2O$ may rise, because the cross interference caused by water cannot be eliminated totally in all circumstances. $C_2H_6$ is subject to interference by other saturated hydrocarbons; acetaldehyde has a broad, nonspecific absorption band mainly interfered by formaldehyde, and ethanol measurement is interfered by methanol.

Hydrogen cyanide was not found above the detection limit in any of the tested cases.

Up to 21 components in the method spectra can be recorded at a rate of one scan per second. If this number is exceeded, the scanning rate is slightly reduced, but in most cases it is still quite sufficient. To date a maximum of 26 components have been calibrated for. In addition to the unregulated pollutants, also CO, the total hydrocarbons (corresponding to the FID response), $NO_x$, $H_2O$ and $CO_2$, as well as unburned fuel components, n-pentane, isopentane, propane and n-octane are monitored. The accuracy of CO, $CO_2$ and $NO_x$ measurements is very good. The total hydrocarbons given by the SESAM is a calculated sum, based on all the calibrated organic compounds in the method. Therefore, its correlation with the FID readings is not always satisfactory.

The CO readings of the SESAM were used to check the calibration, the drift of the instrument itself and to verify the integrated SESAM values against bag sampling values.

One of the main advantages of the FTIR system is the capability to store the original spectral information and subject it to post-processing. This means that all original data is saved, and it can be re-analyzed, should new, updated and revised calculation methods later be developed. However, one full spectrum contains 60-70 kilobytes (kB) of data. Therefore, the data file from one complete test run, such as the first 505 sec of the FTP cycle, is very large, about 60 megabytes (MB). In VTT's system, optomagnetic discs are used to store data. The capacity of one such disc is about 600 MB.

Correlation tests between the FTIR and conventional analyzers were carried out for hydrocarbons and aldehydes.

# 10. TEST PROCEDURES AND CALCULATION OF THE RESULTS

## 10.1 Experimental procedure

In most cases, one test combination (fuel/temperature) was executed each day. The main test was carried out in the morning after an overnight soak period. The test was repeated in the afternoon. Usually a test was repeated 2-4 times.

The test engine was started with the mechanical clutch disengaged and the engine dynamometer disconnected. After the engine had started, a 30 second period was allowed for the engine to stabilize. During this period the clutch was engaged cautiously in order to avoid stalling of the engine. After this the engine and dynamometer were subjected to computer control.

The load sequence started with a 60 second idle period, so the total idling period at the beginning of a test was 90 seconds. The exhaust emission measurements, both the on-line measurements and the bag sampling, started when the cranking of the engine started. Thus, the emissions of the starting process itself are included in the results.

## 10.2 Calculation of the results

The overall emissions of the regulated emission components (CO, HC and $NO_x$) were calculated from diluted CVS bag samples. The calculation followed, in principle, the procedure described in the Swedish A14 emission regulation /22/, similar to the US-FTP. In this present case, however, the total emissions were calculated from two sample bags. The same weighting factor was used for both bags. The dilution ratio was between 10:1 and 15:1.

For each engine the emission values obtained by bag sampling were also expressed in terms of the actual amount of work (kWh) performed during the test.

Emission rates were also determined through integration of the continuous readings from the AMA-system. In this case the instantaneous exhaust flow was determined with the help of the $CO_2$-tracer.

The emissions of the unregulated components were also determined by integrating the instantaneous values of exhaust concentration and flow. Due to the large amount of data generated, the measurements were limited only to the first phase of the test (930 seconds).

In the case of the regulated components CO, HC and $NO_x$, the difference between the integrated value and the bag value was on average less than 10 %. The accuracy of the integration is affected by the very high peaks of CO and HC just after start. Also, the possible inaccuracies in matching the various traces and differences in response time between different instruments can affect the result.

When calculating the cumulative CO, HC and $NO_x$ emissions as a function of time, the total integrated values were corrected to agree with the bag sample values. No corrections were made to the integrated emission values of the unregulated components, as the results very clearly showed the effect of both temperature and fuel type on the unregulated emissions.

No correction for ambient air humidity on the $NO_x$ emission was done. The relative humidity in temperatures of 0 °C and below is very high (>75 %), and the correction factor formulas are intended to be used for testing carried out at normal ambient temperature.

The loading of the engine was chosen so that it would, to some extent reflect the size and the power need of the car it originated from. The emission results are calculated as grams per test, and also, to eliminate engine size, in grams per kWh. From the results expressed in grams per test the influence of test temperature on the results can clearly be seen. A way to estimate the emissions in grams per km, would be to assume that the average speed over the fictitious driving cycle would be 40 km/h.

# 11. RESULTS AND DISCUSSION

## 11.1 Starting times

All engines started relatively easily at +20 °C, the gasoline engine being the fastest one. With decreasing temperature, however, considerable differences in starting times were found. The approximate starting times are given in Table 7.

Table 7. Starting times (s) for the test engines.

| Engine/fuel | | +20 °C | ±0 °C | -7 °C | -20 °C |
|---|---|---|---|---|---|
| gasoline | HC gasoline | 1 | 2 | 3 | 5 |
| | oxygenated gasoline | 1 | 2 | 3 | 4 |
| gas | LPG | 2 | 3 | 3 | 5 |
| | CNG | 2 | 3 | 4 | - |
| M85 | M85 (gasoline) | 3 | 7 | 20 | - |
| | M85 (isopentane) | 3 | 5 | 10 | - |

The starting time of the gas engine was found to be more or less independent of the ambient temperature. The M85 engine was difficult to start at -7 °C. Using isopentane as a primer instead of gasoline improved the startability considerably.

## 11.2 Regulated exhaust emissions

### 11.2.1 CVS-bag sampling results

The emissions of regulated exhaust components based on CVS bag sampling are presented in Table 8. Table 8 gives the values in g/test, g/kWh and as g/km assuming an average speed over the fictitious driving cycle of 40 km/h, corresponding to a driving distance of 20 km.

Gasoline, propane and M85 gave all roughly the same emission levels at +20 °C. They were between 20 and 30 g CO, 2 to 5 g HC and 3 to 5 g $NO_x$ per test corresponding to 1.0 to 1.5 g CO, 0.1 to 0.25 g HC and 0.15 to 0.25 g $NO_x$ per km.

CNG gave clearly the lowest CO emission. The total values obtained at +20 °C were appr. 3 g CO, 4 g HC and 5 g $NO_x$ per test, corresponding to emission values between 0.15 and 0.25 g/km.

A comparison between results at +20 °C and -7 °C, which was the lowest common test temperature with all engine/fuel combinations, is interesting. For the gasoline engine, the CO emissions increased by a factor of 5 and the HC by a factor of 3. With gaseous fuels the CO emissions increased only by a factor 2 to 3, whereas the HC emissions are more or less independent of temperature. At -7 °C the CO emissions of the CNG engine were only half those of the gasoline engine at +20 °C.

Temperature has a very dramatic effect on the emissions of the M85 engine. The CO emissions increased by a factor of 12 and HC emissions by a factor of around 5. Thus, the M85 engine showed by far the worst emission performance at low ambient temperatures.

The test temperature had no major influence on $NO_x$ emission in any of the engines. With gasoline and M85 both CO and HC emissions resulted from the enrichment at cold-start and during warm-up.

The differences in regulated emissions between conventional and oxygenated gasoline in the gasoline engine were relatively small. The CO emissions were more or less unaffected. The HC emissions were slightly reduced at low temperatures. The $NO_x$ emissions, however, increased in all test temperatures. The results differ somewhat from VTT's previous results with oxygenated and reformulated gasolines /23/. Earlier tests have in general shown both reduced CO and HC emissions and no significant changes in the $NO_x$ emission.

In the gas engine, both LPG and CNG gave the same $NO_x$ emissions. On CNG the HC emissions measured by FID were twice as high as on LPG. The CO emissions were, however, only roughly 1/10 to 1/4 with CNG compared to LPG. Using isopentane instead of gasoline as a primer in the M85 fuel clearly improved startability of the M85 engine, and at ±0 and -7 °C the HC emissions measured with the FID were reduced by some 30 %.

Table 8. Regulated exhaust emissions.

| NORMAL HC GASOLINE | | | | |
|---|---|---|---|---|
| | 20 °C | 0 °C | -7 °C | -20 °C |
| CO | | | | |
| g/test | 19 | 78 | 101 | 134 |
| g/kWh | 7.8 | 32 | 41 | 54 |
| g/km | 1.0 | 3.9 | 5.1 | 6.7 |
| HC | | | | |
| g/test | 3.7 | 8.0 | 11 | 22 |
| g/kWh | 1.5 | 3.3 | 4.5 | 9.0 |
| g/km | 0.2 | 0.4 | 0.6 | 1.1 |
| $NO_x$ | | | | |
| g/test | 4.2 | 4.6 | 4.9 | 4.5 |
| g/kWh | 1.7 | 1.9 | 2.0 | 1.8 |
| g/km | 0.2 | 0.2 | 0.2 | 0.2 |

| OXYGENATED GASOLINE | | | | |
|---|---|---|---|---|
| | 20 °C | 0 °C | -7 °C | -20 °C |
| CO | | | | |
| g/test | 21 | 79 | 96 | 137 |
| g/kWh | 8.2 | 31 | 38 | 55 |
| g/km | 1.0 | 4.0 | 4.8 | 6.9 |
| HC | | | | |
| g/test | 3.7 | 8.4 | 9.6 | 20 |
| g/kWh | 1.5 | 3.3 | 3.8 | 7.9 |
| g/km | 0.2 | 0.4 | 0.5 | 1.0 |
| $NO_x$ | | | | |
| g/test | 5.8 | 5.0 | 5.4 | 5.5 |
| g/kWh | 2.3 | 2.0 | 2.1 | 2.2 |
| g/km | 0.3 | 0.3 | 0.3 | 0.3 |

| LPG | | | | |
|---|---|---|---|---|
| CO | | | | |
| g/test | 23 | 36 | 39 | 43 |
| g/kWh | 10 | 15 | 17 | 19 |
| g/km | 1.2 | 1.8 | 2.0 | 2.2 |
| HC | | | | |
| g/test | 2.1 | 2.4 | 2.4 | 2.6 |
| g/kWh | 0.9 | 1.0 | 1.0 | 1.1 |
| g/km | 0.1 | 0.1 | 0.1 | 0.1 |
| $NO_x$ | | | | |
| g/test | 4.5 | 4.6 | 4.5 | 4.1 |
| g/kWh | 1.9 | 2.0 | 1.9 | 1.8 |
| g/km | 0.2 | 0.2 | 0.2 | 0.2 |

| CNG | | | | |
|---|---|---|---|---|
| CO | | | | |
| g/test | 3.4 | 3.9 | 9.2 | - |
| g/kWh | 1.4 | 1.7 | 4.0 | - |
| g/km | 0.2 | 0.2 | 0.5 | - |
| HC | | | | |
| g/test | 4.5 | 5.0 | 4.7 | - |
| g/kWh | 1.9 | 2.1 | 2.0 | - |
| g/km | 0.2 | 0.2 | 0.2 | - |
| $NO_x$ | | | | |
| g/test | 4.9 | 4.8 | 4.0 | - |
| g/kWh | 2.1 | 2.1 | 1.7 | - |
| g/km | 0.2 | 0.2 | 0.2 | - |

| M85/GASOLINE | | | | |
|---|---|---|---|---|
| CO | | | | |
| g/test | 27 | 207 | 313 | - |
| g/kWh | 8.0 | 61 | 93 | - |
| g/km | 1.3 | 10 | 16 | - |
| HC | | | | |
| g/test | 5.7 | 16 | 25 | - |
| g/kWh | 1.7 | 4.6 | 7.3 | - |
| g/km | 0.3 | 0.8 | 1.2 | - |
| $NO_x$ | | | | |
| g/test | 3.4 | 3.0 | 3.2 | - |
| g/kWh | 1.0 | 0.9 | 0.9 | - |
| g/km | 0.2 | 0.1 | 0.2 | - |

| M85/ISOPENTANE | | | | |
|---|---|---|---|---|
| CO | | | | |
| g/test | 29 | 193 | 321 | - |
| g/kWh | 8.4 | 57 | 94 | - |
| g/km | 1.4 | 10 | 16 | - |
| HC | | | | |
| g/test | 5.9 | 11 | 17 | - |
| g/kWh | 1.7 | 3.2 | 5.1 | - |
| g/km | 0.3 | 0.5 | 0.9 | - |
| $NO_x$ | | | | |
| g/test | 3.7 | 2.8 | 2.6 | - |
| g/kWh | 1.1 | 0.8 | 0.8 | - |
| g/km | 0.2 | 0.1 | 0.1 | - |

## 11.2.2 Real-time measurement results

Figures 11 to 13 show the CO traces (before and after catalyst) at +20 and -at 7 °C for the different engines and fuels (hydrocarbon gasoline, LPG and M85 primed with gasoline).

The time required for the gasoline engine to reach the stoichiometric (lambda=1) operating point was appr. 100 seconds at +20 °C and 210 seconds at -7 °C. It was interesting to see that the CO reduction in both cases starts to take place after 210 seconds. This means that the catalyst is not hot enough for light-off when the engine goes to stoichiometric operation (lambda=1) at +20 °C.

The enrichment with LPG in the retrofitted gas engine was caused by the fact that the basic mechanical setting of the fuel system was rich. When the air-fuel ratio control system starts to work, it leans out the mixture to the stoichiometric value (lambda=1). These conditions were reached around 100 seconds in both of the tested temperatures. Also, in this case the light-off of the catalyst took place independently of the temperature after some 200 seconds.

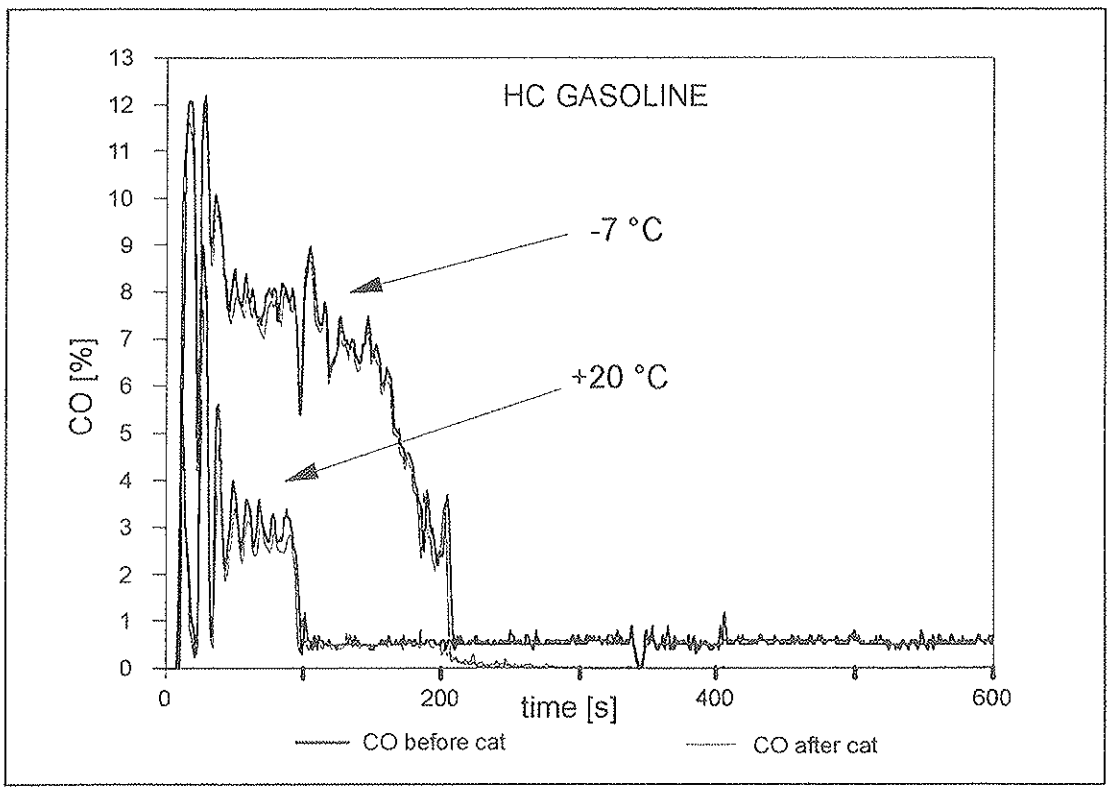



Figure 11. CO traces before and after catalyst (hydrocarbon gasoline).

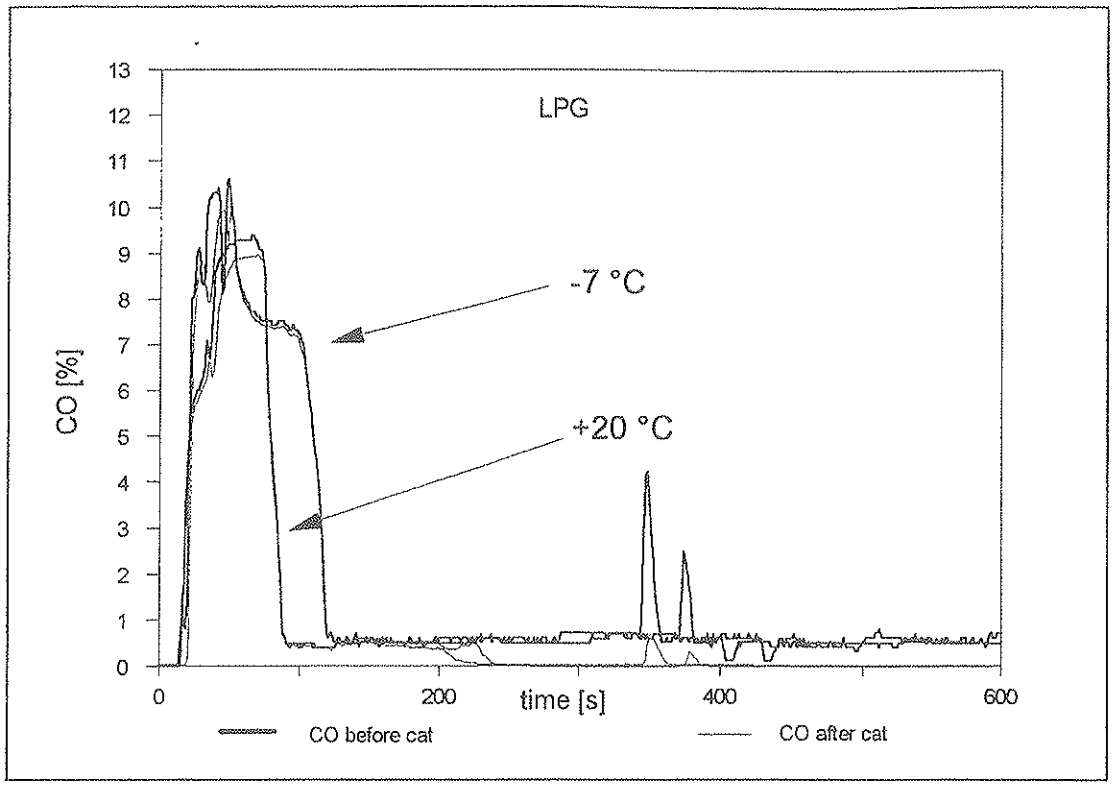



Figure 12. CO traces before and after catalyst (LPG).

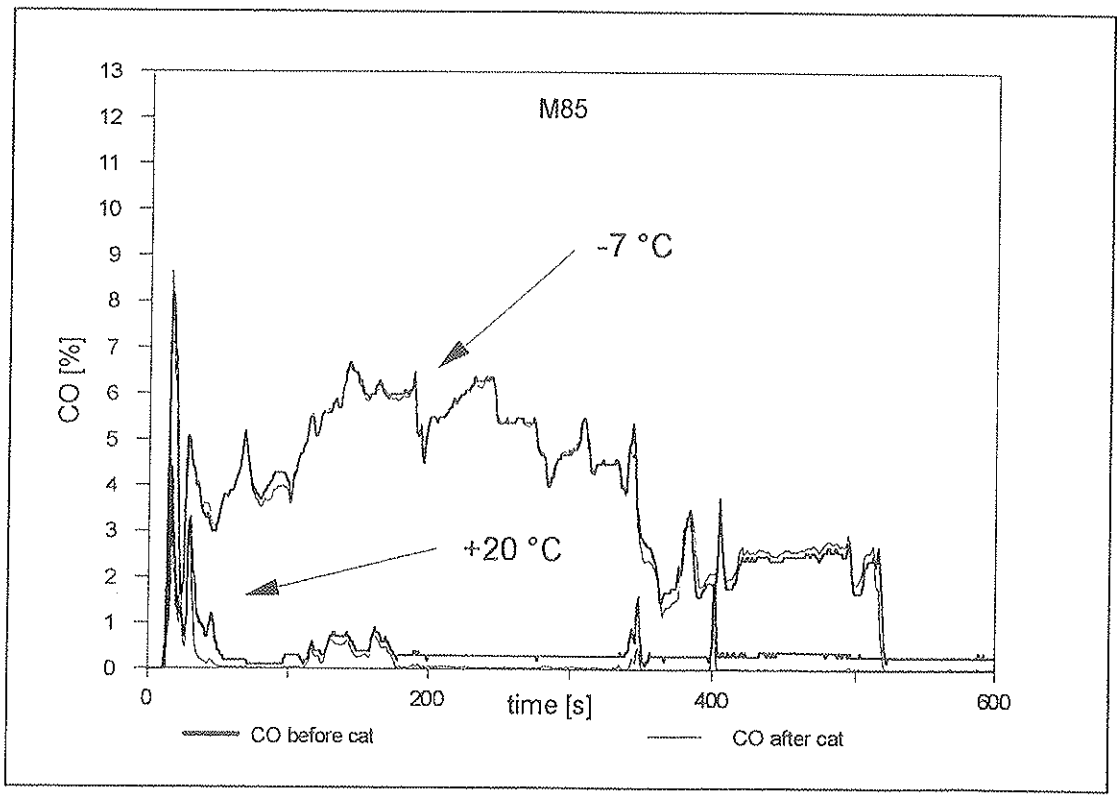



Figure 13. CO traces before and after catalyst (gasoline primed M85).

As Figure 13 shows, the M85 engine was working quite differently. At +20 °C the air-injection system, which was automatically switched on right from the start, gave a very fast light-off of the catalysts due to their mounting near the exhaust manifolds. Therefore, the CO concentration was close to 0-level even at 50 seconds. However, the picture was quite different at -7 °C. The engine ran on a rich mixture for more than 500 seconds. For some reason the air-injection was not engaged, and this resulted in very high CO emission.

### 11.2.3 Cumulative emissions

Figures 14 to 16 show the cumulative CO emission for the corresponding engine/fuel combinations. The first 200...500 seconds of the test are decisive for the total emissions of both CO and HC. After the light-off of the catalyst the curves are essentially horizontal. If this nearly horizontal portion is extrapolated to the y-axis, the reading on the y-axis can be thought of as the contribution to the emissions caused by the cold-start. For the gasoline engine this 'extra' CO emission caused by a cold-start is appr. 20 g at +20 °C, 80 g at ±0 °C, 100 g at -7 °C and 130 g at -20 °C.

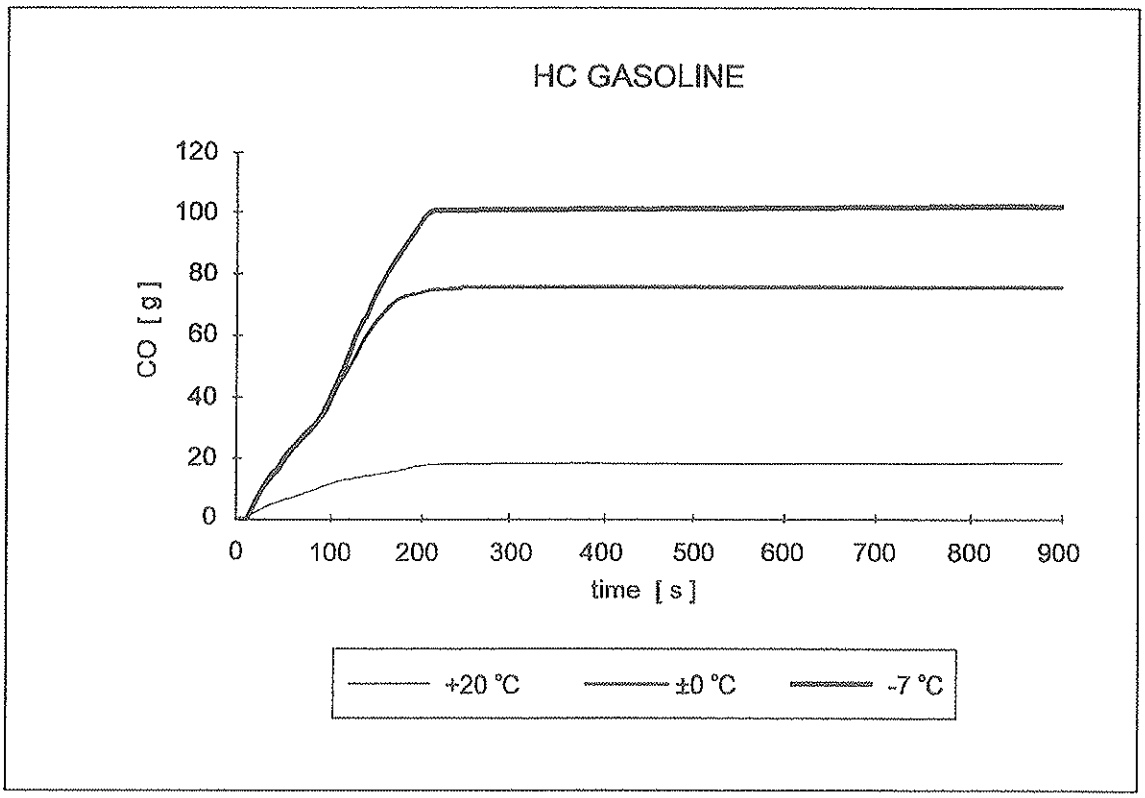



Figure 14. Cumulative CO emission on the gasoline engine (HC gasoline).

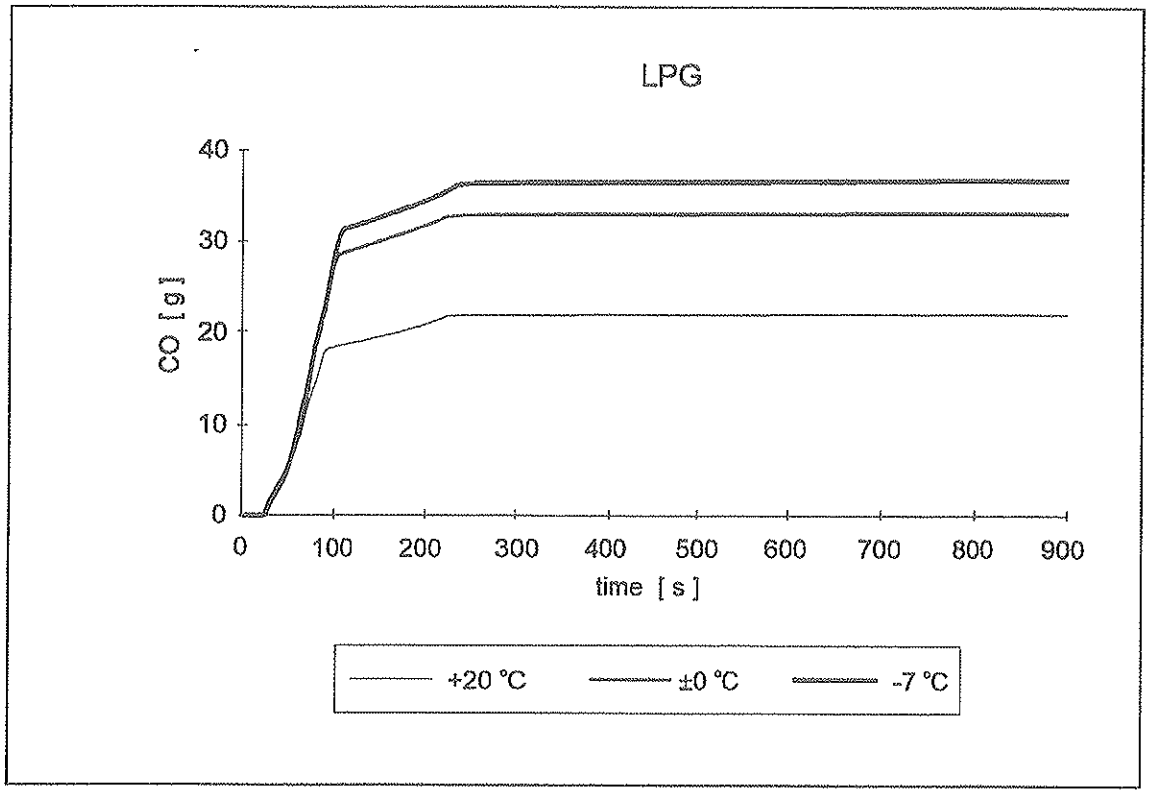



Figure 15. Cumulative CO emission of the gas engine (LPG).

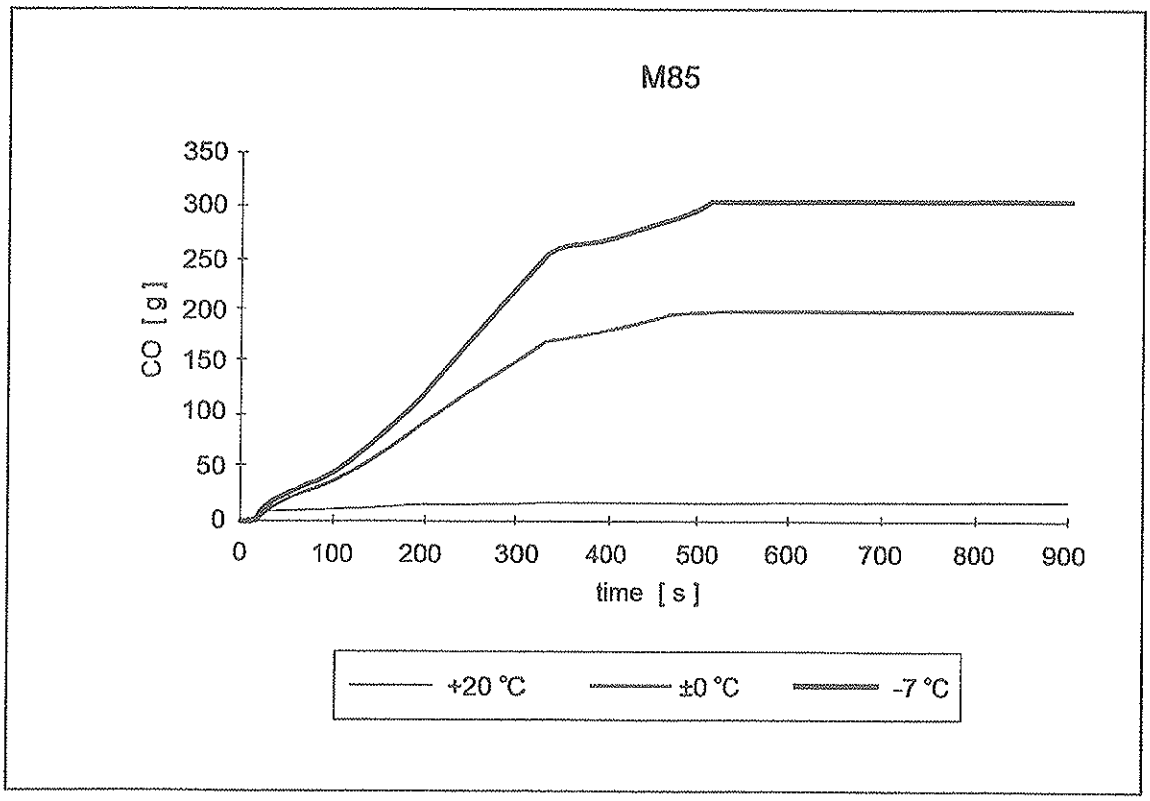



Figure 16. Cumulative CO emission on the M85 engine (M85 primed with gasoline).

## 11.3 Unregulated exhaust emissions

### 11.3.1 General remarks

In the final tests, emphasis was focused on the measurement of unregulated exhaust components. The new FTIR instrument was used for these measurements. Due to the large amount of data generated using the SESAM FTIR -system, the recording of the measurements was limited to the first part of the test cycle, i.e. the first 930 seconds of the test. The emission values presented contain the contribution of the cold start.

In the graphic presentations the following harmful components are displayed:

* $C_2H_2$ (acetylene)
* $C_2H_4$ (ethylene)
* $C_3H_6$ (propylene)
* $C_4H_6$ (1,3-butadiene)
* AHC (sum of light aromatic hydrocarbons)
* formaldehyde
* unburned methanol or ethanol

Ethanol is included here, although it is not a "real" toxic component. Due to the fairly high detection limit of the FTIR technology for acetaldehyde in engine exhausts, acetaldehyde was not included in the discussion.

### 11.3.2 Results

The results expressed as g/kWh are given in Figures 17-19. The values are valid for the first part (930 seconds) of the test. If the measurements had been carried out over the whole test, the values would have been some 50 % lower for most of the components. The reason for this is that the catalyst reduces also most of the unregulated compounds very effectively after light-off. Figures 20-22 show the total emissions of hydrocarbons and the emissions of some saturated hydrocarbons.

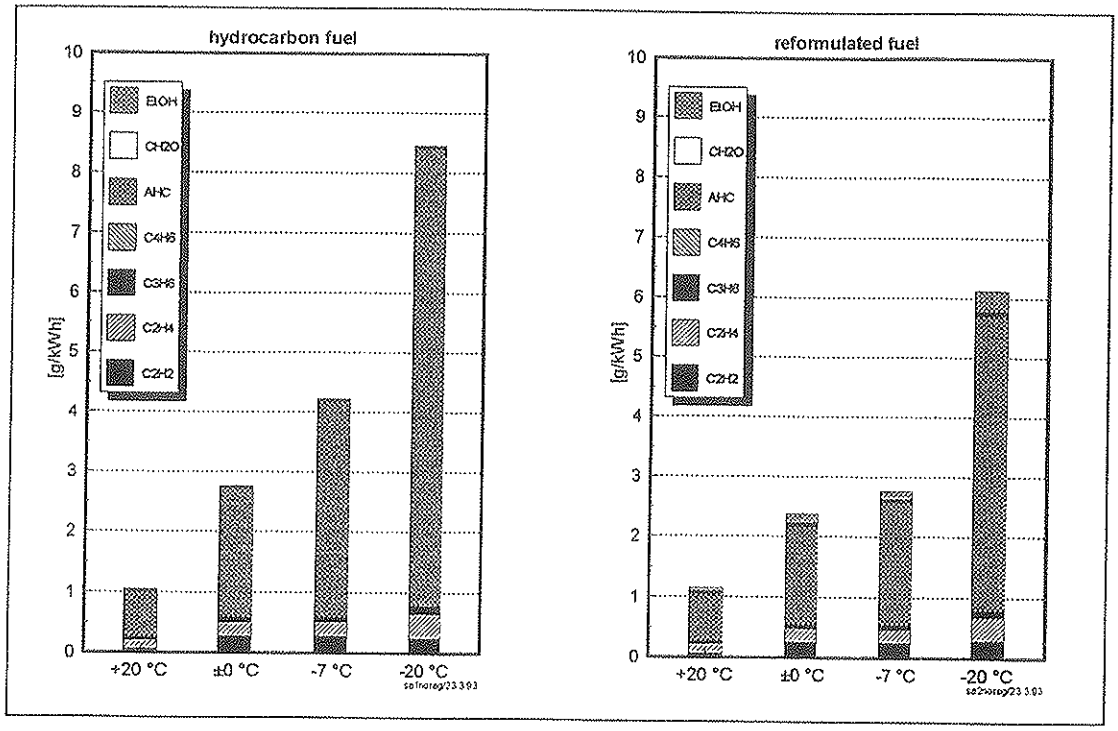



Figure 17. Unregulated emissions with gasoline.

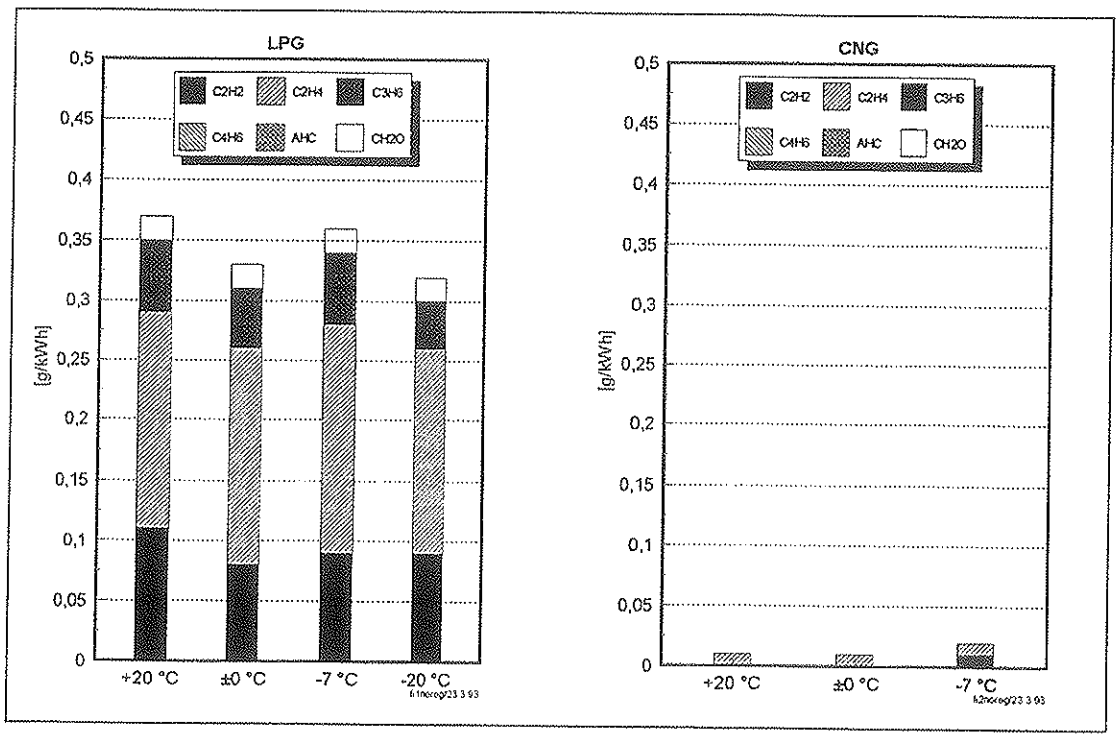



Figure 18. Unregulated emissions with gaseous fuels.

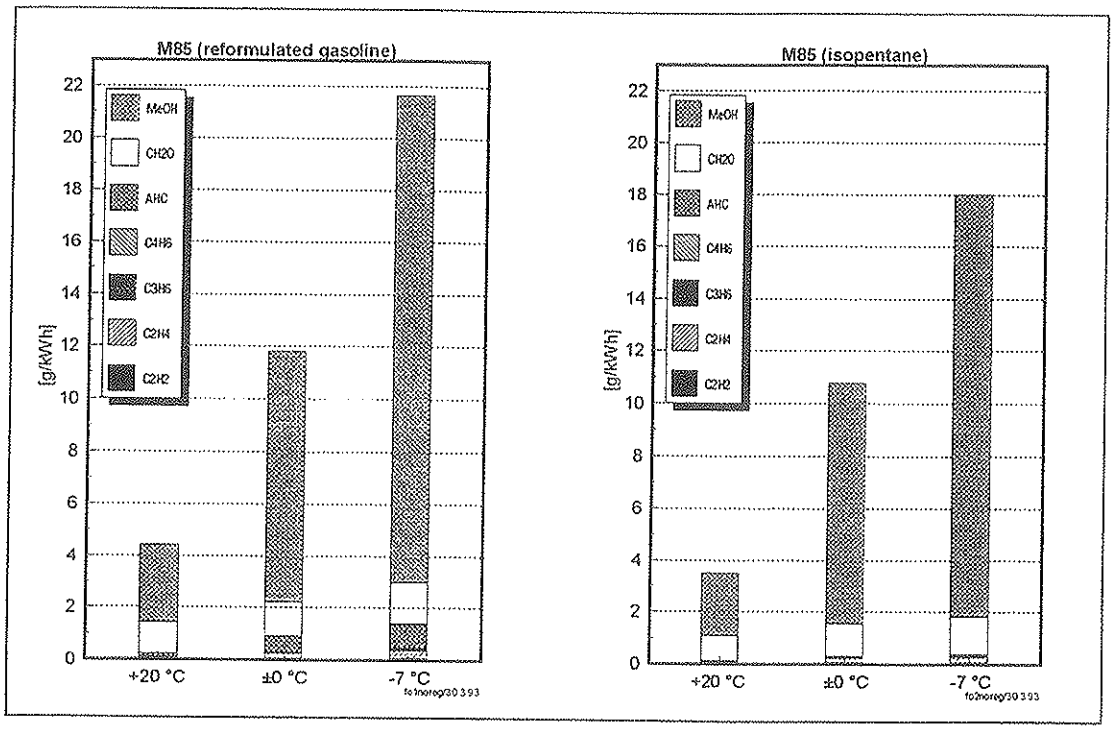



Figure 19. Unregulated emissions with M85.

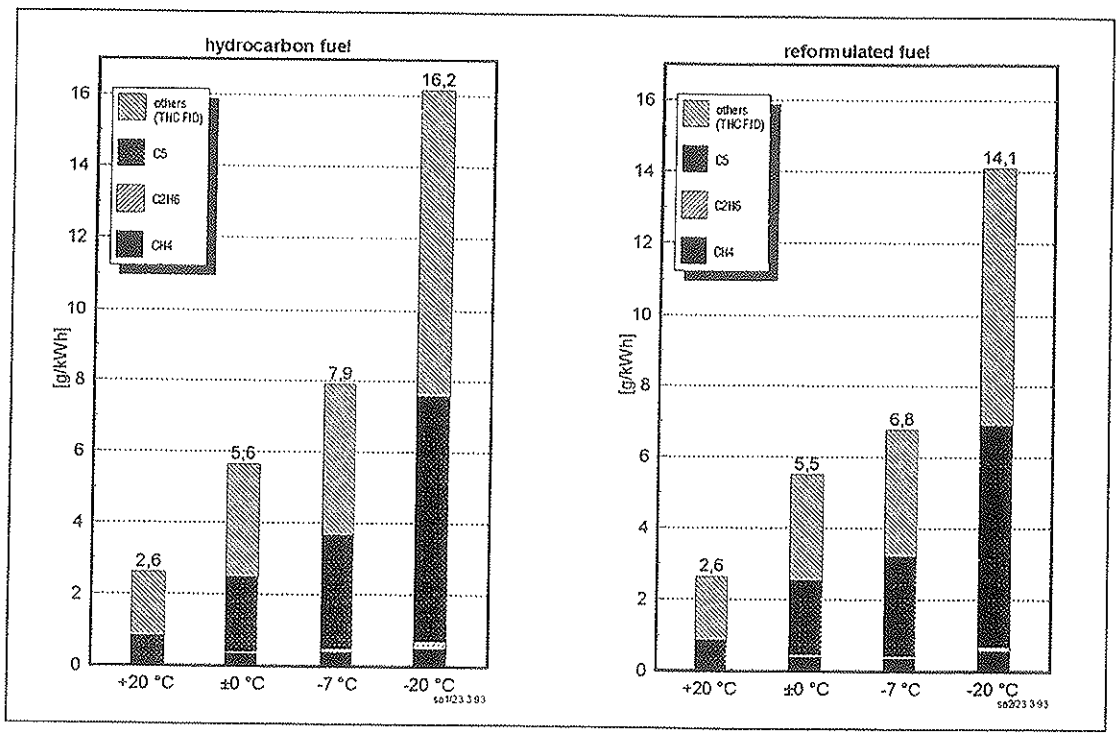



Figure 20. THC emission and emission of saturated hydrocarbons with gasoline.

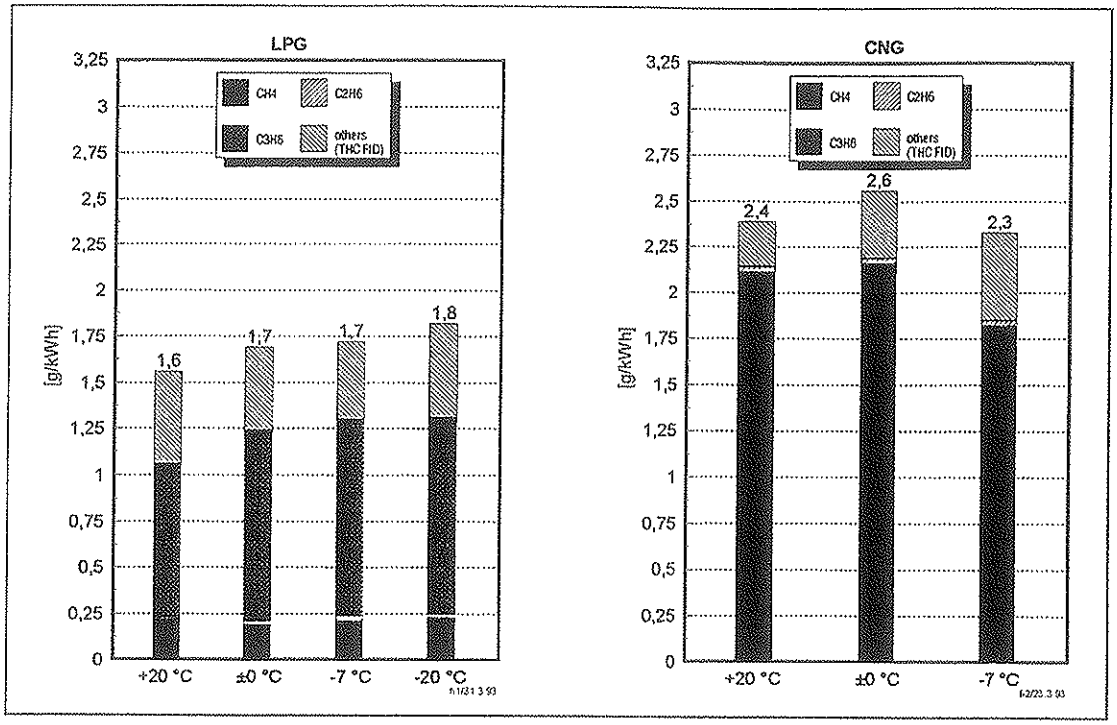



Figure 21. THC emission and emission of saturated hydrocarbons with gaseous fuels.

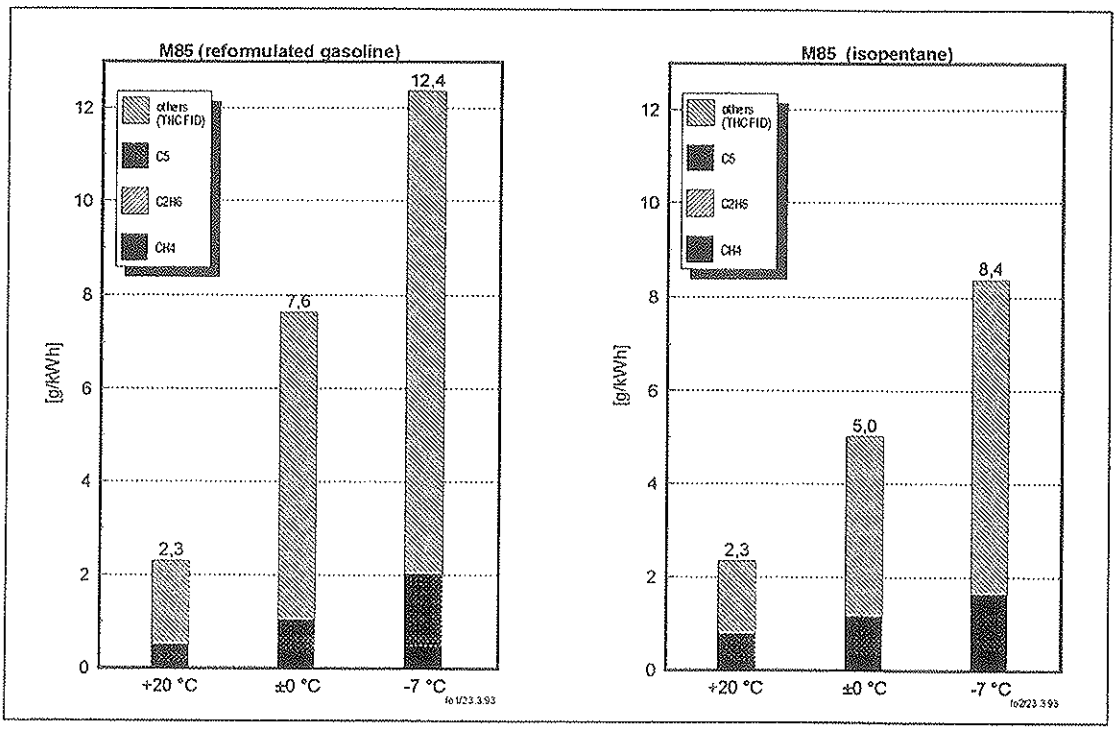



Figure 22. THC emission and emission of saturated hydrocarbons with M85 .

The total amount of harmful components ranged from 1 to 8.5 g/kWh on conventional gasoline (Figure 17). The dominating component was AHC. The value for AHC increased from appr. 0.75 to 7.5 g/kWh when the ambient temperature was lowered from +20°C to -20°C. The AHC concentration corresponds roughly to 40 % of the total FID-reading. As can be seen, small amounts of acetylene, ethylene and propylene were also emitted.

When oxygenated gasoline was used, the total amount of harmful components was reduced, especially AHC at low temperatures. The total amount of harmful components was between 1 and 6 g/kWh. In this case the exhaust also contained unburned ethanol. With both the hydrocarbon and the reformulated gasolines the concentration of 1,3-butadiene was below the detection limit of the FTIR instrument (6 ppm). A weighted concentration of 6 ppm over the first part of the test (15 minutes) would correspond to an emission level of 0.08 g/kWh (total mass 0.10 g).

The gaseous fuels gave very low emissions of harmful components, appr. 0.35 g/kWh for LPG and below 0.025 g/kWh for CNG. The values seemed to be independent of ambient temperature. For propane the concentration of these harmful components was roughly 20 %, and for CNG only less than 1 % of the total FID reading. Of the harmful components considered in this study, ethylene, acetylene, propylene and some formaldehyde were present in the LPG exhaust. In the case of CNG only small amounts of ethylene and acetylene were detected.

With M85 fuel the dominating component in this category of emissions was unburned methanol. The total values of harmful components were between 4 and 22 g/kWh using M85 primed with gasoline and from 3 to 18 g/kWh when isopentane was used as a primer. The methanol values were 3-19 g/kWh and 2-16 g/kWh. These levels of methanol emissions must be considered very high.

The total FID response was equivalent to 2 to 12 g/kWh. This is because the FID has a lower response to oxygenates than to hydrocarbons, mainly because the ratio between carbon (C) and hydrogen (H) is much different in these compounds. The emissions of formaldehyde seemed to be relatively independent of ambient temperature. This observation was also made during the preliminary tests. The values ranged between 1 and 1.5 g/kWh. When gasoline was used to prime the M85 fuel, aromatic hydrocarbons could be found in the exhaust.

Figure 23 shows the AHC concentration of undiluted exhaust as a function of time at different ambient temperatures. As in the case of total hydrocarbons, the AHC drops to practically 0-level after catalyst light-off. The maximum concentration found at -7 °C was appr. 3000 ppm.

Figure 24 shows methanol traces and Figure 25 formaldehyde concentration traces of undiluted exhaust over the test with the M85 engine. As can be seen, the methanol concentration reached extremely high values, around 20,000 ppm, which was well above the normal calibration range of the FTIR instrument. These measurements indicate that the emissions of unburned methanol are a severe problem for this particular M85 engine. Although the methanol concentration goes down after catalyst light-off, formaldehyde concentrations around 100 ppm can still be found after this takes place.

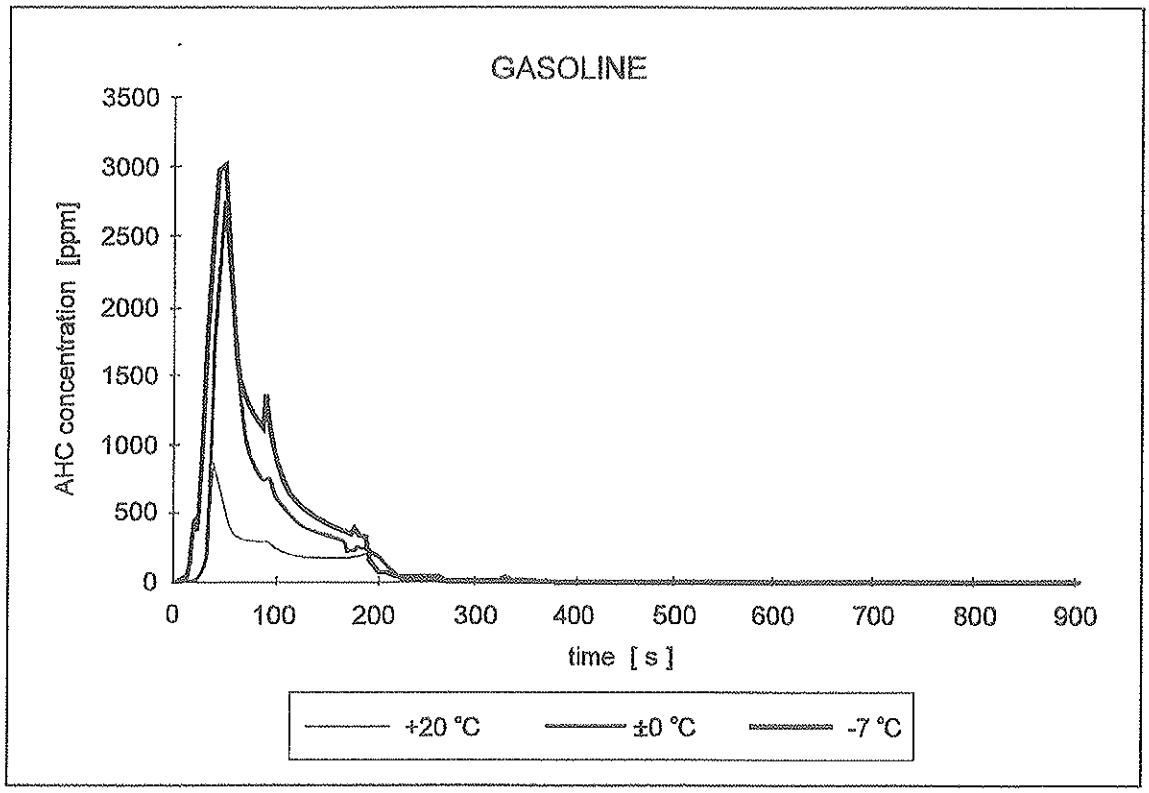



Figure 23. AHC concentration traces with gasoline.

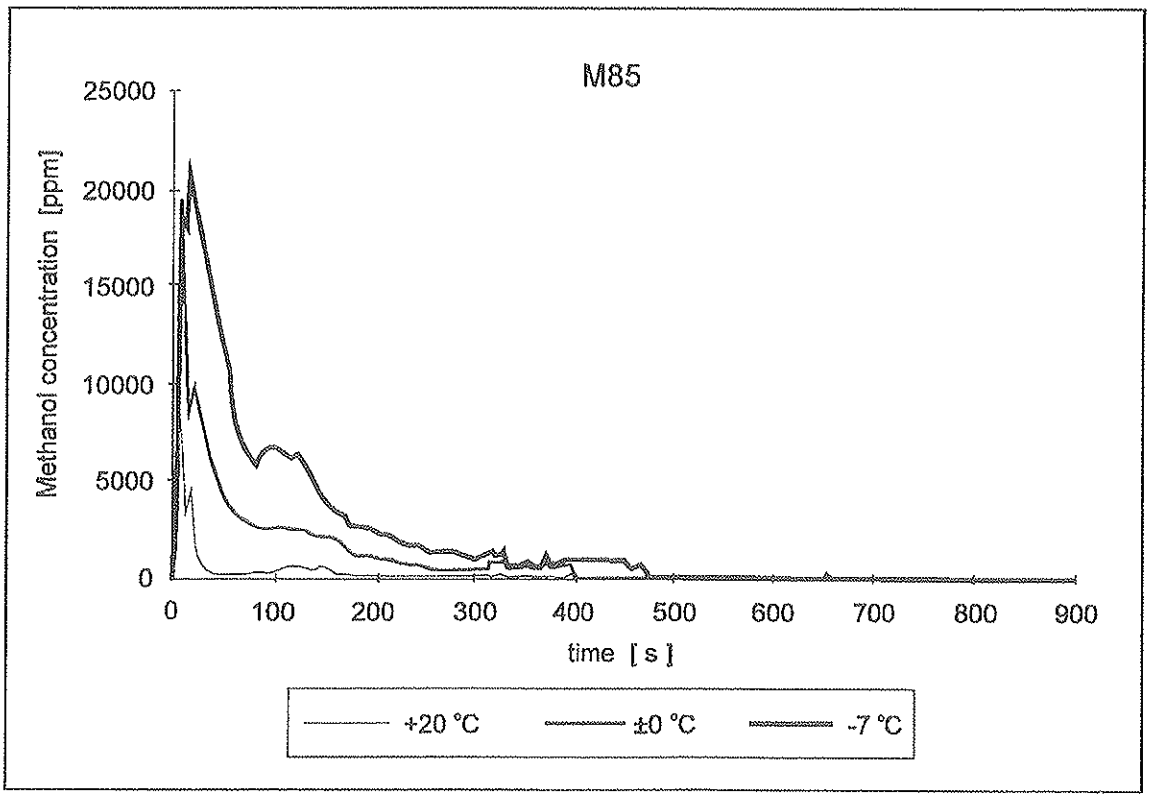



Figure 24. Methanol concentration traces with M85.

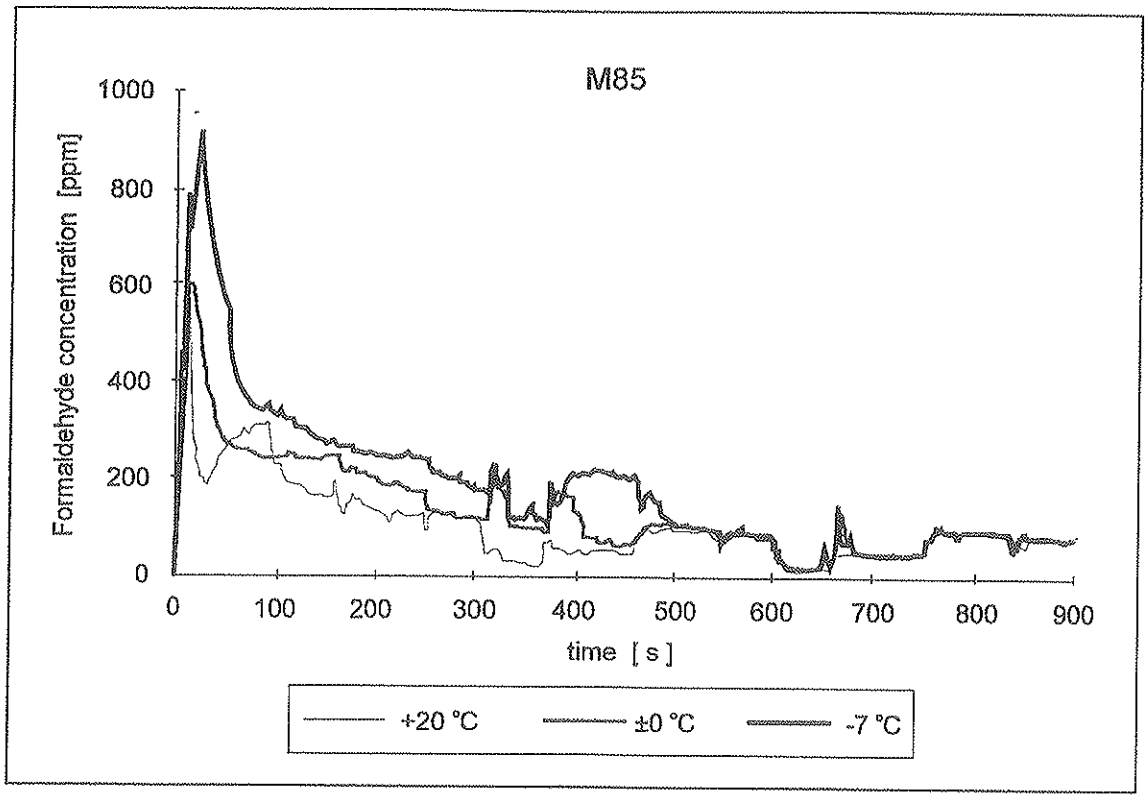



Figure 25. Formaldehyde traces with M85.

Figure 26 shows the cumulative methanol and Figure 27 the cumulative formaldehyde emission. The methanol trace has more or less the same shape as the cumulative HC trace. The formaldehyde trace, however, shows that even after catalyst light-off substantial amounts of formaldehyde were emitted. However, according to Japanese results, 90 % of the formaldehyde emissions over an emission test are generated while the engine is cold /11/. The results obtained now are in conflict with this former conclusion.

The estimated formaldehyde emissions in g/km for the first part of the test (930 seconds/10 km) would be appr. 200 mg/km at +20 °C. An extrapolation of the cumulative formaldehyde curve to 1800 seconds would give a total formaldehyde emission of some 3.5 grams. The overall average formaldehyde emission for whole test (1800 seconds/20 km) would thus be in the order of 170 mg/km. This is substantially higher than the values given in Table 2 (40 mg/mile). The formaldehyde emissions are about 10 times higher than the California limit value for formaldehyde (15 mg/mile /1/).

Similarly, the estimated result for methanol emissions would be 500 mg/km for the first part, and 300 mg/km for the whole test. These values should be compared with the value of 215 mg/mile (134 mg/km) in Table 2.

These high values obtained in the engine tests are probably due to "old" engine technology (MY 1986) and the high mileage (110.000 km) of the catalysts. The catalysts, however, still reduced regulated emissions efficiently. In the case of formaldehyde, one reason might also be the fact that for formaldehyde FTIR results in general, according to our experience, were higher than those obtained with DNPH impinger/cartridge sampling and HPLC analysis.

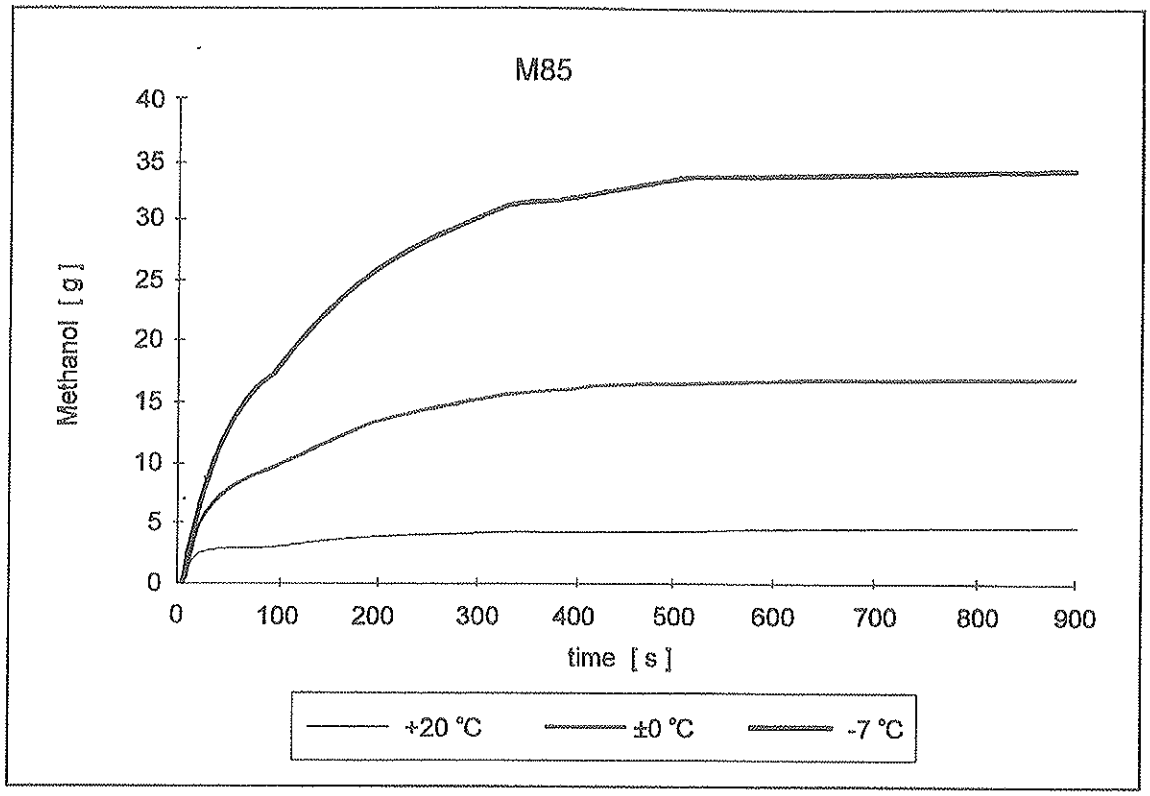



Figure 26. Cumulative methanol emission.

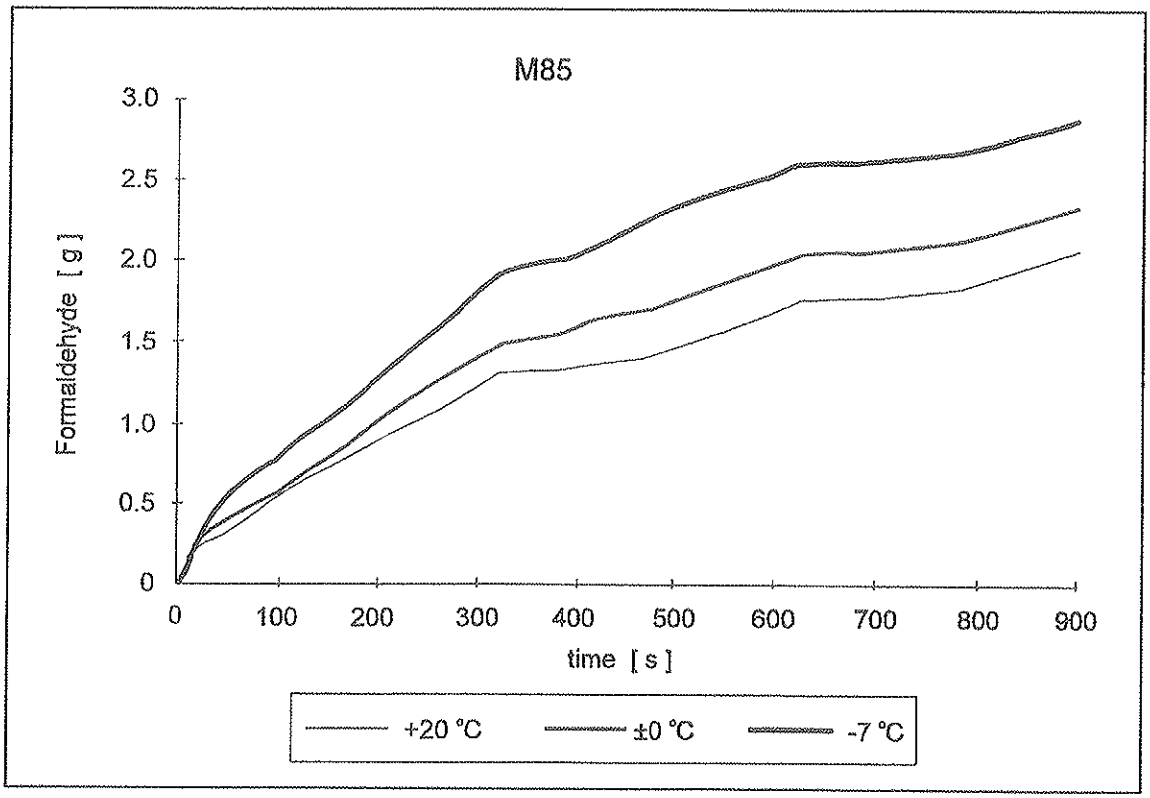



Figure 27. Cumulative formaldehyde emission.

## 12. SUMMARY OF ENGINE TESTS

Three engines (one gasoline engine, one engine on gaseous fuels and one engine fueled with M85) were tested for regulated and unregulated exhaust emissions at the ambient temperature range of +20 to -7 °C. Some tests were also carried out at -20 °C. All engines were equipped with a closed-loop fuel system and a TWC.

The tests were carried out as engine tests, with the test engines connected to a computer controlled eddy-current type engine dynamometer. Test duration was 30 minutes. The engines were connected to a normal CVS-type exhaust sampling system. The emissions of regulated components were determined by diluted bag sampling and the exhaust gas compositions before and after the catalyst were monitored continuously with a dual-bench analyzer system.

All engines gave roughly the same level of regulated pollutants at +20 °C. However, when the ambient temperature decreased, considerable differences appeared. As no cold start enrichment is needed when gaseous fuels are used, the emissions of CO and HC were more of less unaffected by the test temperature for the engines fueled with LPG or CNG. On the other hand, lowering the test temperature from +20 to -7 °C increased the CO and HC emissions of the gasoline engine by a factor of 3 to 5. However, using oxygenated gasoline instead of normal hydrocarbon gasoline resulted in a small reduction of HC emission at low temperatures.

For gasoline and the gaseous fuels, the emissions outputs stabilized within appr. 200 seconds after a cold-start at -7 °C. In the case of the gasoline engine, an estimated extrapolation of emission values in g/km for the whole test cycle (1800 seconds) correlated well with FTP-results obtained with a corresponding vehicle.

Cold start is a problem with alcohol fuels. When isopentane was used as a primer instead of gasoline in the M85 fuel, the startability was somewhat improved. Lowering the test temperature from +20 to -7 °C increased the CO emissions by a factor of 12 and the HC emissions (measured by FID) by a factor of 5. The specific CO emissions expressed as g/kWh for the M85 engine were thus 5 to 20 times higher than for the test engine fueled with LPG and CNG at -7 °C.

A new type of instrument based on FTIR technology was used to measure unregulated exhaust components. This instrument called SESAM (supplied by SIEMENS) is capable of measuring 20 to 25 different components at 1 second time resolution. This made the modal analysis of components like methanol and formaldehyde possible. Overall, mass emissions of the unregulated components were determined through integration. The SESAM-instrument has some limitations in measuring benzene and acetaldehyde.

Comparisons of the unregulated harmful emissions of the engines were made. The comparisons included acetylene, ethylene, propylene, 1,3-butadiene, gaseous aromatic hydrocarbons, formaldehyde and unburned alcohol. The unregulated emissions were measured over the first part of the test cycle (15 minutes), and the emission values were expressed as specific emissions (g/kWh).

For the gasoline engine the emissions of harmful unregulated components varied from 1 to 9 g/kWh depending on the test temperature. This would be equivalent to an emission value of 0.1 to 1.1 g/km over the first part of the test. The dominating components in this group of emissions were aromatic hydrocarbons. The gaseous fuels gave by far the lowest emissions of harmful components (appr. 0.3 g/kWh for LPG and 0.025 g/kWh for CNG) and these were independent of test temperature.

The emissions of harmful unregulated components varied from 3 to 22 g/kWh for the M85 engine - unburned methanol being the dominating component. These values would be equivalent to emissions values between 0.5 and 4 g/km for the first part of the test. Peak values of up to 20,000 ppm unburned methanol could be found under cold start conditions. The emissions of formaldehyde were between 1 and 1.5 g/kWh independent of ambient temperature. Thus, the differences in unregulated emissions are even greater than the differences in regulated emissions with the different fuel alternatives.

The tests indicated that both the fuel and the test temperature have a major impact on the regulated as well as on the unregulated emissions. CNG gave by far the lowest total emissions and the emissions were almost independent of temperature. LPG also gave very good results. The fuel system used for the gaseous fuels was not, however, fully developed. There is still room to improve control accuracy, among other things.

The gasoline engine performed reasonably well. Ambient temperature had, however, a relatively strong influence on both regulated and unregulated emissions. The gasoline engine was the only engine to start and operate without any problems at -20 °C.

The M85 engine had low emission rates of regulated emission components at +20 °C. The emissions of formaldehyde and especially methanol, however, were fairly high. The emission performance deteriorated dramatically even at ±0 °C. This is a clear indication that systems designed for operation in warm conditions may not be very suitable for general service. One reason for the results obtained with the M85 engine might be the outdated engine technology (MY 1986) and the high mileage of the catalysts (110,000 km).

Part One, Engine Tests, served as a starting platform for the work within Annex V. It very clearly demonstrated that there are significant differences in emission performance with different fuels. Much of the experience gained from Part One, i.e. emission measurement technology, was utilized in the continuation on the work in Part Two, light-duty vehicle tests.

## REFERENCES FOR PART ONE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# PART TWO: VEHICLE TESTS

# 13. GENERAL

Part Two of Annex V, "Light-duty vehicle tests", was also focused on low temperature emissions of different technologies with more emphasis given to unregulated emissions. Included in the work were not only new vehicle technologies for alternative fuels, but also conventional gasoline vehicles were tested as a basis for comparison.

The objectives written down in the description of Part Two of Annex V were:

* to continue the generation of emission data on both regulated and unregulated emissions from different light-duty concepts
* to determine the emission potential of both alternative and reformulated fuels
* to determine what can be accomplished with oxygenated fuel components
* to increase the knowledge of fuel composition effects on the unregulated emission components
* interaction with Annex VII in the future

and in addition:

* to generate data on serviceability and emission system durability of fuel flexible vehicles (FFV's) and natural gas vehicles (NGV's) operating in severe climatic conditions (in cooperation with a national research program in Finland, to be reported later).

# 14. VEHICLES AND FUELS

## 14.1 Test vehicles

Altogether 11 vehicles were involved in Part Two. The test vehicles are identified by code numbers. Test vehicles 1, 2, 3 and 4 were gasoline vehicles, vehicles 5, 6, 7 and 8 were FFV's, and vehicles 9, 10 and 11 were gaseous fuel vehicles.

### 14.1.1 Conventional vehicles

Both hydrocarbon gasoline and oxygenated/reformulated gasoline were tested in conventional vehicles which represented the following technologies:

* carburetted engine (vehicle 1) (representing pre 1985 technology)
* fuel injected engine (vehicle 2) (representing 1985-1990 technology)
* TWC engine (vehicle 3) (MPFI, representing technology of the 90's)
* TWC engine with secondary air injection (vehicle 4) (MPFI, representing the latest technology)

The conventional vehicles were included to form a basis for comparison. These vehicles were run on several fuel formulations. Since the number of vehicles was limited (one per category), the results cannot give a statistically conclusive picture of the influence of gasoline quality on emissions.

### 14.1.2 Fuel flexible vehicles

Altogether four fuel flexible vehicles using three-way catalyst (TWC) technology were tested. The vehicles tested were:

* 2 Nordic vehicles (codes 5 and 8, prototype vehicles)
* 1 European vehicle (code 6)
* 1 US vehicle (code 7)

Vehicle 5, which is a prototype vehicle, has no fuel composition sensor. Instead it uses a mixing tank in the fuel line to make the fuel supplied to the engine change composition so slowly that the lambda control system has time to adjust to the new fuel quality. This vehicle can run on any gasoline/methanol or gasoline/ethanol blends.

Vehicle 6 is equipped with an alcohol sensor. Roughly 200 vehicles of this type have been produced. Vehicle 7 has also an alcohol sensor and it is commercially available in the US. Vehicle 8 has also a sensor and it is a prototype like vehicle 5. Vehicle 8 is equipped with an electrically heated pre-catalyst and secondary air injection into the exhaust system.

### 14.1.3 Vehicles on gaseous fuels

Three vehicles of this type were tested. Two of these are European vehicles retrofitted for gaseous fuels in Holland using the best available commercial technology (multipoint gaseous fuel injection) /24/. The third one is a factory built and commercially available dedicated CNG-vehicle. All vehicles use TWC-technology. The vehicles were:

| | |
|---|---|
| * 1 European passenger car (code 9) | (LPG) |
| * 1 European van (code 10) | (LPG and CNG) |
| * 1 US van (code 11) | (dedicated CNG) |

Technical data on all the test vehicles are given in Appendix 1.

## 14.2 Test fuels

A detailed summary of the test fuels is presented in Appendix 2.

### 14.2.1 Conventional vehicles

The baseline fuel for the gasoline vehicles was Eurograde gasoline without oxygenates. The following test fuels were used:

| | | |
|---|---|---|
| * | baseline HC fuel (fuel code a) | (all vehicles) |
| * | oxygenated gasoline (ETBE) | |
| | 2 % oxygen, 2.3 % benzene, 240 ppm sulphur (code b) | (vehicles 2 & 3) |
| * | oxygenated gasoline (MTBE) | |
| | 2 % oxygen, 2.3 % benzene, 240 ppm sulphur (code c) | (vehicles 2 & 3) |
| * | reformulated gasoline (MTBE) | |
| | 2 % oxygen, 1 % benzene, 100 ppm sulphur (code d) | (vehicles 2 & 3) |
| * | HC fuel blended with ethanol, oxygen content 2...4 % (code e) | (vehicle 1) |

For fuel type "e" different vapor pressure levels were used depending on the test temperature.

### 14.2.2 Fuel flexible vehicles

The fuels used in the FFV's were technical grade methanol and dehydrated ethanol blended with commercial winter grade gasoline. The concentrations of alcohol used were 0, 50 and 85 %. (E50 was not used.) The fuel codes used are M0, M50, M85, E0 and E85 (0 meaning 100 % baseline HC fuel, code a). Vehicle 5 was run on E/M0, M50, M85 and E85. Vehicles 6, 7 and 8 were run on fuels M0, M50 and M85.

### 14.2.3 Vehicles on gaseous fuels

Vehicle 9 was run on commercial grade Dutch LPG, ie. 70 % propane and 30 % butane. Vehicle 10 was run on baseline gasoline, Dutch LPG and Dutch CNG. The main components in Dutch natural gas are methane (81 %), nitrogen (10 %), carbon dioxide (4 %) and ethane (4 %). Vehicle 11 was run on Russian natural gas available in Finland ($CH_4$ > 98 %).

## 15. TEST PROGRAM AND GENERAL PROCEDURE

The tests were carried out as vehicle tests in a climatic test cell equipped with a chassis dynamometer. The testing was carried out according to the US Federal Test Procedure /21/. The temperature, however, was varied between +22 and -20 °C.

Each vehicle was run at 3 or 4 temperatures. The test temperatures used were +22, +7, 0, -7 and -20 °C. Only the gasoline vehicles were run down to -20 °C.

Both regulated and unregulated emissions were measured. In addition to the standard CVS-type bag sampling for the regulated emissions, modal analyses were done. The unregulated components were measured using both on-line measurement technology (FTIR, Fourier Transformation Infra Red) and bag/impinger type sampling.

The testing was carried out over a relatively long time period starting in the autumn 1992. In the summer of 1993, a gas chromatograph (GC) for hydrocarbon speciation was commissioned, but vehicles 1 (gasoline) and 5 (methanol/ethanol FFV) were tested before that. GC measurements were not performed with vehicle 9, either.

For the other vehicles tested the following measurements were performed:

* regulated emissions (bag sampling)
* modal analysis of regulated components (continuous measurement)
* FTIR-measurement for unregulated components (FTP phase 1 and 3)
* hydrocarbon speciation by gas chromatograph (FTP phase 1, 2 and 3)
* emissions of aldehydes by DNPH cartridges/HPLC (FTP phase 1, 2 and 3) (vehicles 7 and 8 only)

(DNPH= 2,4-dinitrophenylhydrazine, HPLC= high pressure liquid chromatograph)

A large number of tests were conducted in the program. Generally, tests were not repeated. Because several temperatures and fuel combinations were run, it was possible to determine whether a test was valid or not, and only those tests that were suspect were repeated. This final report contains data from measurements of roughly 110 vehicle/fuel/temperature combinations, and data from about 140 FTP tests.

The climatic test chamber in which the tests were carried out is big enough to take three vehicles at a time. The chamber was filled with a batch of three vehicles each evening, and the vehicles were tested the next day after overnight conditioning at the test temperature. Three tests can be carried out during a normal working shift if special measurements (unregulated emissions) are performed. For each new vehicle and new fuel a certain preconditioning procedure was carried out in order to stabilize the conditions before each test.

For all vehicles and fuels the testing was started at +22 °C, and then the test temperature was lowered step by step. This sequence was used to give adaptive fuel systems a chance to adjust to the changing temperature.

The test program matrix is given in Table 9.

Table 9. Test program matrix.

| fuel | vehicle | number of fuels | test temperatures (°C) | number of combinations |
|---|---|---|---|---|
| gasoline | 1 | 4 | +22[1], -7, -20 | 12 |
| | 2 | 4 | +22, 0, -7, -20[2] | 14 |
| | 3 | 4 | +22, 0, -7, -20[2] | 14 |
| | 4 | 1 | +22, 0, -7, -20 | 4 |
| methanol/ethanol | 5 | 4 | +22[1], 0, -7 | 12 |
| | 6 | 3 | +22, +7, 0, -7 | 12 |
| | 7 | 3 | +22, +7, 0, -7 | 12 |
| | 8 | 3 | +22, +7, 0, -7 | 11[3] |
| gaseous fuels | 9 | 2 | +22, +7, 0, -7 | 6[4] |
| | 10 | 3 | +22, +7, 0, -7 | 12 |
| | 11 | 1 | +22, +7, 0, -7 | 4 |
| total number of combinations[5] | | | | 113 |

1) +20 °C was used with this vehicle
2) -20 °C was used with two fuels only
3) The vehicle did not start on at -7 °C on M85
4) Only +22 and ±0 °C were used on gasoline
5) Total number of tests is about 140, since some were repeated.

# 16. INSTRUMENTATION AND CALCULATION PROCEDURES

## 16.1 General

The light-duty vehicle emission tests were carried out at VTT in a climatic test cell equipped with a chassis dynamometer (Figure 28). The chassis dynamometer is a single axle, 1,0 meter roller diameter DC-type machine manufactured by Froude Consine. The dynamometer is mounted flush with the floor, so nothing obstructs the air flow from the windage simulation blower in the room. In these tests the blower was set to a constant air speed of 25 km/h.

The dynamometer has only 6 bearings: two for the rollers, two inside the DC machine and two for the DC machine cradle. The bearings are heated to stabilize friction. The machine does an automatic warmup and friction compensation routine, and this procedure is carried out before each series of measurements.

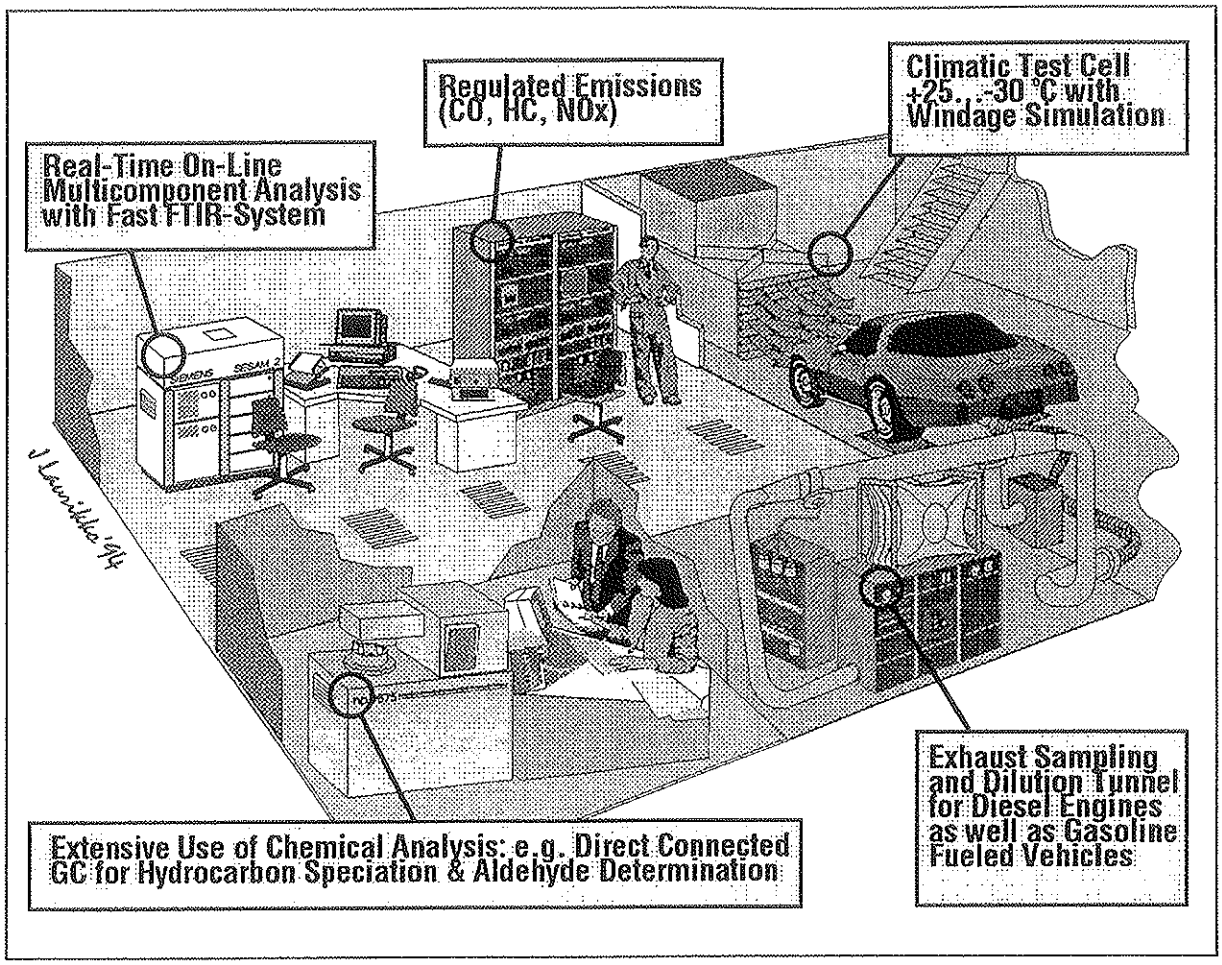



Figure 28. The climatic emissions test cell at VTT.

## 16.2 Exhaust emissions

### 16.2.1 Regulated components

Basically the same instrumentation was used as for THE engine tests, i.e. a US FTP-compatible emissions measurement system by Pierburg (Germany). The system consists of a PDP (Positive Displacement Pump) type CVS-sampler (Pierburg 12,5 WT, maximum flow 12.5 $m^3$/min) and a versatile analytical bench (Pierburg AMA 2000). The analytical system is described in detail in Part One of this report. The analytical system was used to perform the bag analyses and to continuously measure the exhaust gas composition.

In sub-zero measurements an electrically heated tube was used between the end of the vehicle tailpipe and the CVS device. The CVS device is placed in a separate warm room outside the climatic chamber.

## 16.2.2 Unregulated components

In Part One, the FTIR instrument (SESAM II by SIEMENS) was used to measure certain unregulated exhaust components. Also, the SESAM II instrument is described in detail in Part One of this report. In Part Two, hydrocarbon speciation by gas chromatography and aldehyde measurement by DNPH cartridge sampling and high pressure liquid chromatography analyses were added to the program.

Due to the huge amount of data generated, the measurement period of the SESAM instrument was limited to about 15 minutes so it was not possible to carry out the measurements over the whole FTP test. It was decided to use the SESAM to measure phase one and phase three of the FTP test. When calculating estimated composite FTP results phase three values were used for phase two. This leads only to a very small overestimation for the emissions of the different components. For most of the components phase one alone almost determines the overall result. In general, phase two (hot stabilized) gives lower emissions than phase three (hot transient).

The SESAM instrument measures undiluted exhaust. Therefore, it is necessary to determine the instantaneous exhaust flow and corresponding concentrations to calculate mass emissions. The $CO_2$ tracer of the AMA system was used for the calculation of the instantaneous exhaust flow. The exhaust flow calculation and integration were checked by comparing integrated SESAM CO values to bag sampling. For CO, the differences between integrated values and bag values were in general smaller than 10 %. Thus, the integrated SESAM values are considered to be relatively reliable.

A two-channel Hewlett Packard 5890 Series II gas chromatograph equipped with two FID detectors was installed close to the CVS room. The GC draws its diluted samples from the CVS tedlar bags. The GC is equipped with Chrompack PLOT Fused Silica columns. With the calibrations used the GC is capable of detecting the following hydrocarbons:

* methane $CH_4$
* acetylene $C_2H_2$
* ethylene $C_2H_4$
* ethane $C_2H_6$
* propylene $C_3H_6$
* propane $C_3H_8$
* isobutene $C_4H_8$
* 1,3-butadiene $C_4H_6$
* isopentane $C_5H_{12}$
* benzene $C_6H_6$
* toluene $C_7H_8$
* xylene ($C_8H_{10}$) (not measured from vehicle 10, $C_4H_{10}$ measured instead)

Hydrocarbon speciation was carried out for all three phases of the FTP test. The results were compensated for ambient air concentrations.

The FTIR is suitable for continuous measurements and for modal analyses. However, it has some limitations regarding sensitivity. The GC offers the opportunity to determine very small concentrations of, for example, benzene and 1,3-butadiene.

As formaldehyde and acetaldehyde are the dominating aldehydes, the analyses were limited to these two species. The aldehyde samples were analyzed with a Hewlett Packard HPLC according to the method of Lipari and Swarin /25/.

Aldehydes were sampled in the conventional way using both DNPH impingers and cartridges in parallel. The samples were taken from the diluted exhaust during each of the three FTP phases. The cartridges were found to give higher and more repeatable values than those obtained using the impingers. In the later part of testing only cartridges were used.

When comparing impinger sampling to FTIR results, the FTIR technology gave higher values in general. However, cartridge sampling and the FTIR were eventually found to give values consistent with each other. Therefore, FTIR aldehyde values are used in this report.

A summary of the analysis techniques used is given in Table 10.

Table 10. Summary of analyses.

| instrument/method | bag analysis | modal analysis |
|---|---|---|
| AMA 2000 | CO, THC, $NO_x$, $CO_2$ | CO, THC, $NO_x$ |
| SESAM FTIR | | $CH_3OH$, $C_2H_5OH$, HCHO, $CH_3CHO$ *) |
| GC | $CH_4$, $C_2H_2$, $C_2H_4$, $C_2H_6$, $C_3H_6$, $C_3H_8$, $C_4H_8$, $C_4H_6$, $C_5H_{12}$, $C_6H_6$, $C_7H_8$, $C_8H_{10}$ | |
| HPLC | HCHO, $CH_3CHO$ | |

*) altogether some 15 components measured with this instrument

All results, both for regulated and unregulated compounds are given as composite FTP results with weighting factors for the different phases given by the US Code of Federal Regulations.

# 17. RESULTS

Complete results are given in Appendices 3 (regulated emissions) and 4 (unregulated emissions). The unregulated emissions are given separately for the GC, FTIR and DNPH methods. The results of regulated emissions are illustrated by Figures 29...33 (section 17.1) and the results of unregulated emissions by Figures 34...38 (section 17.2).

## 17.1 Regulated emissions

The regulated emissions of the gasoline vehicles with conventional gasoline are given in Figure 29. At +22 °C the CO emissions of the non-catalyst vehicles are some 5 times and the HC emissions some 15 times those of the TWC vehicles. Both CO and HC emissions increase strongly with falling temperature. The $NO_x$ emissions are more independent of temperature. As expected, temperature has the strongest relative influence on the emissions of the TWC vehicles.

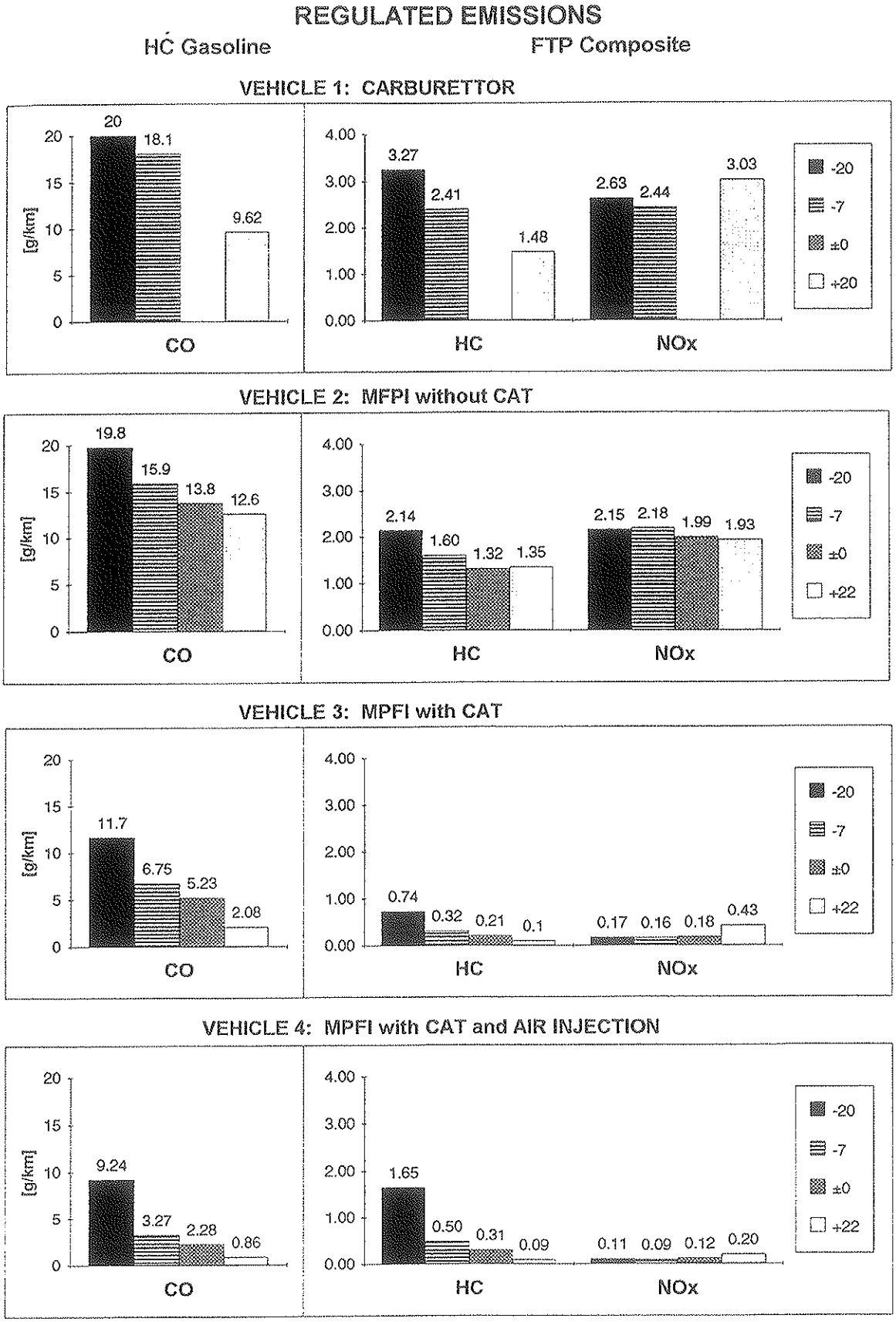



Figure 29. Regulated emissions of the gasoline fueled vehicles 1, 2, 3 and 4.

For the TWC vehicles CO and HC emissions will increase by a factor of 3...5 in the temperature interval +22...-7 °C. Vehicle 3 exceeds slightly the US low-temperature CO standard of 6.2 g/km at -7 °C, whereas, vehicle 4 with secondary air injection rates well below it /21/. The air injection in vehicle 4 has the strongest effect on CO emissions. However, the HC emissions for this vehicle are a little higher than for vehicle 3.

For the non-catalyst vehicles the increases in CO and HC emissions from +22 to -7 °C are only some 20...40 %. At -20 °C the CO emissions of the TWC vehicle are at the same level as the CO emissions of the non-catalyst vehicles at +22 °C.

Figure 30 shows the regulated emissions of FFV's 5 (M85 and E85) and 6 (M85). Vehicle 5 shows rather similar emission values on both M85 and E85. In both cases, however, the standards for CO (2.1 g/km) and HC (0.25 g/km) are exceeded at +22 °C. If the OMHCE value were available for this vehicle, the result would be even greater. The increase in emissions with falling temperature ( +22 to -7 °C) is moderate, roughly a factor of 2 for CO and 3...4 for HC. This was a prototype vehicle, which has to be considered evaluating the results. The vehicle did not perform well on gasoline, as the limit values for both CO and HC were exceeded.

Vehicle 6 performs rather well on M85. The levels of both CO, HC and $NO_x$ are significantly lower compared to the corresponding gasoline TWC vehicle 3, and at roughly the same level as for the advanced gasoline vehicle 4. As the temperature drops from +22 to -7 °C, the CO increases by a factor of 5. The HC emissions measured by FID, however, increase by a factor of roughly 15. The vehicle would pass the new US limit value of 6.2 g CO/km at -7 °C. The additional CO emissions caused by the cold start at -7 °C was roughly 70 g compared to 300 g for the M85 engine tested in Part One.

Figure 31 shows the regulated emissions of vehicles 7 and 8 (M85). Vehicle 7, which is the only commercial FFV vehicle tested, had the highest emissions of the methanol vehicles. The influence of temperature is very similar for vehicles 6 and 7.

Vehicle 8 is a special prototype vehicle for the California market and has been especially engineered to obtain low emission results. The emission control equipment in this vehicle includes an electrically heated small pre-catalyst and secondary air injection to the exhaust system after the lambda sensor, but before both of the catalytic converters.

The CO and HC results of vehicle 8 are about the lowest that have ever been measured at VTT on liquid fuels. However, the $NO_x$ values were generally higher than with the methanol fueled vehicles 6 and 7.

Vehicle 8 did not start at -7 °C on M85, apparently because of flooding. Since this vehicle was manufactured for California conditions, the engine control system had not been programmed for low temperatures. This can be seen also in the high CO value at ±0 °C compared to higher temperatures. The starting time on M85 was also a little longer than normal at ±0 °C. With an engine control system programmed for low temperatures, this vehicle would probably have low emissions even at -7 °C.

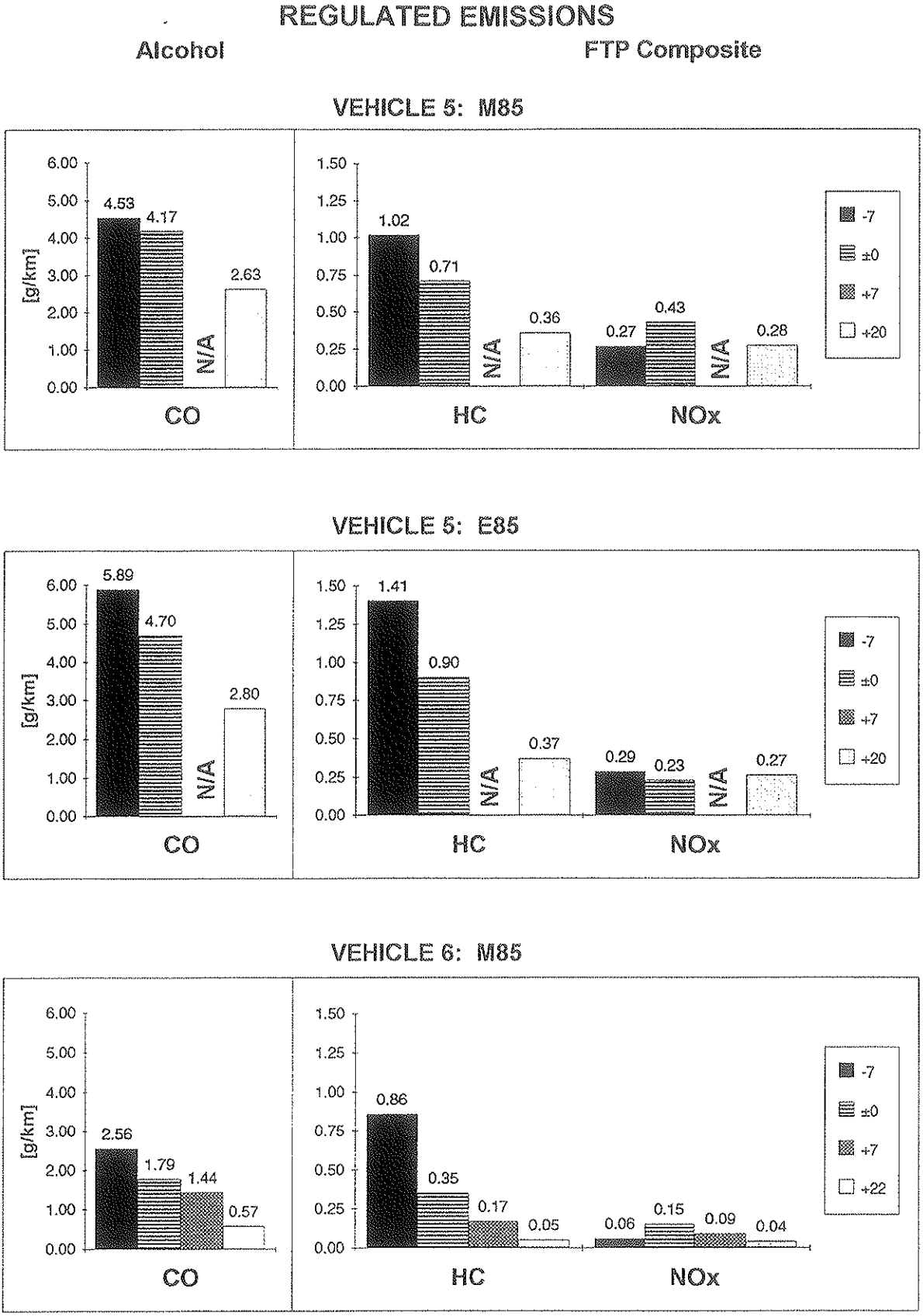
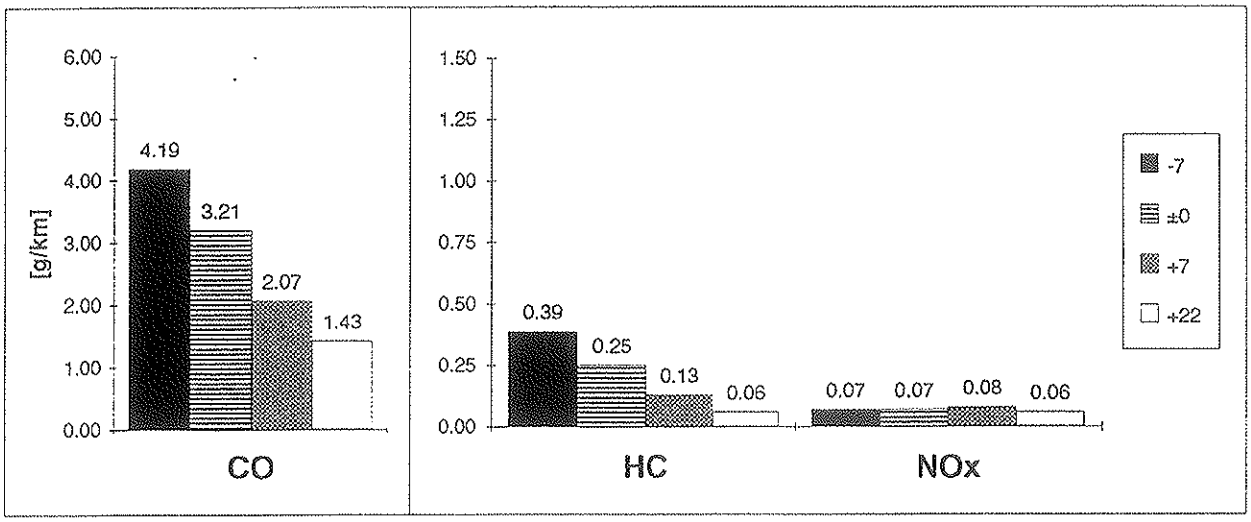



Figure 30. Regulated emissions of flexible fuel vehicles 5 and 6.

## REGULATED EMISSIONS

Alcohol FTP Composite

VEHICLE 7: M85




VEHICLE 8: M85

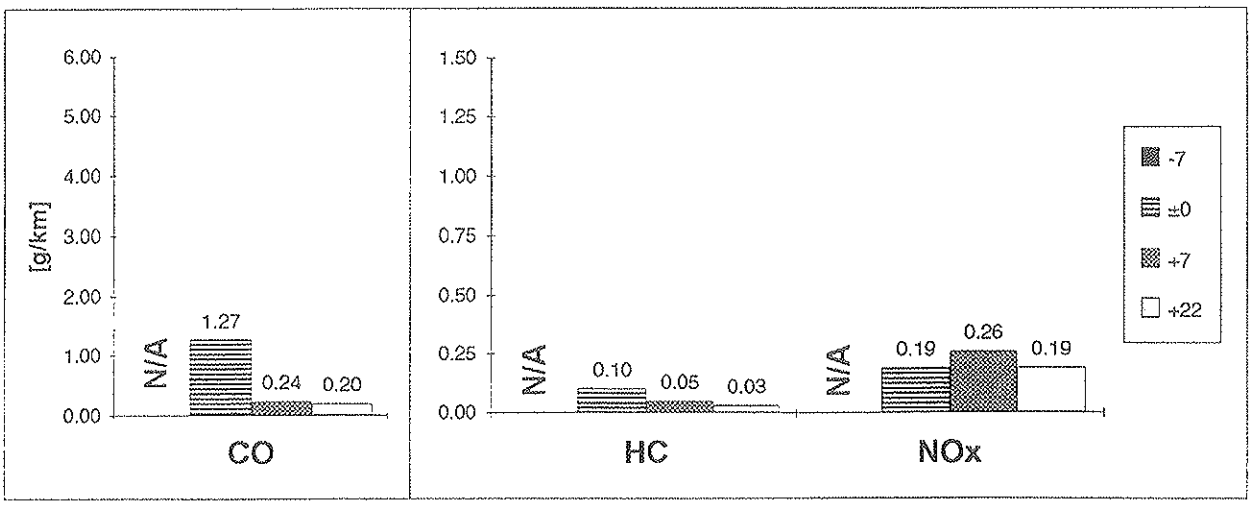



Figure 31. Regulated emissions of flexible fuel vehicles 7 and 8.

Compared to the M85 engine tested in Part One (CO increased by a factor of 12 from +20 to -7 °C), all the flex fuel vehicles performed rather well - actually better than the corresponding reference gasoline vehicle (3) in terms of CO at low temperatures. This was somewhat surprising, and it indicates that the M85 engine tested in Part One (MY 1986) clearly represents out-of-date technology. Of the gasoline vehicles tested, only the air injected vehicle(4) could reach the low CO levels achieved by the FFV's on M85. However, unlike the flexible fuel vehicles, the gasoline vehicles could easily be operated at -20 °C.

Figure 32 shows the regulated emissions of the vehicles running on gaseous fuels. Here can be seen what was already shown in Part One: emissions from these vehicles are more or less independent of temperature. With the exception of the HC emissions of the CNG vehicle (10), the emissions are moderate. However, 90 % of the HC is methane, so the NMHC (non-methane hydrocarbons) value for vehicle 10 is 0.06...0.09 g/km. The significant difference in HC between vehicles 10 and 11 is probably due to the fact that vehicle 11 is a dedicated CNG vehicle and its catalyst is especially formulated for CNG.

Figure 33 shows CO traces and cumulative CO emissions for vehicle 3 on gasoline, vehicle 6 on M85 and vehicle 10 on CNG. The CO emissions are is to a very high degree determined by what happens before catalyst light-off, i.e. how strong the enrichment of the mixture is. After catalyst light-off, the cumulative CO traces turn almost horizontal.

For the gasoline vehicle 3 (not representing latest technology), catalyst light-off takes place after appr. 250 seconds at -7 °C an the CO concentration peaks at almost 13 %. For the M85 vehicle (6), light-off at -7 °C takes place after some 150 seconds, and the maximum CO concentration is about 7 %. This results in lower CO emissions compared with the gasoline vehicle. For CNG, enrichment is practically nonexistent so that CO levels are low right from the start.

As expected, the vehicles on gaseous fuels performed well at all temperatures. Starting times and driveability were not affected by the temperature.

The CNG vehicle 11 was refueled at VTT, and the refueling system used has no gas drying equipment. This resulted in an accumulation of water in the tanks of the vehicle. At -7 °C this led to freezing of the primary pressure regulator soon after start. At that time the test could not be carried out. Later, after drying the fuel system, the test could be completed also at -7 °C. The results showed some increase in CO and HC emissions at this temperature.

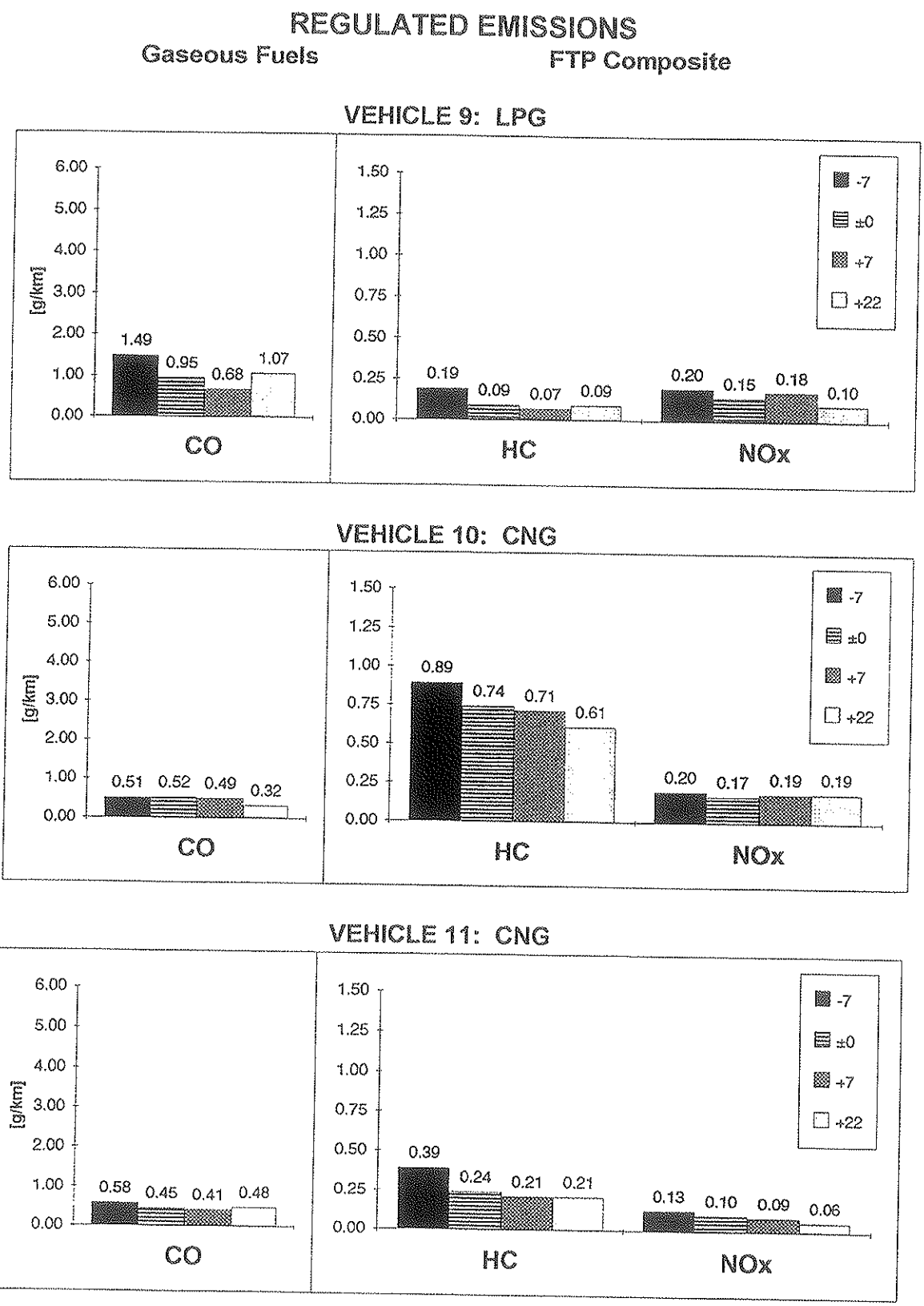
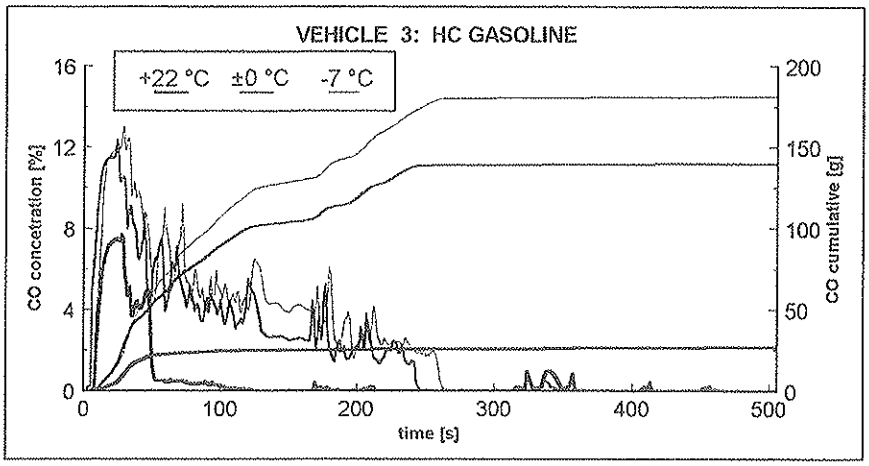
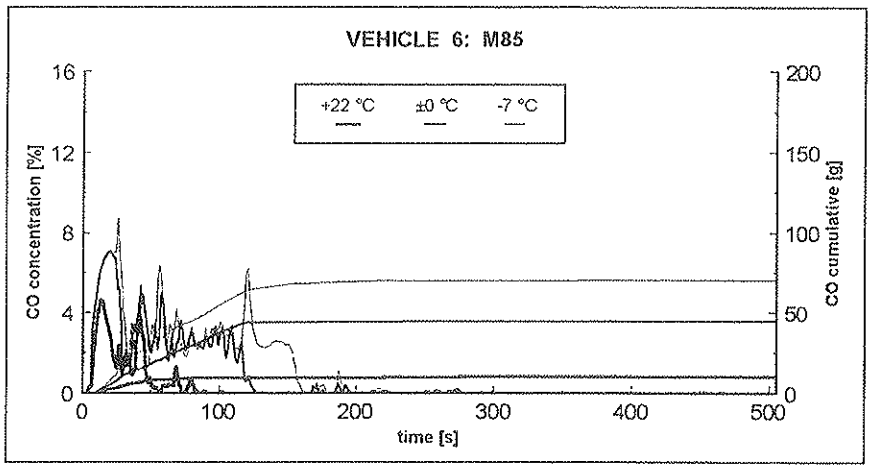



Figure 32. Regulated emissions of the vehicles 9, 10 and 11 on gaseous fuels.

# REGULATED EMISSIONS

## Cumulative CO emission / CO concentration



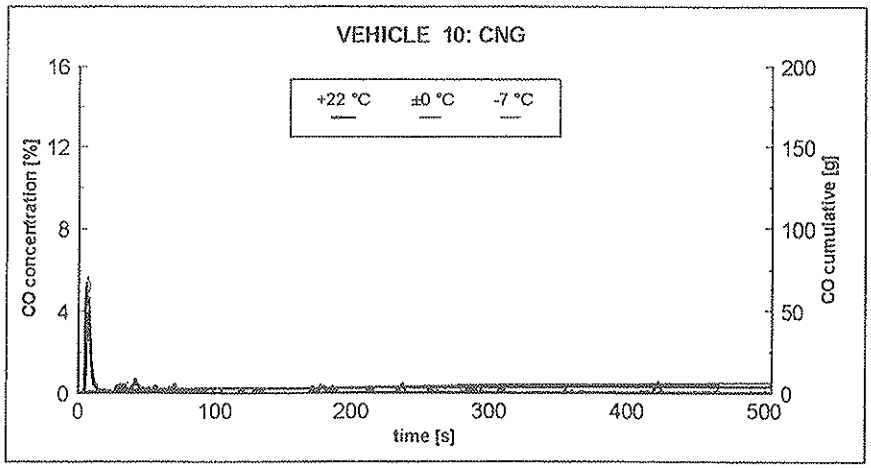




Figure 33. Cumulative CO emissions and CO traces with gasoline, M85 and CNG (vehicles 3, 6 and 10).

## 17.2 Unregulated emissions

The emissions of certain unregulated components calculated as composite FTP results over the whole test are presented in Figures 34 to 36. The hydrocarbon speciation is based on GC analyses. Aldehyde emissions and unburned alcohol were measured with the FTIR instrument.

Figure 34 shows unregulated emissions for vehicles 3 and 4 on conventional gasoline at +22 and -7 °C. The hydrocarbons in the Figure (including xylene) make up roughly 2/3 of the total HC reading. The different hydrocarbons form a relatively even distribution curve with a minimum at propane and isobutane. The emissions of 1,3-butadiene will increase from roughly 0.5 to 1.5 mg/km with falling temperature, at about the same rate as the total HC value increases. Benzene follows the same behavior, with values ranging from 5 to 20 mg/km. The formaldehyde emissions are around 3 mg/km. The secondary air injection of vehicle 4 does not have a major effect on hydrocarbon levels and distribution, but influences CO rather than HC. Actually, vehicle 4 gave higher total HC reading and more heavy hydrocarbons than vehicle 3 at -7 °C

Figure 35 shows unregulated emissions of vehicle 6 on M85 at +22 and -7 °C. The formaldehyde emissions are 11 mg/km at +22 °C, close to the California limit value of 15 mg/mile. The value increases to 31 mg/km at -7 °C. The methanol emissions are high, some 0.12 g/km at +22 °C. It increases by a factor of nearly 10 to 1,1 g/km when the temperature is lowered to -7 °C. Corresponding FID HC values are only 0.05 and 0.86 g/km. As can be expected, the levels of $C_1$ to $C_8$ hydrocarbons are low at +22 °C. Benzene and 1,3-butadiene levels are 1/5 those of gasoline (Figure 34). The level of 1,3-butadiene found at -7 °C on M85 is close to that of the gasoline vehicle 3 at +22 °C.

The unregulated emissions for vehicle 8 at +22 °C are also shown in figure 35. Because of the air injection and heated pre-catalyst, most of the HC's measured by the GC are not detectable. The most significant differences to vehicle 6 are the values of formaldehyde (<2 vs. 11 mg/km) and unburned methanol (30 vs. 124 mg/km). It would have been interesting to see the emissions of this vehicle at -7 °C, but it did not start because of flooding. As stated earlier, this was a prototype vehicle for California and the fuel system was not programmed for low temperatures.

The formaldehyde and methanol values for vehicle 5 on M85 at +22 and -7 °C (not illustrated) are 12/17 mg/km and 0.76/1.6 g/km, respectively. Vehicle 5 gave also significantly higher FID HC readings than vehicles 6 and 8. The corresponding values for vehicle 7 on M85 are 5/14 mg/km formaldehyde and 0.08/0.5 g/km methanol, thus roughly 50 % less than those for vehicle 6.

Figure 36 shows unregulated emissions of vehicle 10 on CNG. As discussed in 17.1, 90 % of the HC emissions are methane. Although some ethane can be found, no traces of 1,3-butadiene were present. However, as with LPG, there was some benzene in the exhaust, roughly 1 mg/km or less. There is some evidence that catalysts can produce some benzene during specific running conditions. Aldehyde emissions are below the detection limit, and so is 1,3-butadiene. Figures 37 (vehicle 5) and 38 (vehicle 6) show methanol and formaldehyde traces with M85. The maximum concentrations are 500...1.000 ppm for formaldehyde and 20.000 ppm for methanol.

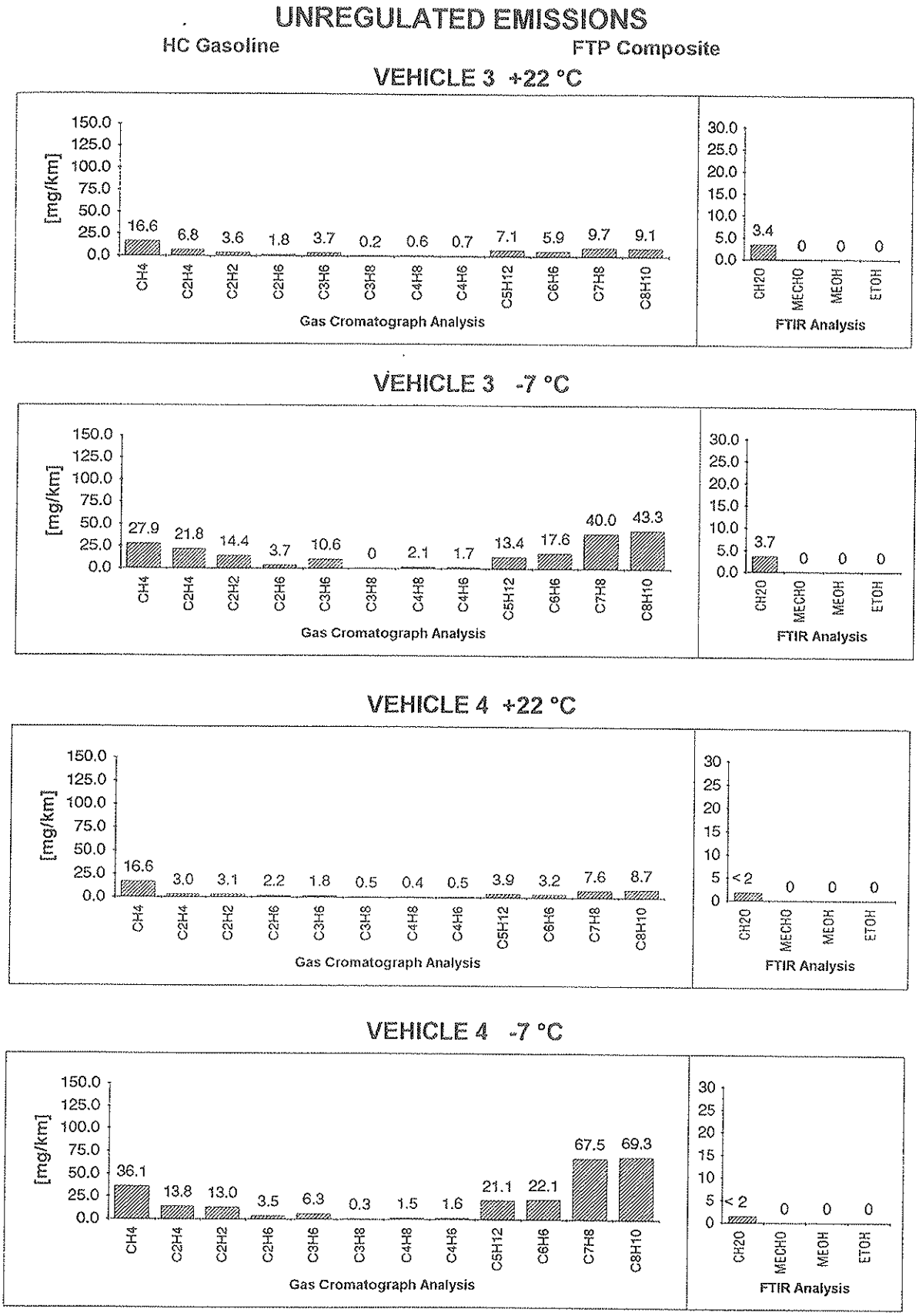



Figure 34. Unregulated emissions on conventional gasoline ( +22 and -7°C, vehicles 3 and 4).

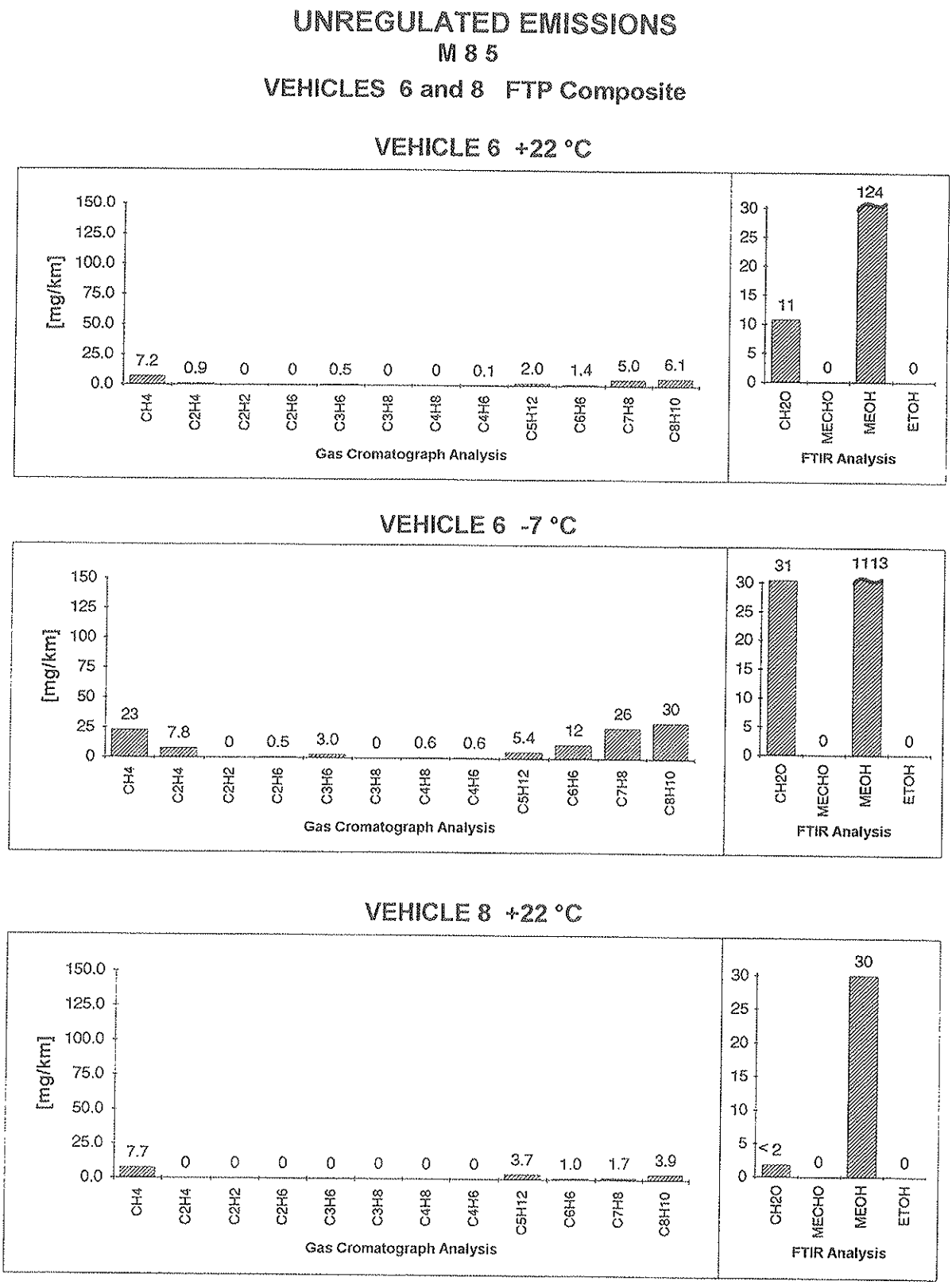



Figure 35. Unregulated emissions on M85. Vehicle 6 at +22 and -7 °C, vehicle 8 at +22 °C

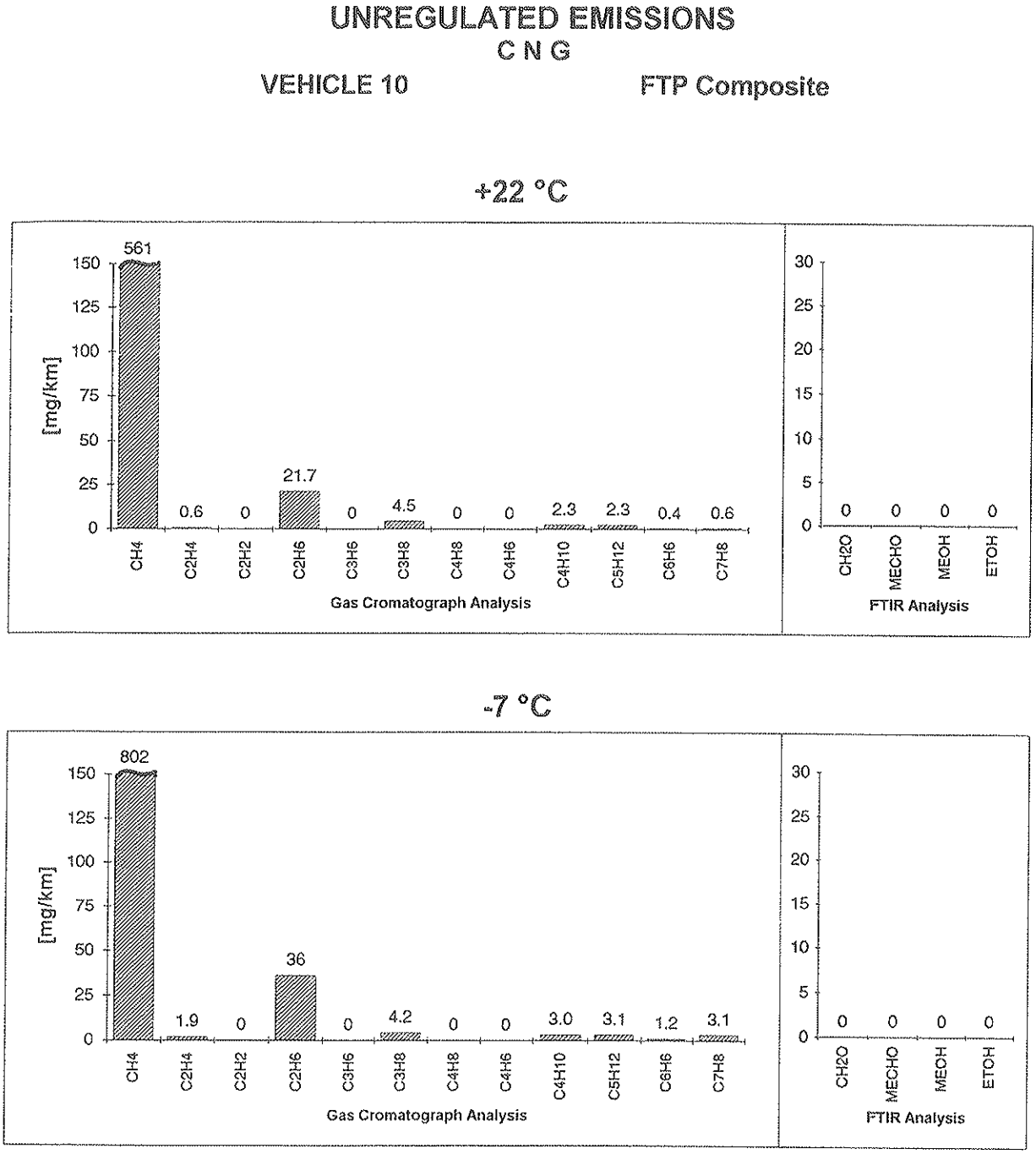
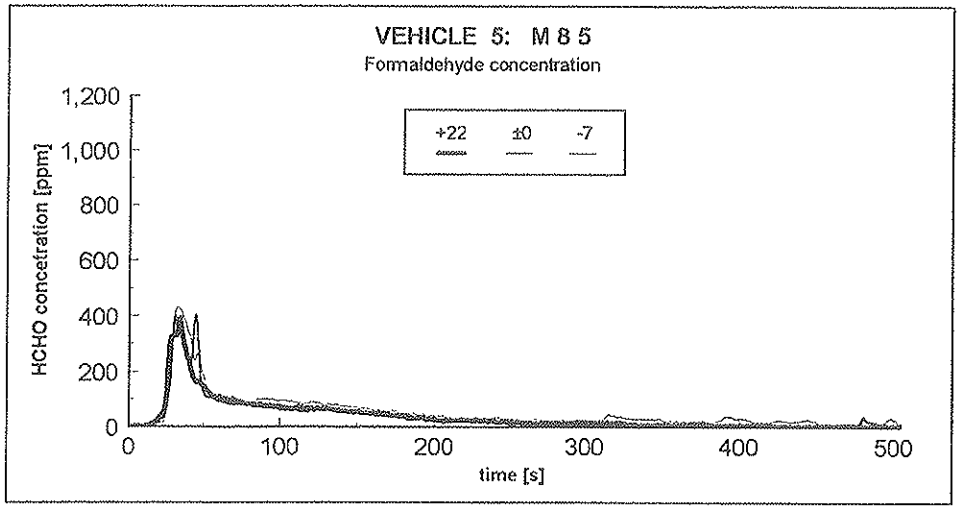



Figure 36. Unregulated emissions with CNG ( +22 and -7 °C, vehicle 10).

## UNREGULATED EMISSIONS

### Formaldehyde / Methanol concentration

### FTP bag 1



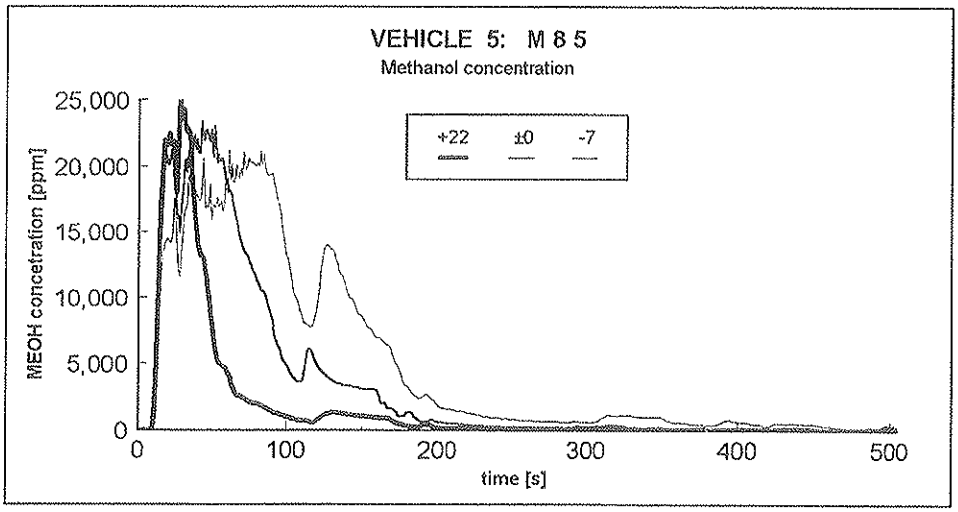
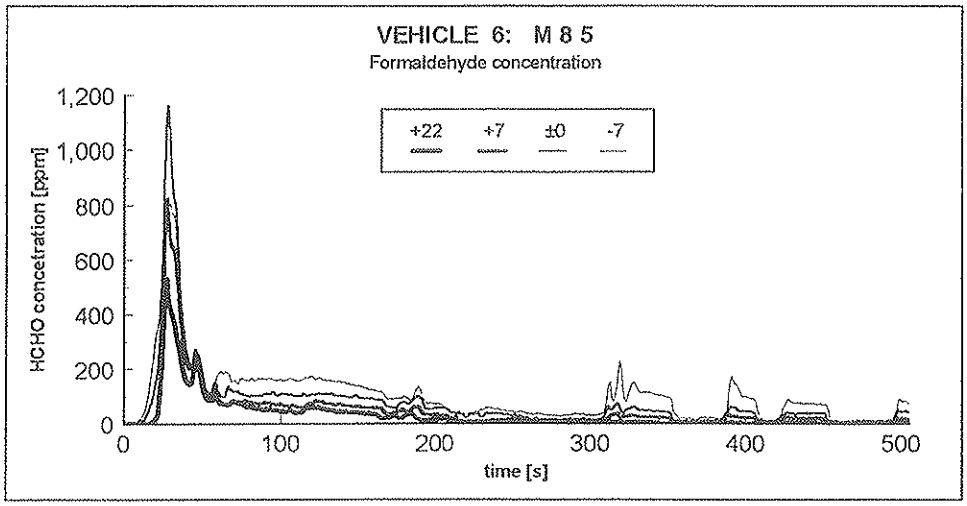




Figure 37. Formaldehyde and methanol traces on M85, vehicle 5.

## UNREGULATED EMISSIONS

### Formaldehyde / Methanol concentration

### FTP bag 1



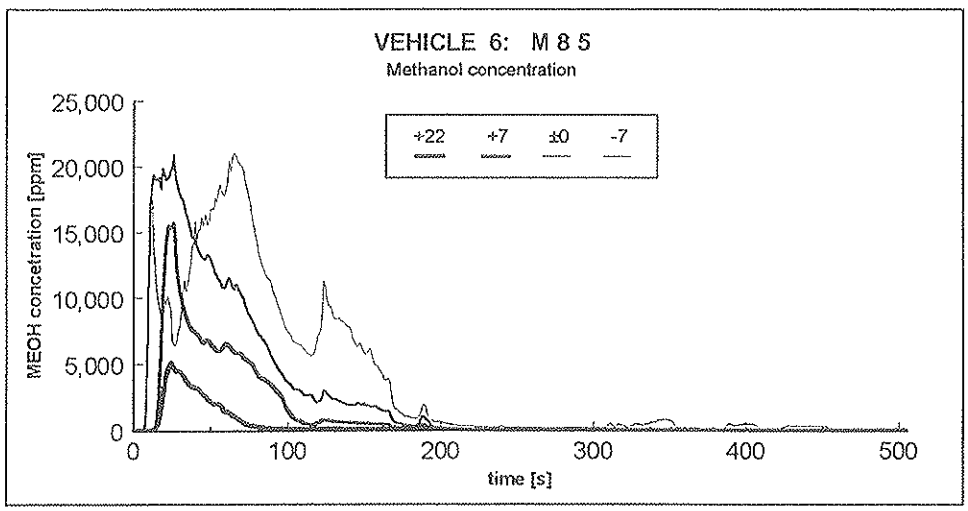




Figure 38. Formaldehyde and methanol traces on M85, vehicle 6.

## 17.3 Influence of fuel composition on emissions

Figure 39 shows the influence of ethanol addition on the regulated emissions of the carburetted vehicle 1 at +22 and -7 °C. Both CO and HC emissions decrease steadily with increasing ethanol content (up to 12 %). The reductions can amount to 20...30 %. The $NO_x$ emissions increase up to 10 %. Splash-blending ethanol into gasoline also reduces the emissions of aromatic hydrocarbons, but the emissions of acetaldehyde and especially unburned ethanol will increase with increasing ethanol content of the fuel. Figure 40 shows the average FTP phase 1 concentrations of aldehydes and ethanol in the undiluted exhaust.

Figure 41 shows the influence of gasoline formulation on regulated emissions of vehicle 3 equipped with a TWC. All oxygenated fuels reduced CO emissions at both +22 and -7 °C. Although the influence of fuel formulation on the HC emissions was small, the reformulated low sulphur/low benzene fuel gave the lowest $NO_x$ emissions at both temperatures.

Figure 42 shows the unregulated emissions of vehicle 3 with conventional and MTBE based oxygenated gasoline at +22 °C. The oxygenated gasoline reduces benzene by some 15 %. The variations from test to test were, however, rather big, so Figure 42 should be used with caution. Multiple tests with several vehicles would be needed for definite conclusions. Variations were especially high with the high molecular weight xylene.

Figure 43 shows the regulated emissions of vehicle 6 on M0, M50 and M85. At +22 °C, M85 gives the lowest regulated emissions. M0 gives the highest CO emission, and M50 the highest $NO_x$ emission. At -7 °C, M0 and M50 give rather similar results. M85 gives the lowest CO but highest HC emission.

Figure 44 shows the unregulated emissions of vehicle 6 on M0, M50 and M85 at +22 °C. Formaldehyde emissions range from 3 to 11 mg/km and methanol emissions from 0 to 0.12 g/km. For emissions of all $C_1$ to $C_8$ hydrocarbons, M85 gives the lowest and M0 (gasoline) the highest values, with M50 values right between.

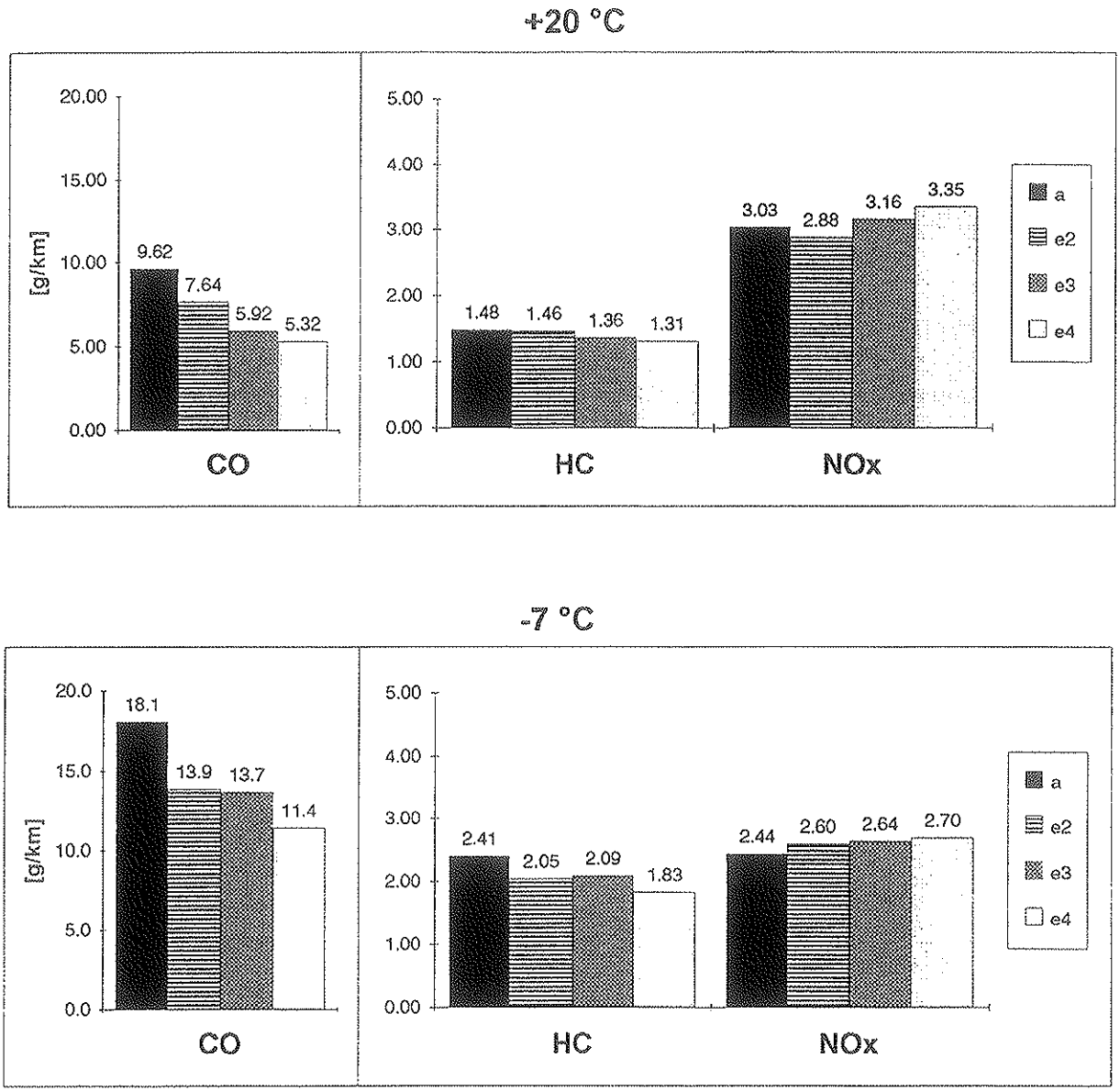
Figure 45 shows the regulated emissions of vehicle 10 with gasoline, LPG and CNG. All three fuels gave roughly the same $NO_x$ emissions. CNG gives the lowest and gasoline the highest CO emission. LPG gives the lowest HC values. Here again, 90 % of the total HC value of the CNG fuel is methane.

Figure 46 shows the unregulated emissions of vehicle 10 with the same three fuels at +22 °C. The pattern seen in Figures 34 and 36 is repeated. Fuel composition was the primary factor, with engine technology playing a secondary role. When using gasoline, $C_4$ and higher hydrocarbons plus methane dominated the HC emissions. When using LPG, the HC emissions were primarily propane, methane and butane. These components made up for roughly 90 % of the total HC emissions measured by the FID. The emissions of 1,3-butadiene were below the detection limit (0.1 mg/km).

## INFLUENCE OF FUEL COMPOSITION
### GASOLINE

**Regulated emissions** **FTP Composite**

### VEHICLE 1: CARBURETTOR




a = HC gasoline
e2 = HC gasoline blended with ethanol, oxygen content appr. 2 %
e3 = HC gasoline blended with ethanol, oxygen content appr. 3 %
e4 = HC gasoline blended with ethanol, oxygen content appr. 4 %

Figure 39. Influence of ethanol addition on the regulated emissions of vehicle 1.

## ALDEHYDE AND ETHANOL EMISSIONS

Carburetted vehicle (1)

Fuels a, e2, e3 and e4

(see Fig. 39)

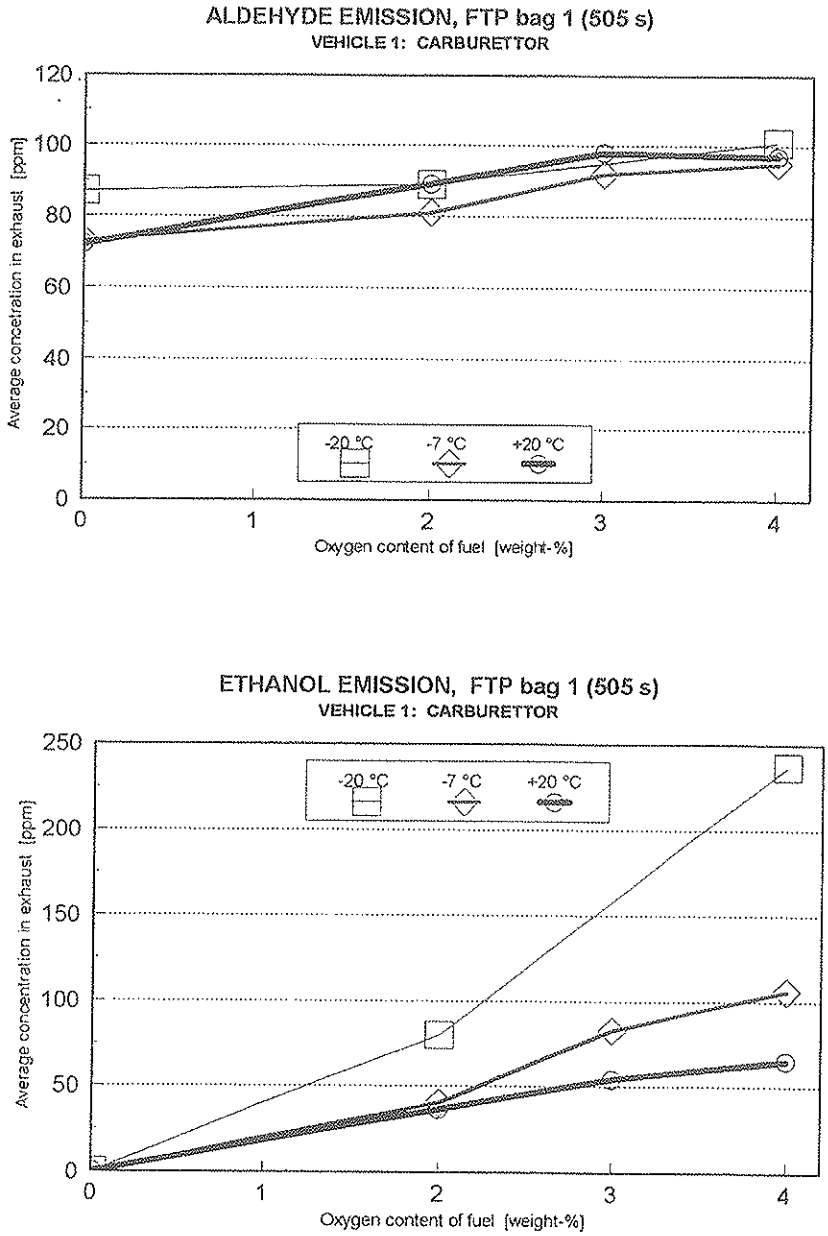


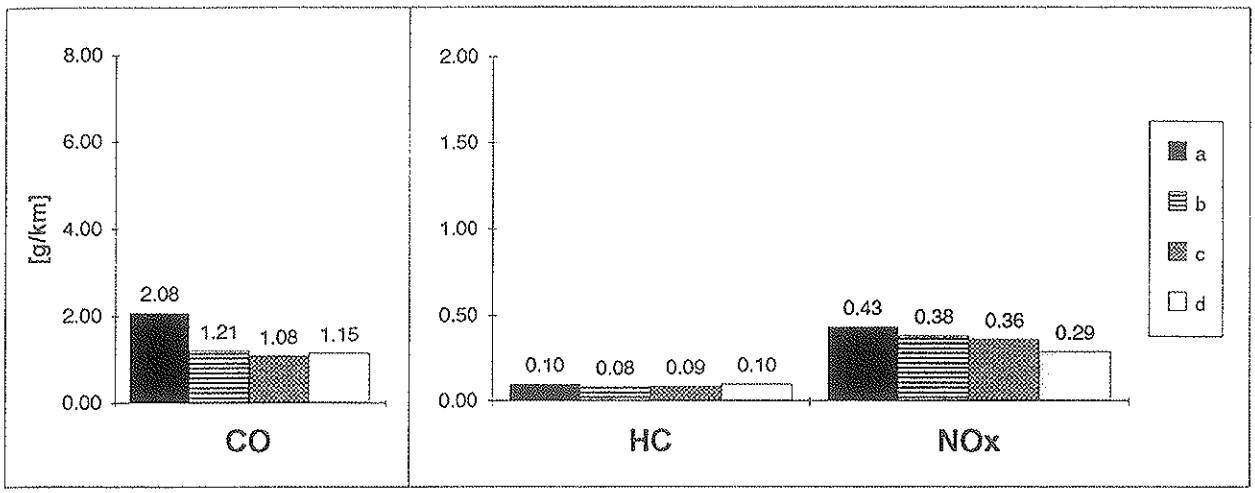

Figure 40. Average FTP phase 1 aldehyde (sum of form- and acetaldehyde) and ethanol concentrations as a function of fuel oxygen content (vehicle 1).

## INFLUENCE OF FUEL COMPOSITION
### GASOLINE

**Regulated emissions** **FTP Composite**

### VEHICLE 3: MPFI WITH CATALYST

+22 °C




-7 °C

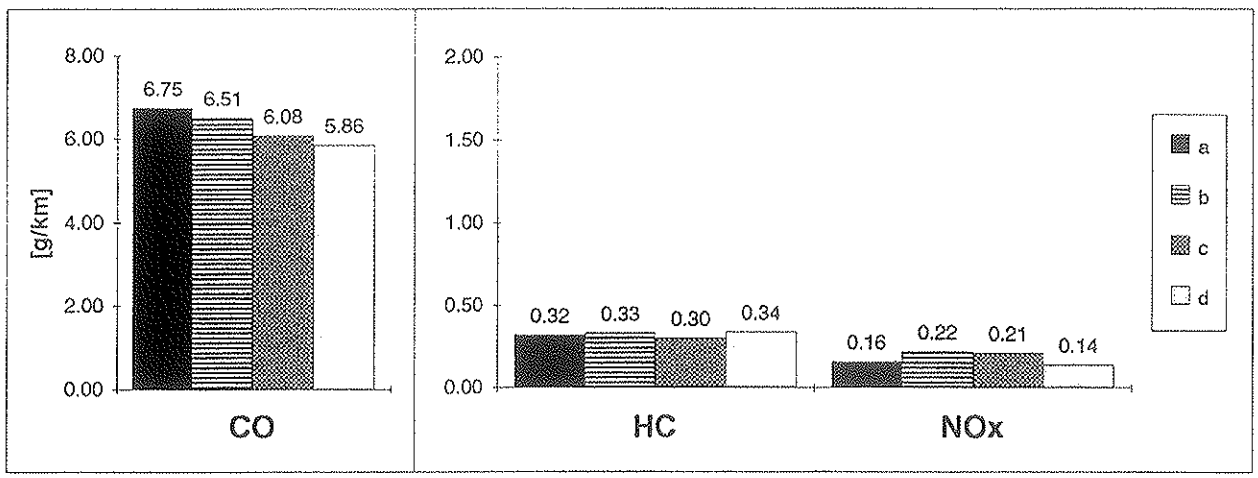
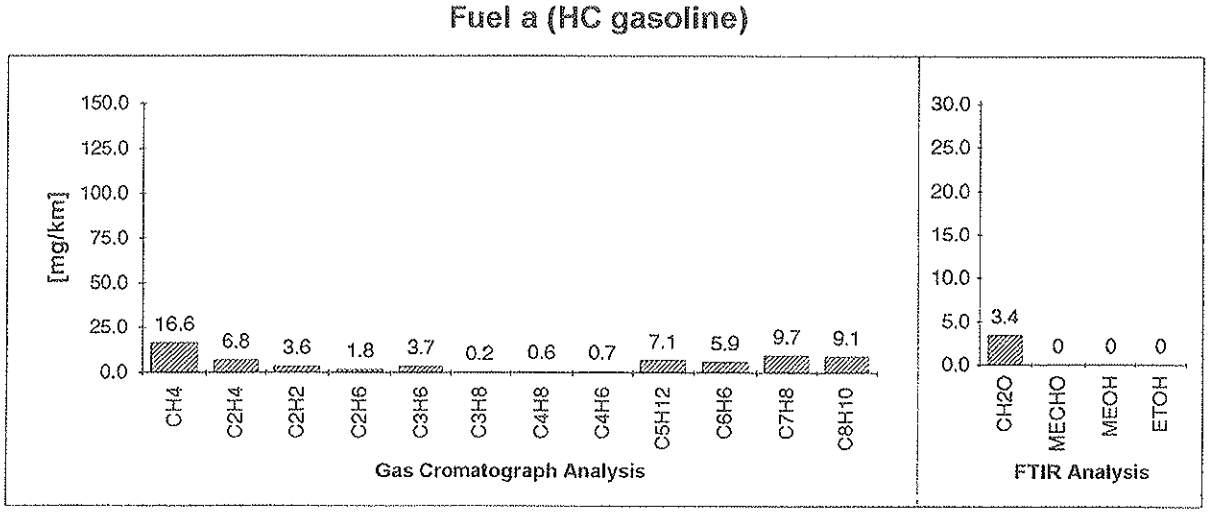



Figure 41. Influence of gasoline quality on regulated emissions ( +22 and -7 °C, vehicle 3).

## INFLUENCE OF FUEL COMPOSITION
### UNREGULATED EMISSIONS
### GASOLINE

VEHICLE 3 FTP Composite +22 °C



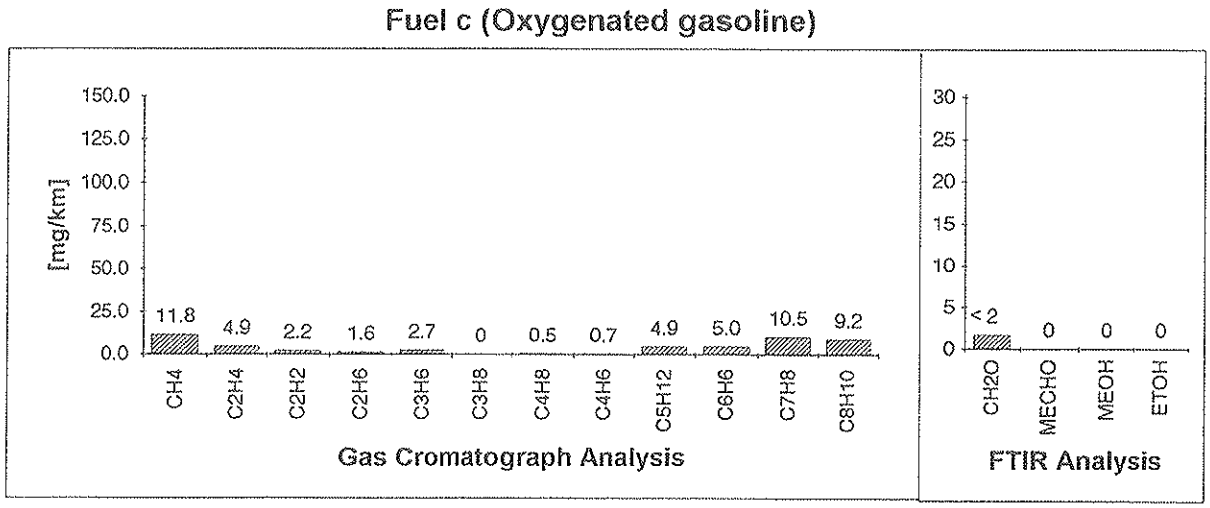



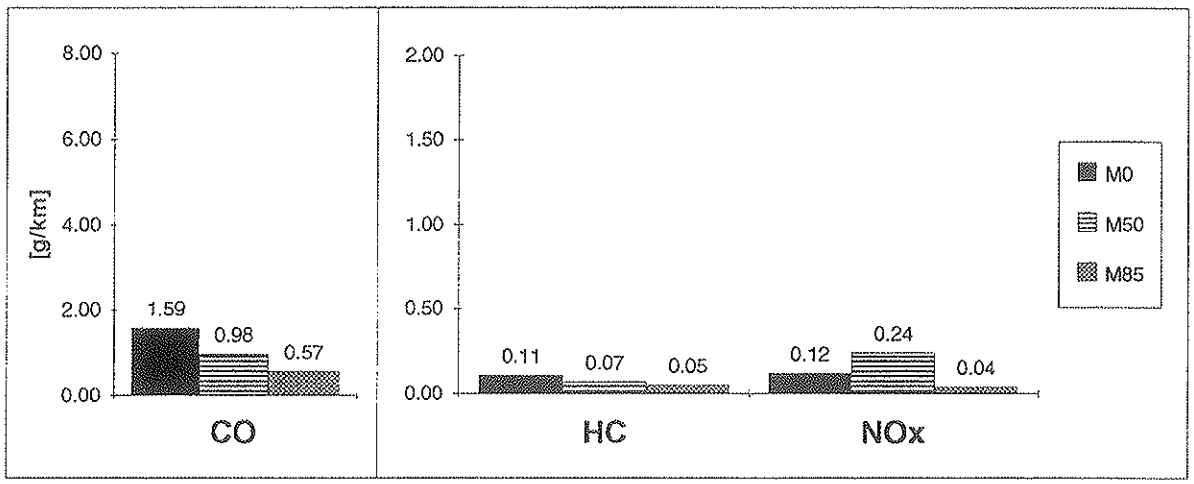

Figure 42. Unregulated emissions with conventional and reformulated gasoline ( +22 °C, vehicle 3).

## INFLUENCE OF FUEL COMPOSITION
### METHANOL BLENDS

**Regulated emissions** **FTP Composite**

VEHICLE 6: FFV

+22 °C




-7 °C

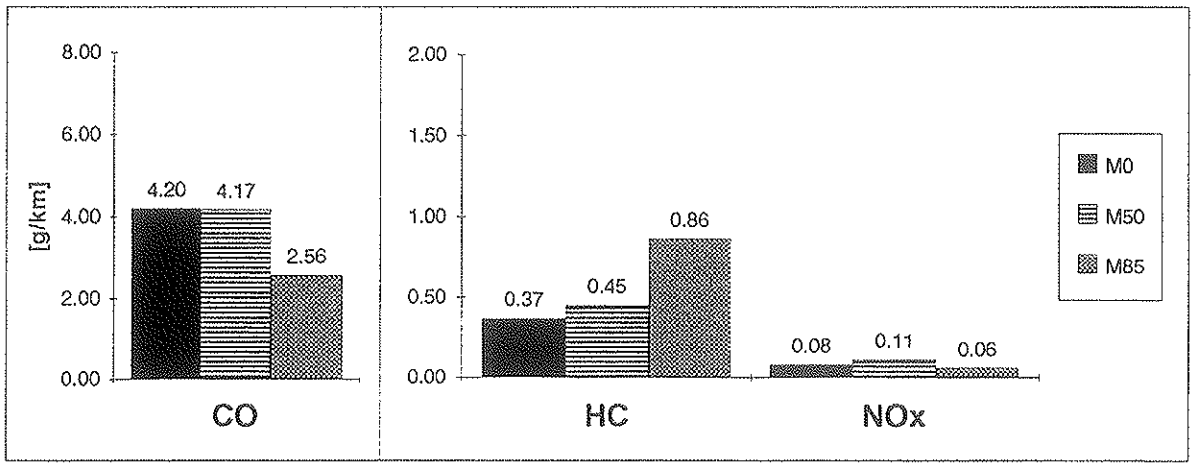



Figure 43. Regulated emissions with M0, M50 and M85 ( +22 and -7 °C, vehicle 6).

## INFLUENCE OF FUEL COMPOSTION
## UNREGULATED EMISSIONS
## GASOLINE / M50 / M85
## VEHICLE 6 FTP Composite +22 °C

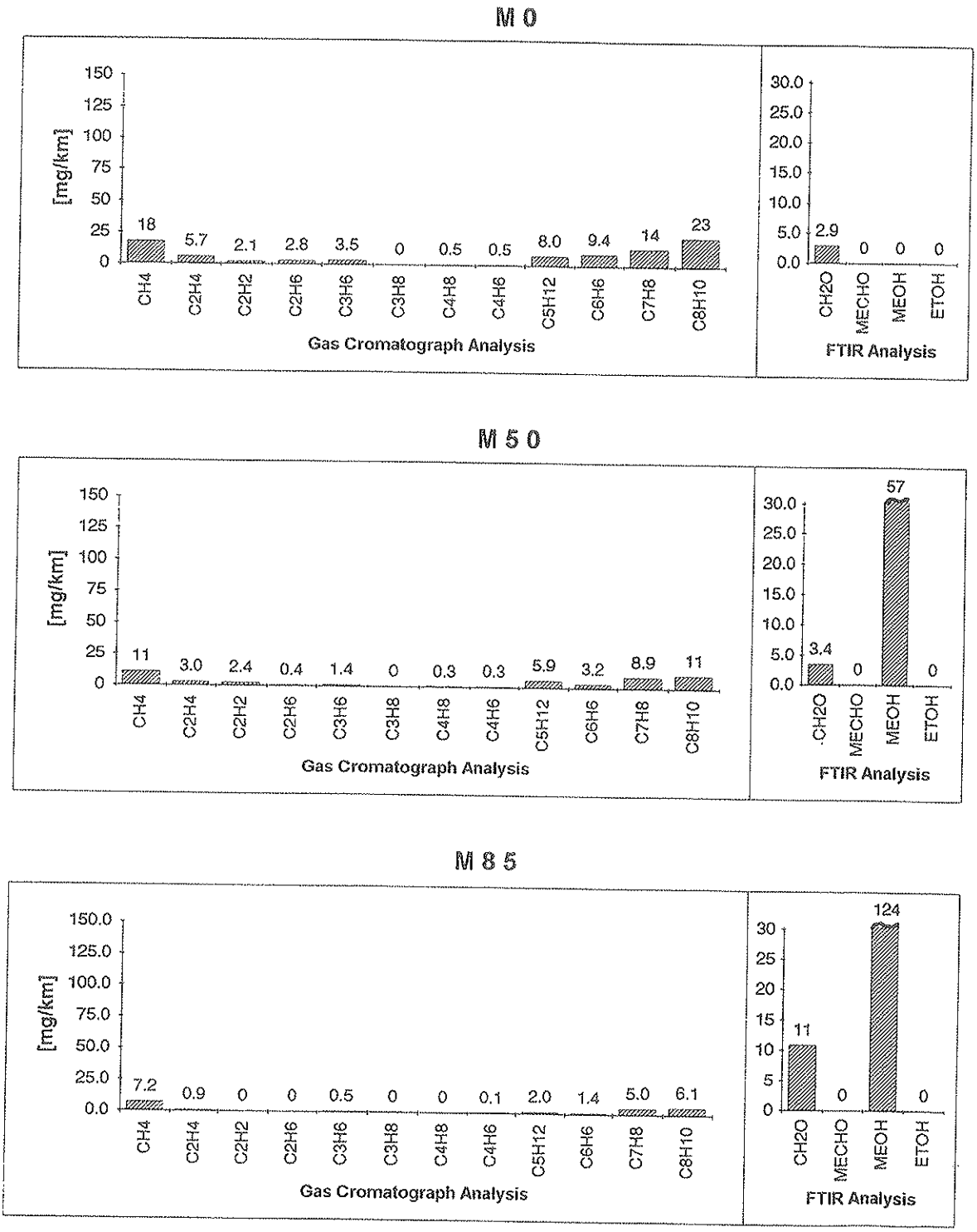


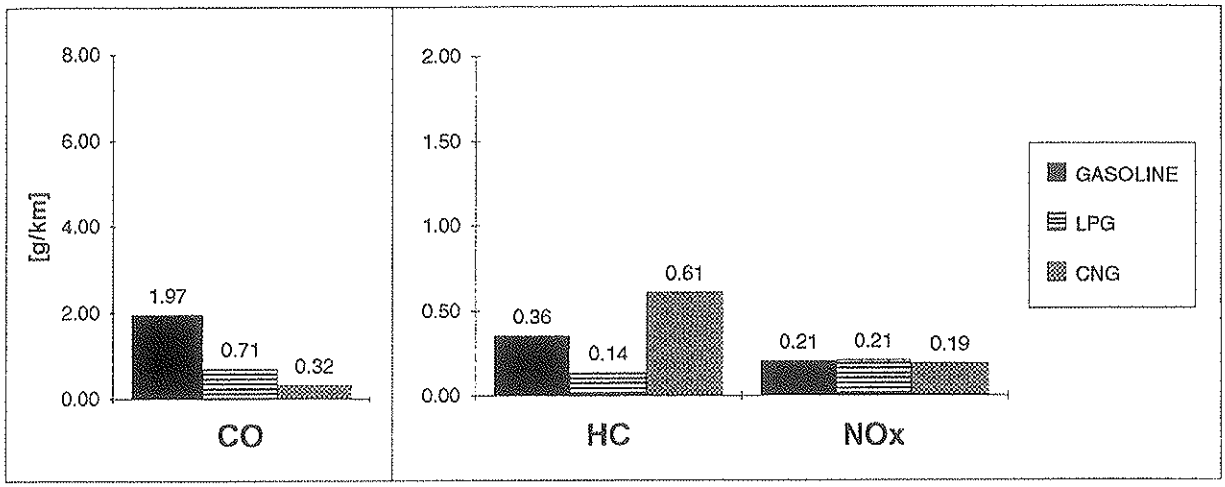

Figure 44. Unregulated emissions with M0, M50 and M85 ( +22 °C, vehicle 6).

## INFLUENCE OF FUEL COMPOSITION
### GASOLINE / LPG / CNG

**Regulated emissions** **FTP Composite**

**VEHICLE 10**

**+22 °C**




**-7 °C**

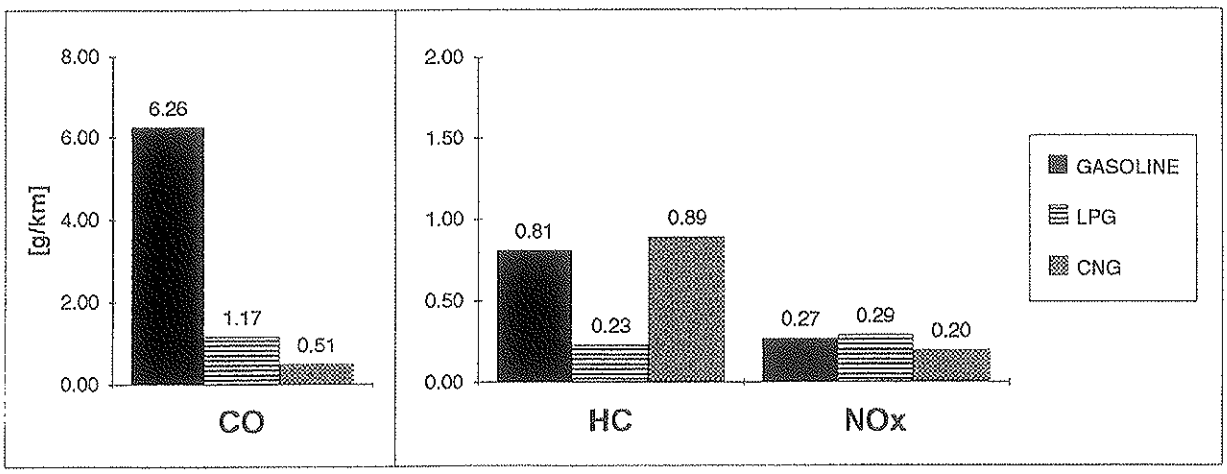



Figure 45. Regulated emissions with gasoline, LPG and CNG ( +22 and -7 °C, vehicle 10).

# INFLUENCE OF FUEL COMPOSITION
## UNREGULATED EMISSIONS
## GASOLINE / LPG / CNG
## VEHICLE 10 FTP Composite +22 °C

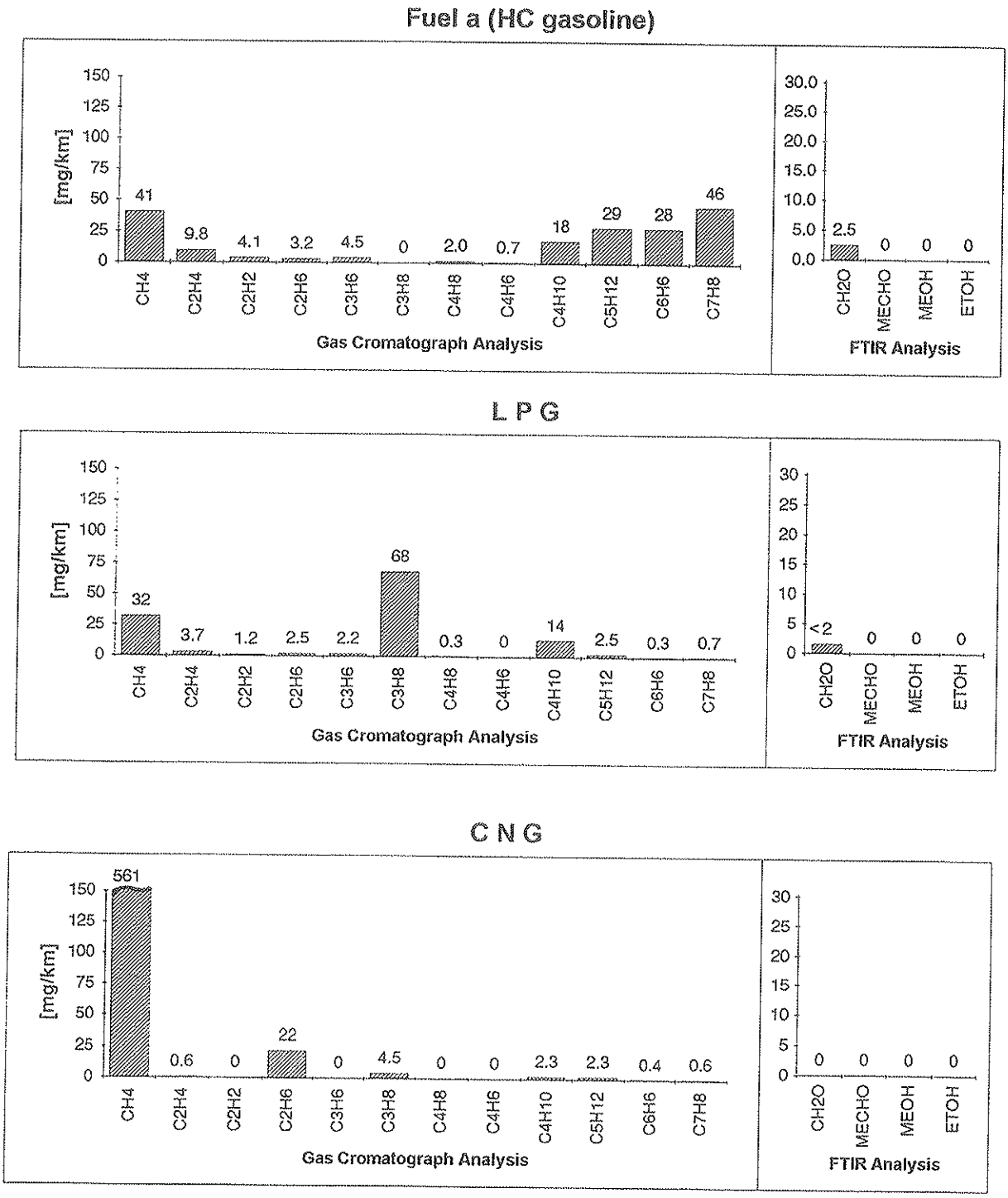



Figure 46. Unregulated emissions with gasoline, LPG and CNG (+22 °C, vehicle 10).

# 18. CORRELATION OF TEST RESULTS

Because the engine tests, conducted in Part One, were non-standardized engine tests, it was difficult to establish a correlation between the results of the engine and vehicle tests. However, since the cold start part of all the tests dominated the results, the estimated "would be" emissions expressed in g/km of the gasoline reference engine used for Part One came quite close to what had been measured for a vehicle equipped with the same engine over the FTP emission tests. As an example, the estimated CO emission values for the engine were 1.0, 5.1 and 6.7 g CO/km at +20, -7 and -20 °C, whereas the measured values for the vehicle were 1.2, 6,0 and 11 g/km.

In Part Two, where the testing was carried out on a chassis dynamometer using standardized test procedures for the regulated emission compounds, comparisons with other results were easier to carry out.

## 18.1 Regulated emissions

The two vehicles supplied by TNO in Holland were tested for regulated emissions at TNO and at VTT. TNO preferred to carry out the reference measurements according to the European test method /24, 26/. The European test method is more severe than the FTP test, as the initial speed is lower and thus catalyst light-off takes more time. In general, the European test gives roughly 50 % higher CO and HC values.

For comparison purposes, the vehicles supplied by TNO were tested at VTT according to both the European and the US test procedure. The results of TNO's and VTT's measurements are given in Table 11. The general correlation between the results is good, and this indicates that the instrumentation and protocols are in order.

Table 11. Comparison of TNO and VTT test results at +22 °C.

| Vehicle | Fuel | Component [g/km] | US-FTP75 | Eurocycle | | | |
|---|---|---|---|---|---|---|---|
| | | | VTT | VTT | | TNO | |
| 9 | HC-gaso-line | CO | 1.07 | 1.72 | 1.75 | 1.70 | 1.89 |
| | | HC | 0.09 | 0.27 | 0.27 | 0.26 | 0.34 |
| | | $NO_X$ | 0.10 | 0.14 | 0.14 | 0.23 | 0.15 |
| 10 | LPG | CO | 0.71 | 1.37 | 1.42 | 1.43 | 1.38 |
| | | HC | 0.14 | 0.17 | 0.19 | 0.18 | 0.21 |
| | | $NO_X$ | 0.21 | 0.19 | 0.23 | 0.22 | 0.25 |

## 18.2 Unregulated emissions

Correlation tests were performed to compare the FTIR (SESAM) results with results obtained by conventional analytical methods using bag/impinger/cartridge sampling and analysis by GC/HPLC.

For hydrocarbons, comparisons were made for methane, acetylene, ethylene, ethane, propylene, 1,3-butadiene and benzene in gasoline engine exhaust. The SESAM results were obtained through a measurement of undiluted exhaust and integration, whereas the bag sampling was done from diluted exhausts from the CVS collected in Tedlar bags. The bag sampling results were multiplied by the dilution factor to obtain comparable component concentrations in the raw exhausts.

The correlations between the FTIR and bag analysis by CG for $CH_4$, $C_2H_2$ and $C_2H_4$ were good. The variations were on average ±10%. For $C_2H_6$ there was a systematic difference between the FTIR and GC analyses. This was due to the limited selectivity of the FTIR technique to paraffinic hydrocarbons. Other saturated hydrocarbons like propane, n- and i-pentane interfere with the FTIR $C_2H_6$ analysis. The bag sampling results were on average 45% higher than the results obtained by the FTIR system. Furthermore, for $C_3H_6$ the bag sampling results were 15% higher than those using the FTIR system. Presumably the FTIR results are reliable, since the specificity of the analysis for $C_3H_6$ is good and the corresponding detection limit, therefore, quite low.

The 1,3-butadiene concentrations were low with all fuels - close to the detection limit of the FTIR-system. This made a reliable comparison impossible. The order of magnitude, however, was the same with FTIR and GC analysis, and the match was good even at low concentrations (below 30 ppm).

In gasoline exhaust, benzene was generally found at relatively low concentrations, i.e. from 3 to 28 ppm (average concentration in undiluted exhaust). At this concentration level a comparison with the CG-analysis is not possible, as the detection limit of the FTIR system for benzene is close to 20 ppm. However, two tests that generated high average concentrations of benzene were carried out. The concentrations obtained with the FTIR system were 109 and 68 ppm, and from bag sampling 85 and 71 ppm, respectively. For these limited cases the correlation seemed to be reasonably good.

In the case of formaldehyde, the FTIR system gave generally higher values than both impinger sampling and analysis by HPLC. The specificity of the formaldehyde by the FTIR is very good, and the minimum detectable concentration is low. As the exhaust sample is drawn through a heated sampling line into the heated gas cell of the instrument, no losses caused by condensation should occur. In conventional impinger sampling, the gas flow is at least one order of magnitude lower than in the FTIR system. Therefore, there is a higher probability that aldehydes are partly lost by water condensation in cold spots, as aldehydes are highly soluble in water. The same applies to methanol. For these reasons it was believed that the FTIR system gives more accurate values.

Ultimately aldehyde samples were taken using DNPH cartridges instead of impingers. This reduced test-to-test variations of the conventional analyzing method, and brought the formaldehyde values very close to those obtained by the FTIR system. This demonstrated that most of the problems were due to the sampling system, not the HPLC analysis itself.

There is still room for improving the accuracy of the unregulated emissions measurements. This is especially true for the control of the reliability of sampling system setups. Furthermore, the process needed to calculate mass emission rates from the FTIR concentration values is somewhat elaborate and requires careful matching of several separate concentration traces from different instruments.

Deriving speciated hydrocarbon concentrations from bag samples by GC is quite convenient. A combination of an FTIR system for modal emission values and GC system for overall emissions of the different components would probably be the best solution. With the FTIR system, however, some limitations still remain in measuring benzene and 1,3-butadiene at low concentrations.

The on-line FTIR technique can be used to produce reliable and repeatable results for formaldehyde.

There is some unregulated emission data available for normal ambient conditions /5, 6, 27, 28, 29/. A comparison between this data and results obtained in IEA Annex V for selected components is given in Table 12. The data from reference 29 (US Auto/Oil Program) for gasoline vehicles is based on a very large number of tests, and can be considered very reliable.

Table 12. A comparison of data on selected unregulated components over the FTP test cycle /5, 6, 27, 28, 29/.

| fuel | company | 1,3-butadiene | benzene | formaldehyde | methanol |
|---|---|---|---|---|---|
| gasoline w/o cat | VTT | 12 | 55 | 43 | - |
| | VW | - | 77 | 24 | - |
| gasoline | VTT | 0.6 | 4.7 | 2.5 | - |
| | VW | - | 8.2 | 2.2 | - |
| | Trends... | 0.6 | 6.0 | 4.5 | 0.7 |
| | TNO | - | 5.8 | 1.2 | - |
| | Auto/Oil | 0.5 | 5...6 | 1.5...2 | - |
| M85 | VTT | <0.5 | 1.5 | 5.8 | 79 |
| | Trends... | 0.25 | 1.2 | 23 | 134 |
| | Auto/Oil | <0.2 | 1.2 | 8 | - |
| LPG | VTT | <0.5 | <0.5 | <2 | - |
| | TNO | - | 1.1 | 1.2 | - |
| CNG | VTT | <0.5 | 0.7 | <2 | - |
| | TNO | - | 0.46 | 0.32 | - |

The agreement among the various sources of data is good in general. The benzene emission values for catalyst-gasoline vehicles are 4.7...8.8 mg/km (Auto-Oil average 5...6 mg/km) and VTT's values for a non-catalyst car, 55 mg/km, is slightly lower than VW's value of 77 mg/km. The 1,3-butadiene values for catalyst gasoline vehicles are 0.5...0.6 mg/km, and the formaldehyde values are 1.5...4.5 mg/km (VTT value 2.5 mg/km).

The benzene emissions for M85 vehicles are 1.2...1.5 mg/km, and the 1,3-butadiene emissions are below 0.5 mg/km. The formaldehyde emissions range from 5.8 to 23 mg/km. Here it should be noted, that the California emission limit is 10 mg/km, so 23 mg/km probably represents outdated technology. The methanol emissions for M85 as listed in reference /5/ are 134 mg/km compared with 79 measured by VTT.

The benzene and formaldehyde emissions for LPG and CNG measured at TNO and VTT are of the same magnitude.

In general it can be said that the values generated by VTT fall in line with results from other sources. Thus, the conclusion can be made that the methods used at VTT are in order and that the results generated by VTT for low ambient temperatures should also be valid. No low ambient references were available to enable comparisons to be made.

## REFERENCES FOR PART TWO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# PART THREE: ADDENDUM OF DIESEL VEHICLES

## 19. GENERAL

After finishing Part Two it was realized that the emissions performance evaluation work done is not complete without including diesel vehicles. In some European countries the market share of diesel passenger cars is about 50 %, and the production of diesel engines can be up to 25 % of total passenger car engine production for some European manufacturers.

The Addendum of diesel vehicles was approved by the 18th Executive Committee Meeting held in Toronto in October 1994.

## 20. TEST PROGRAM FOR DIESEL VEHICLES

The tests were carried out as vehicle tests at VTT in the climatic test cell, which is equipped with a chassis dynamometer. The procedure were the same as in Part Two. The testing was performed basically according to the US Federal Test Procedure with the exception that the temperature was varied between +22 and -20 °C.

Each of the three test vehicles were run at 4 temperatures. The temperatures used were +22, ±0, -7 and -20 °C. Only one of the three test fuels was able to run down to -20 °C.

Both regulated and unregulated emission components were measured like in Part Two. In addition to the gaseous regulated components (CO, HC an $NO_x$), also the particulate mass emissions were measured. The regulated components were analyzed with both standard type bag sampling and modal analysis. The unregulated components were measured using GC and FTIR instruments and DNPH cartridges/HPLC method. The FTIR analysis was performed for the FTP phases 1 and 3 only. All other measurements were carried out during all three FTP phases.

Also the semivolatile and particulate phase emissions were measured from one of the test vehicles. One gasoline TWC vehicle and one FFV vehicle running on M85 were used as reference for these measurements.

## 21. DIESEL VEHICLES AND FUELS

Three diesel vehicles were used. All three vehicles represented different engine configurations. They were products of the same European corporation and they all shared the same 1.9 liter engine block. The three configurations were as follows:

| | |
|---|---|
| Vehicle 12: | Indirect injection (IDI), no catalyst |
| Vehicle 13: | Indirect injection, oxidation catalyst and turbocharger |
| Vehicle 14: | Direct injection (DI), oxidation catalyst, turbocharger and intercooler |

All the test vehicles were model year 1995 vehicles. The odometer readings varied from 5500 km to 12000 km. More detailed summary of the test vehicles is given in Appendix 1.

Three different fuels were used for the diesel vehicle tests. The fuels were as follows:

| | |
|---|---|
| MK1: | Swedish Environmental Class 1 (Miljöklass 1). Very high quality reformulated diesel fuel with sulphur content below 10 ppm and content of aromatics below 5 %. |
| RME/MK1: | A blend of Rapeseed Methyl Ester and MK1. The ratio was 20 % of RME and 80 % of MK1. |
| CEC: | CEC RF-03-A-84 Reference Diesel with sulphur content of 300 ppm |

Tests with fuel MK1 were run down to -20 °C. For the other two fuels the lowest temperature used was -7 °C. A detailed summary of properties of the test fuels is presented in Appendix 2.

# 22. RESULTS FROM DIESEL VEHICLES

## 22.1 Regulated emissions

At +22 °C the levels of CO and total HC from diesel vehicles are comparable to the gasoline TWC vehicles. Instead, the $NO_x$ emissions from diesel vehicles are higher than with any other fuel measured in Annex V with the exception of the non-catalyst gasoline vehicles. In fact, the $NO_x$ results of vehicle 12 exceed clearly the FTP limit value (0.62 g/km).

At low temperature (-7 °C) the CO and HC emissions from diesel vehicles are considerably lower than from gasoline TWC vehicles. The $NO_x$ emissions are high also at -7 °C.

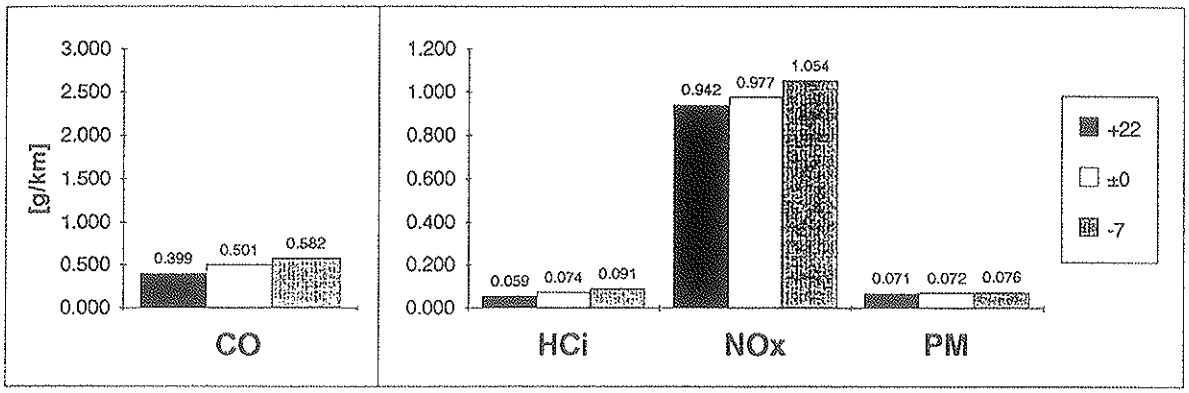
The differences between the three diesel engine configurations and the effect of temperature can be seen in Figure 47 with the reference fuel. Noticeable is that vehicle 13, which has an oxidation catalyst, gives higher CO, total HC (integrated) and particulate emissions than vehicle 12, which has no catalyst. $NO_x$ emissions from vehicle 13, instead, are lower than from vehicle 12. The explanation might be, that vehicle 13 is optimized for low $NO_x$ formation. This is carried out by late fuel injection and design of the combustion chamber, which may have led to unacceptable high CO, HC and PM levels, if the oxidation catalyst were not used.

Vehicle 14, which represents the most up-to-date technology, gives the lowest overall gaseous emissions of all three diesel vehicles. With this vehicle the particulate emissions, however, are a little higher than from vehicle 12 with no catalyst. This can be due to the fact that the CEC reference fuel has sulphur content of 300 ppm which is fairly high in terms of obtaining the most advantage from the catalyst. High sulphur level can under some conditions lead to increase of particulate mass because of sulfate formation.

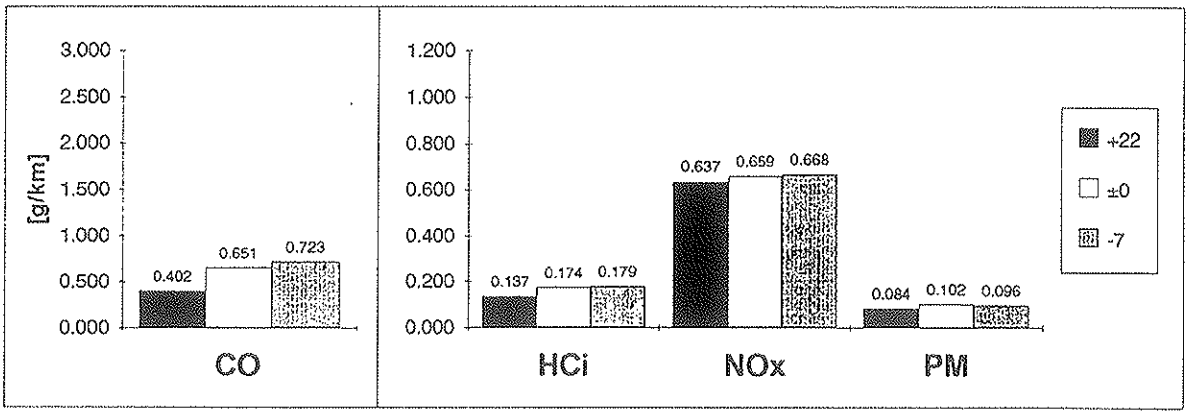
## REGULATED EMISSIONS

CEC Reference Diesel FTP Composite

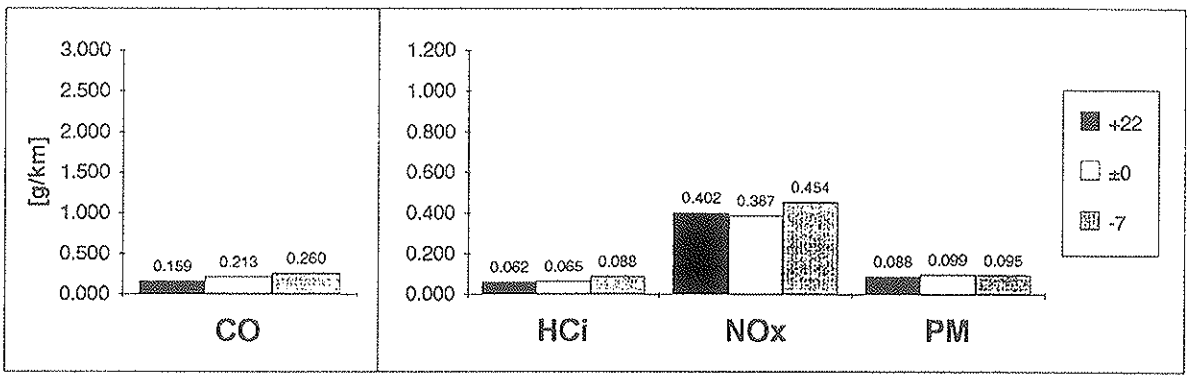
### VEHICLE 12: IDI, NO CATALYST




### VEHICLE 13: IDI, CATALYST AND TURBOCHARGER




### VEHICLE 14: DI, CATALYST, TURBO AND INTERCOOLER




HCi = integrated total hydrocarbons

Figure 47. Regulated emissions from diesel vehicles with the CEC reference fuel.

At low temperature (-7 °C), the CO and HC emissions from diesel vehicles increase by a factor less than two compared to +22 °C. The increase caused by falling temperature is lower than with gasoline TWC or FFV vehicles, whose CO and HC emissions are 4...5 times higher at -7 °C than at +22 °C. $NO_x$ emissions from diesel vehicles are affected very little by temperature.

The influence of fuel composition to the diesel vehicles is presented in Figures 48, 49 and 50. Generally, MK1 gives the lowest emissions, RME/MK1 is the intermediate fuel, and CEC gives the highest emissions with some exceptions.

Figure 48 shows the results of vehicle 12, which has no catalyst. CO, HC and particulate levels are almost equal on fuels MK1 and the RME/MK1 blend. On the CEC reference fuel all these emissions are slightly higher. $NO_x$ level of vehicle 12 is the highest of all three diesel vehicles, (above the FTP limit value) and the influence of fuel is somewhat indefinite.

Figure 49 illustrates the regulated emissions of vehicle 13 with oxidation catalyst and turbocharger. The influence of fuel is similar to vehicle 12. Fuel MK1 gives the lowest emissions regardless of component. Total HC emissions are higher than from vehicle 12, like already mentioned, but the difference is smaller with the other fuels than with the CEC fuel. For example, at normal temperature, the total HC reading from vehicle 13 is about 130 % higher than from vehicle 12 on the CEC fuel, but the only about 80 % higher on MK1. In terms of CO, the emissions at normal temperature from vehicles 13 and 12 are about equal on the CEC fuel, but on the other fuels vehicle 13 gives lower emissions than vehicle 12. On average, the $NO_x$ emissions from vehicle 13 are some 35 % lower than from vehicle 12.

Figure 50 gives the regulated emissions from vehicle 14 with DI engine, turbocharger, intercooler and oxidation catalyst. In this case, the overall gaseous emissions levels are lower than with the two other vehicles, but the particulate level is about the same as with vehicle 13. $NO_x$ emissions from vehicle 14 are the lowest, and they are about 25 % lower than from vehicle 13 and about 55 % lower than from vehicle 12. With vehicle 14, unlike with the other two vehicles, $NO_x$ emissions are somehow lower on the CEC fuel than with the other fuels.

Particulate emissions from the catalyst vehicles 13 and 14 are strongly dependent on fuel. The overall average particulate emissions on the CEC fuel are about 30 % higher for vehicle 13 and about 35 % higher for vehicle 14 than on fuel MK1. The corresponding percentage for vehicle 12 is below 20. Higher sulphur content in the CEC fuel promotes the formation of sulfates in the catalyst, which increases the total particulate mass. Sulphur also deactivates the reactivity of the catalyst.

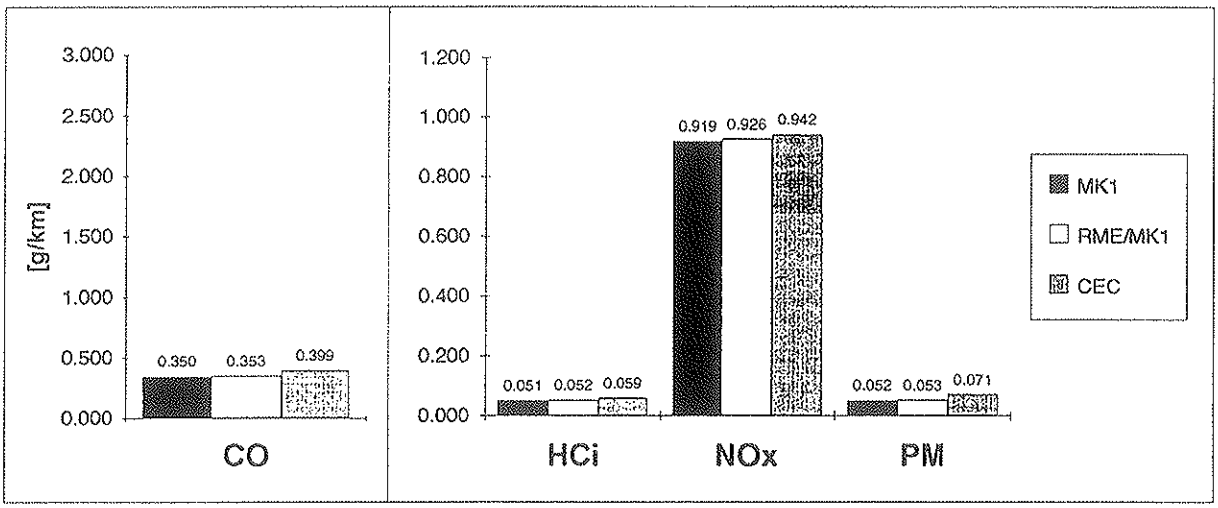
The RME fuel blend seems to give the lowest overall particulate emissions from the catalyst vehicles. This is caused by the fact that RME forms more soluble organic fraction (SOF) around the carbon center of a single particle than the other fuels. This soluble organic matter is easier to oxidate in the catalyst than other types of compounds.

## INFLUENCE OF FUEL COMPOSITION
### DIESEL

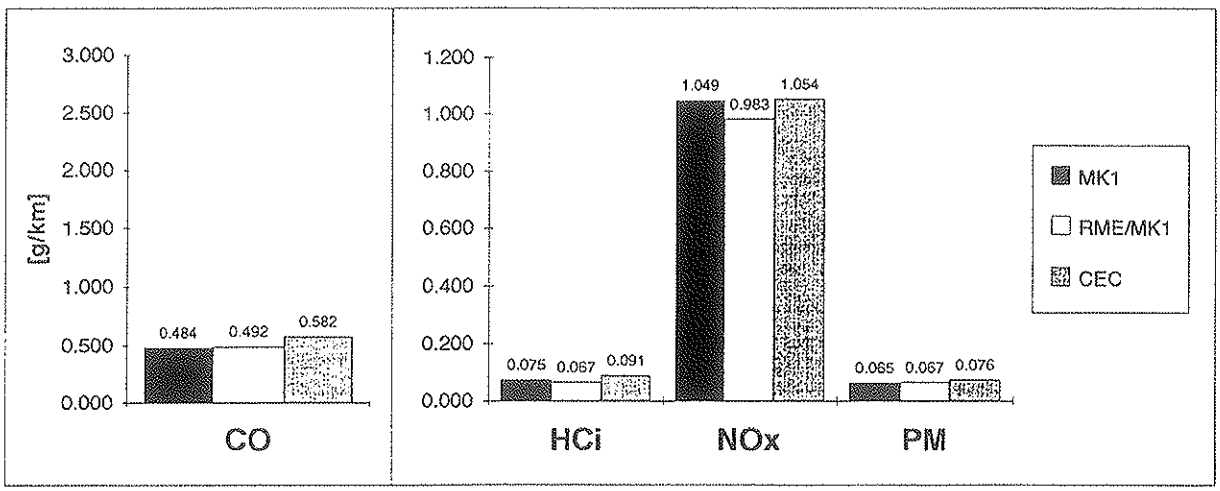
**Regulated emissions** **FTP Composite**

### VEHICLE 12: IDI, NO CATALYST

+22 °C




-7 °C



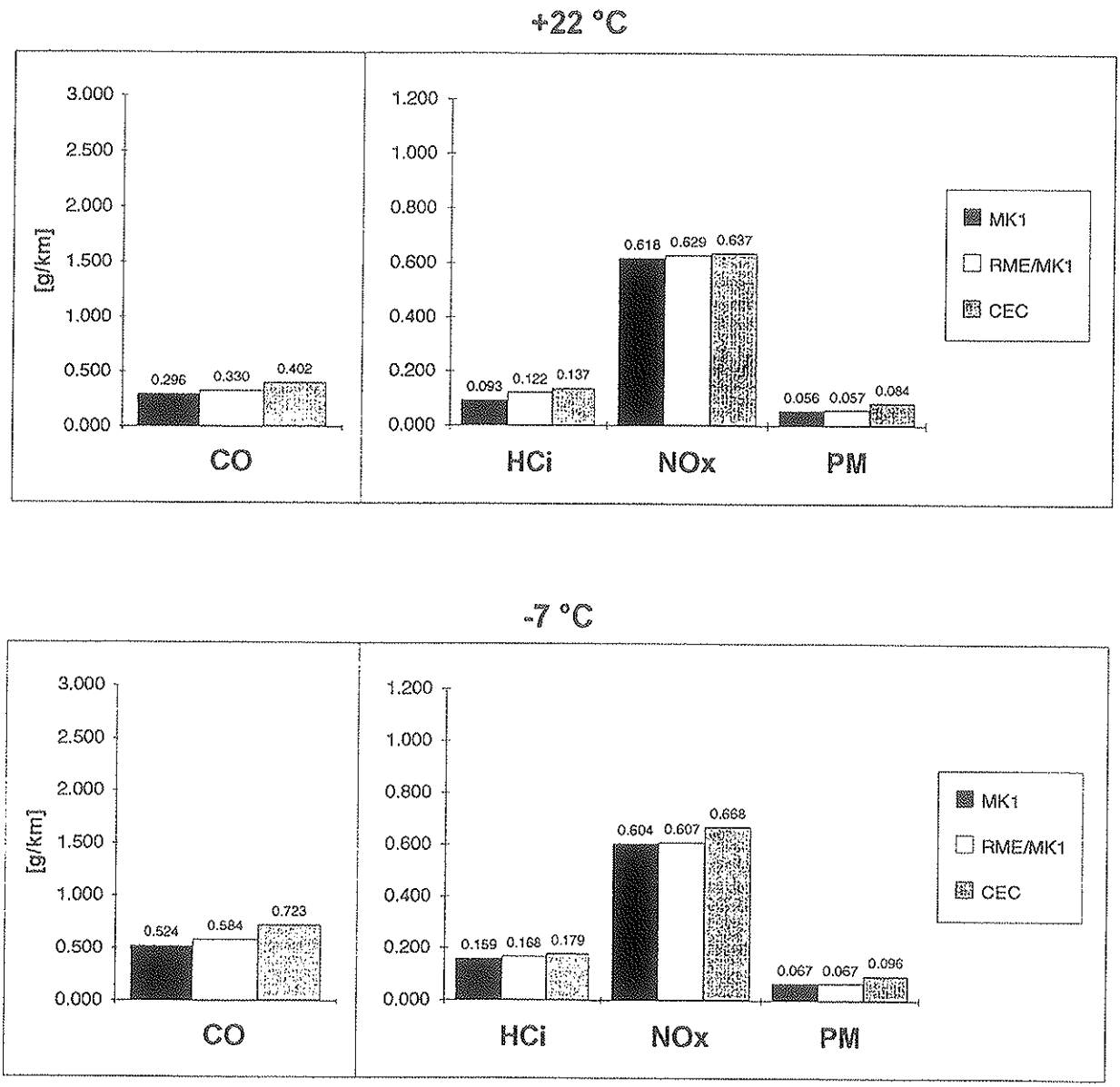

HCi = integrated total hydrocarbons

Figure 48. Influence of fuel composition on regulated emissions, vehicle 12.

## INFLUENCE OF FUEL COMPOSITION
### DIESEL

**Regulated emissions** **FTP Composite**

### VEHICLE 13: IDI, CATALYST AND TURBOCHARGER



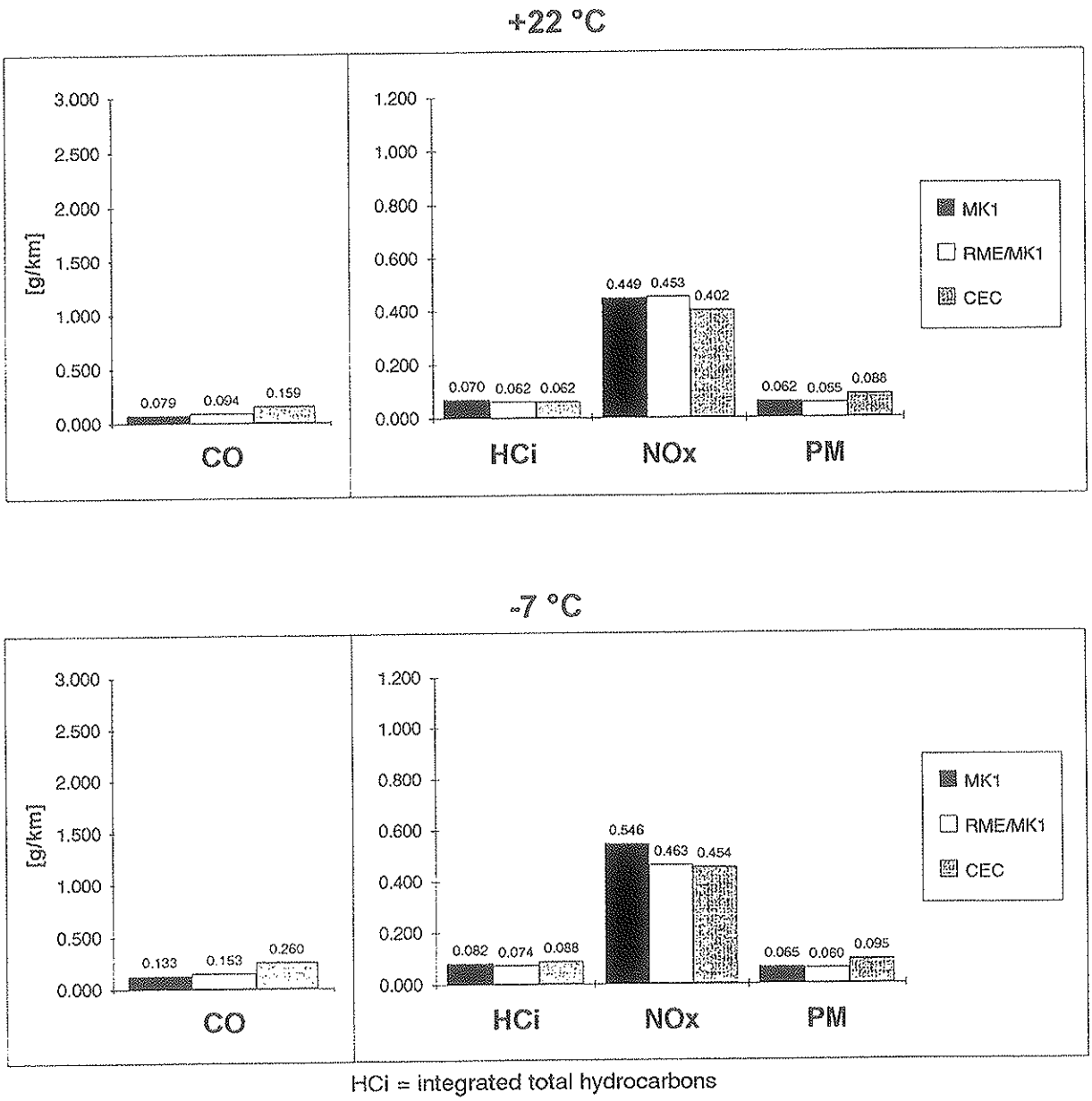

HCi = integrated total hydrocarbons

Figure 49. Influence of fuel composition on regulated emissions, vehicle 13.

## INFLUENCE OF FUEL COMPOSITION
### DIESEL

**Regulated emissions** **FTP Composite**

### VEHICLE 14: DI, CATALYST, TURBO AND INTERCOOLER




HCi = integrated total hydrocarbons

Figure 50. Influence of fuel composition on regulated emissions, vehicle 14.

It is often said that biofuels like Rapeseed Methyl Ester (RME) give lower emissions than hydrocarbon based fuels. This is true only, if we compare biofuels to conventional diesel fuels with high sulphur level and high content of aromatics. With reformulated diesel fuels like the MK1, with the exception of particulate and perhaps $CO_2$ emissions, there are no other advantages that can be gained when switching from a high quality hydrocarbon based diesel fuel to biodiesel.

## 22.2 Unregulated gaseous emissions

The speciation of hydrocarbons measured by GC and the results of aldehydes sampled and analyzed by the DNPH/HPLC method are presented in Figures 51 and 52. Figure 51 shows the influence of temperature on the catalyst vehicles 13 and 14 with the MK1 fuel. Figure 52 illustrates the differences between all three test vehicles on the CEC fuel at normal temperature. Propane ($C_3H_8$) was not measured from diesel vehicles.

The scale in the GC result illustrations is narrower than the corresponding scale is in the figures of Part Two, because the levels of most components measured by GC are lower than for the gasoline TWC vehicles. However, the GC results from diesel vehicles represent only about 20...35 % of the total HC reading, whereas the GC results from gasoline vehicles cover about 50...70 % of the total hydrocarbons. This means, that diesel exhaust contains more heavier compounds that are not measurable with GC.

Figure 51 indicates, that the distribution between the different species is completely different from the spark ignited engines reported in Part Two (e.g. Fig. 34). With the diesel vehicles, ethylene, propylene and also methane are the dominating compounds. The influence of temperature is fairly small and some heavy compounds even decrease, when the temperature is lowered.

The DNPH results show, that aldehyde emissions from diesel vehicles are relatively high, comparable to the FFV vehicles measured for Part Two. Lowering the temperature increases the aldehyde emissions by a factor of about 1.5, which is much less than for the FFV vehicles. The emission of formaldehyde is about twice as much as the emission of acetaldehyde.

Figure 52 shows that in most cases the results with the CEC fuel are higher than with the MK1 fuel (Figure 51). The measured unregulated components are in general lowest for the direct-injected vehicle 14. Surprisingly, the other catalyst vehicle (vehicle 13), gives the highest unregulated emissions. The same phenomenon could be seen already when discussing the CO and total HC results of vehicle 13. Higher hydrocarbon levels for vehicle 13 than for vehicle 12 (which has no catalyst) are probably due to optimizing the $NO_X$ emissions of vehicle 13.

The aldehyde emissions are in all cases higher with the CEC fuel than with the MK1 fuel. The results of the RME/MK1 fuel (not illustrated) are in most cases between the two other fuels. The direct-injected vehicle 14 gives the lowest aldehyde emissions, and the non-catalyst vehicle 12 gives the second lowest. The formaldehyde emission (23 mg/km) and acetaldehyde emission (10 mg/km) for vehicle 13 at normal temperature must be considered fairly high.

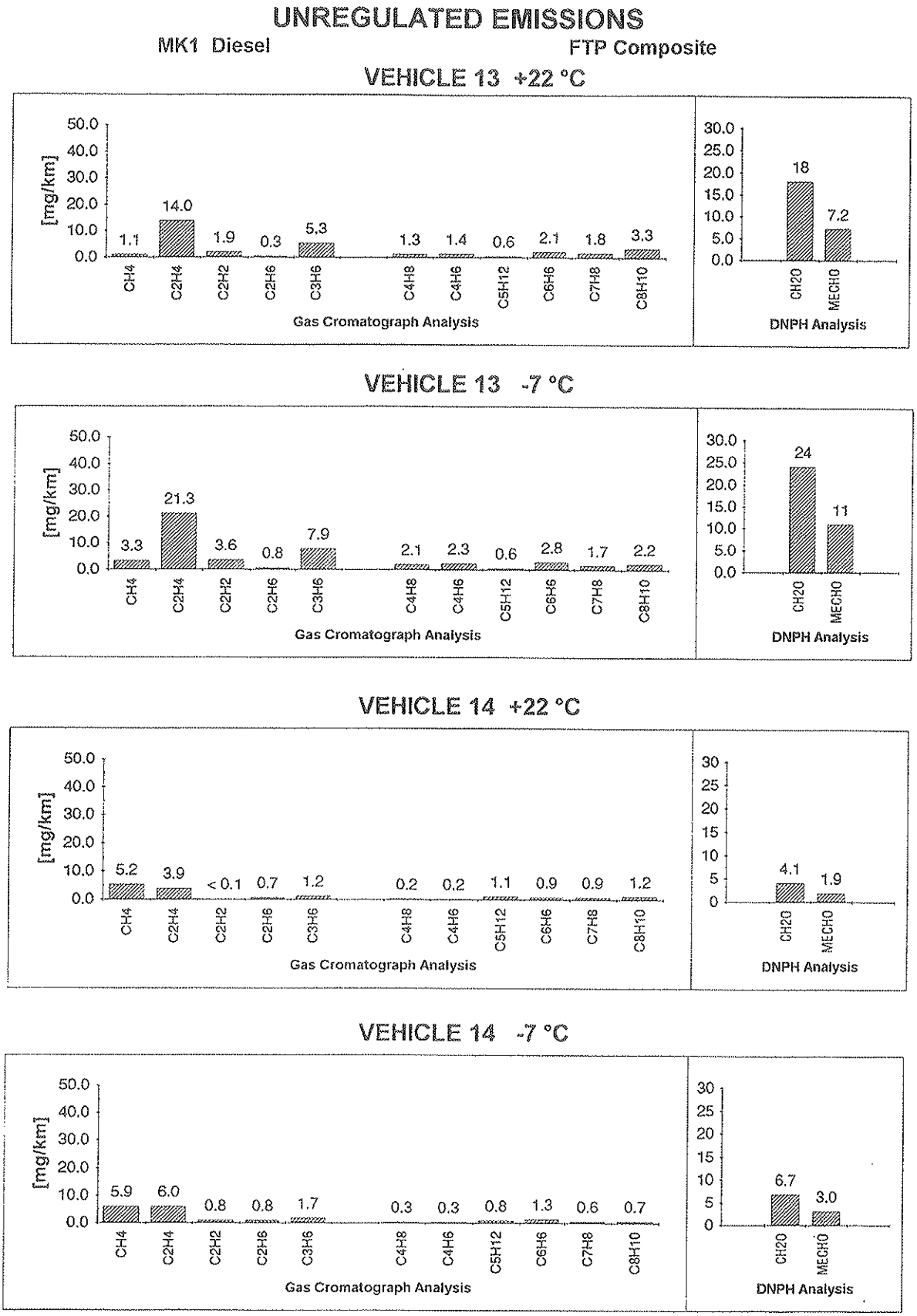
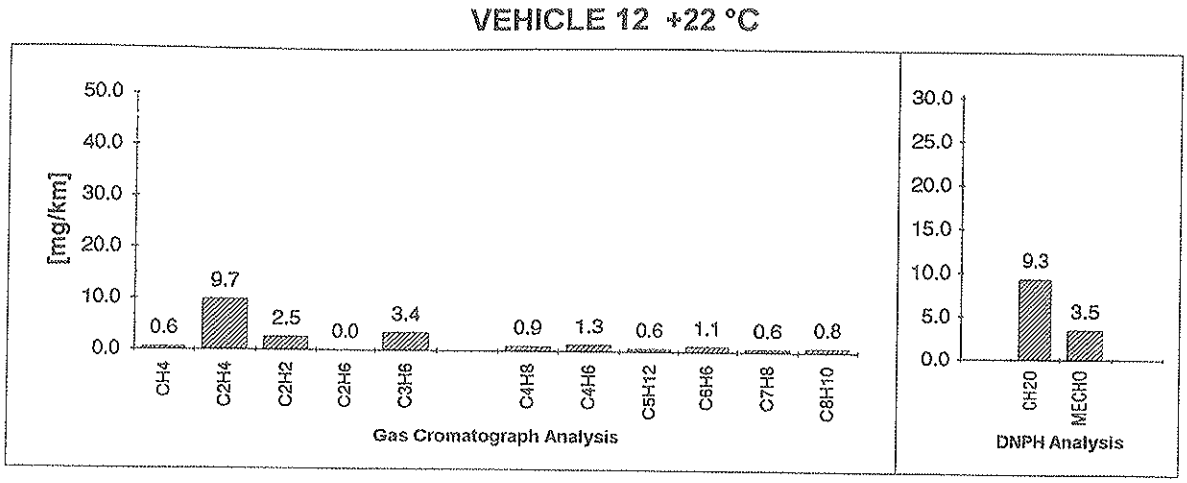
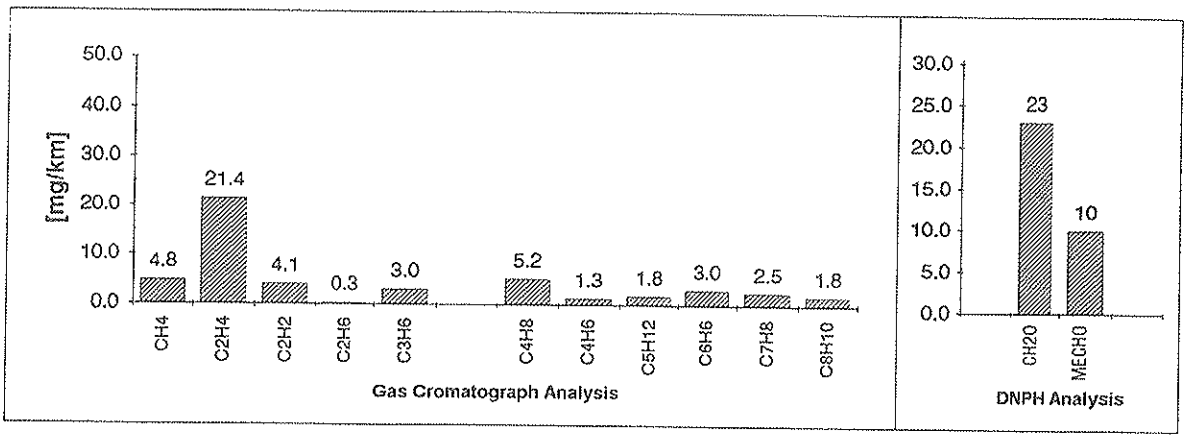



Figure 51. Unregulated emissions on the MK1 fuel (+22 and -7 °C, vehicles 13 and 14).



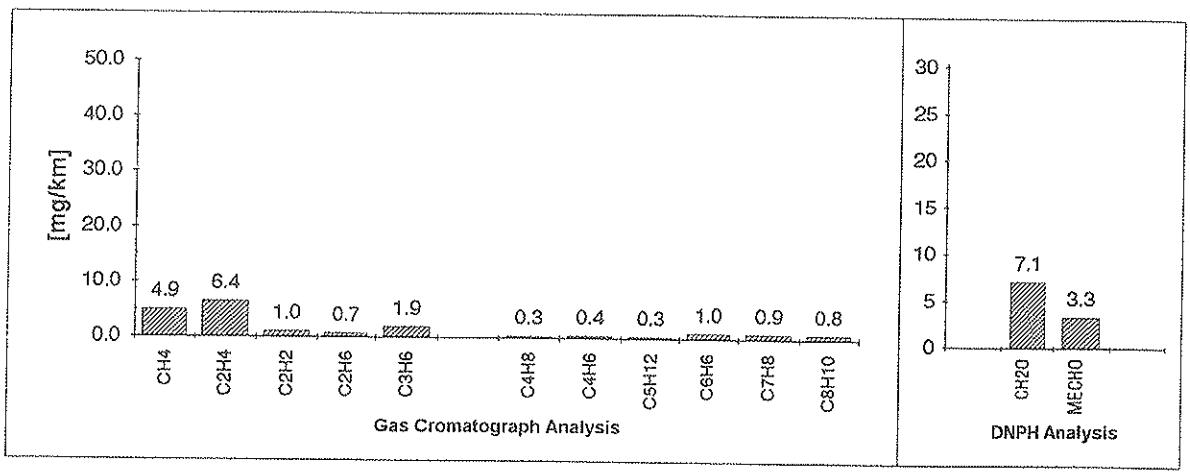




Figure 52. Unregulated emissions on the CEC fuel (+22 °C, vehicles 12, 13 and 14)

## 22.3 Particulate PAH and semivolatile PAH emissions

The diesel vehicle 12 (without catalyst) was selected for measurements of particulate and semivolatile polyaromatic hydrocarbon (PAH) emissions. The tests were carried out by using the polyurethane foam (PUF) sampling in addition to the conventional particle collecting filter. The analysis of polyaromatic hydrocarbons consisted of 29 components. The test fuel used for these tests was the CEC reference diesel. The test temperatures were +22 and ±0 °C.

The sampling of particulate and semivolatile PAH emissions was performed over all three phases of the FTP test in order to obtain enough sample into the filter and sampling foam. Because the sampling was not carried out individually for the three FTP phases, the results (µg/km) are calculated without weighting factors over the whole test.

One gasoline TWC vehicle and one FFV vehicle were used as reference for these measurements. With the FFV vehicle only the semivolatile compounds were analyzed. The gasoline TWC vehicle used for reference was a European model year 1995 passenger car with 1.8 liter engine and multi-point injection. It was not any of the gasoline vehicles tested for Part Two of Annex V. The results of the regulated exhaust components of this vehicle were comparable to test vehicle 3 of Annex V.

The FFV vehicle running on M85 used for the PAH analysis was the test vehicle 6 of Annex V. One has to keep in mind, that the mileage of vehicle 6 was about 50,000 miles when the sample for the PAH analysis was taken. Due to the higher mileage the regulated emissions of this vehicle (especially $NO_x$ and HC) were higher than when the vehicle was tested at below 10,000 miles for Part Two of Annex V.

The 29 components included in the PAH analysis were as follows: Naphthalene, 2-methylnaphthalene, 1-methylnaphthalene, Biphenyl, 3-methylbiphenyl, Acenaphthylene, Dibenzofurene, Fluorene, Dibenzothiophene, Phenanthrene, Anthracene, 2-methylanthracene, 1-methylphenanthrene, 2-phenylnaphthalene, Fluoranthene, Pyrene, Benzo(a)fluorene, Benzo(b)fluorene, Benz(a)anthracene, Chrysenetriphenylene, Benzo(b)fluoranthene, Benzo(k)fluoranthene, Benzo(e)pyrene, Benzo(a)pyrene, Perylene, Indeno(1,2,3,-cd)pyrene, Bibenzo(a,h)antracene, Benzo(g,h,i)perylene and Coronene.

The results of the PAH analysis are shown in Figures 53 and 54. Figure 53 illustrates the particulate PAH results, and Figure 54 gives the semivolatile PAH results.

The particulate PAH results (Fig. 53) show, that from the diesel vehicle the medium-weight compounds from Phenanthrene to Pyrene are the dominating compounds. Out of these, the compounds from Phenanthrene to 2-phenylnaphthalene represent the 3-ringed type, and Fluoranthene and Pyrene represent the 4-ringed type. The overall level is fairly low compared to some older diesel vehicles tested at VTT. The reference results of the gasoline vehicle are much lower, many of the analyzed compounds were not found at all. The dominating compounds of the gasoline vehicle are the heaviest ones from Benz(a)anthracene to Coronene.

# RESULTS OF PARTICULATE PAH ANALYSIS

FTP test without weigh factors

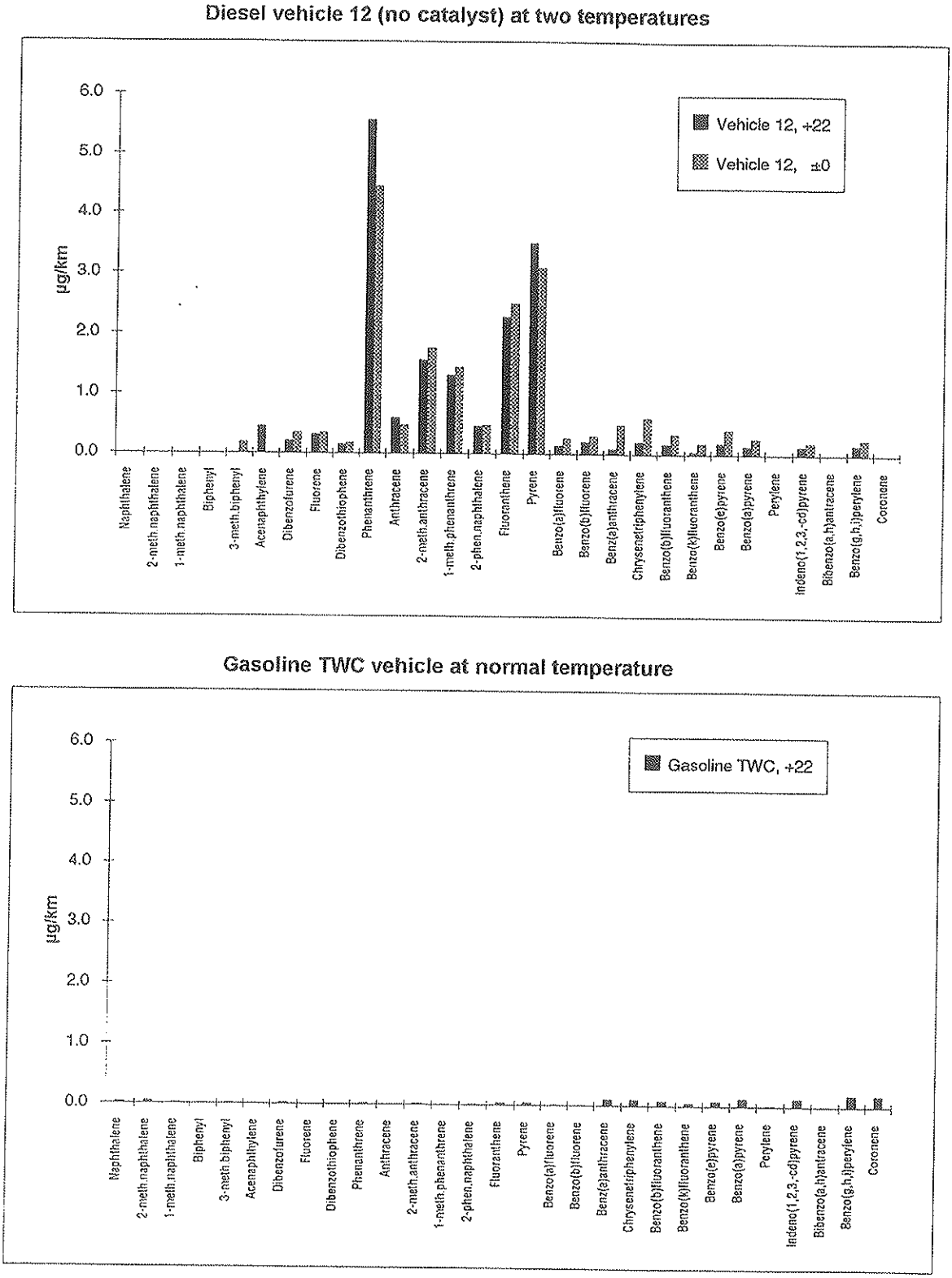



Figure 53. Particulate PAH emissions from vehicle 12 at +22 and ±0 °C. A gasoline TWC vehicle was used as reference at + 22 °C (lower picture).

# RESULTS OF SEMIVOLATILE PAH ANALYSIS

FTP test without weigh factors

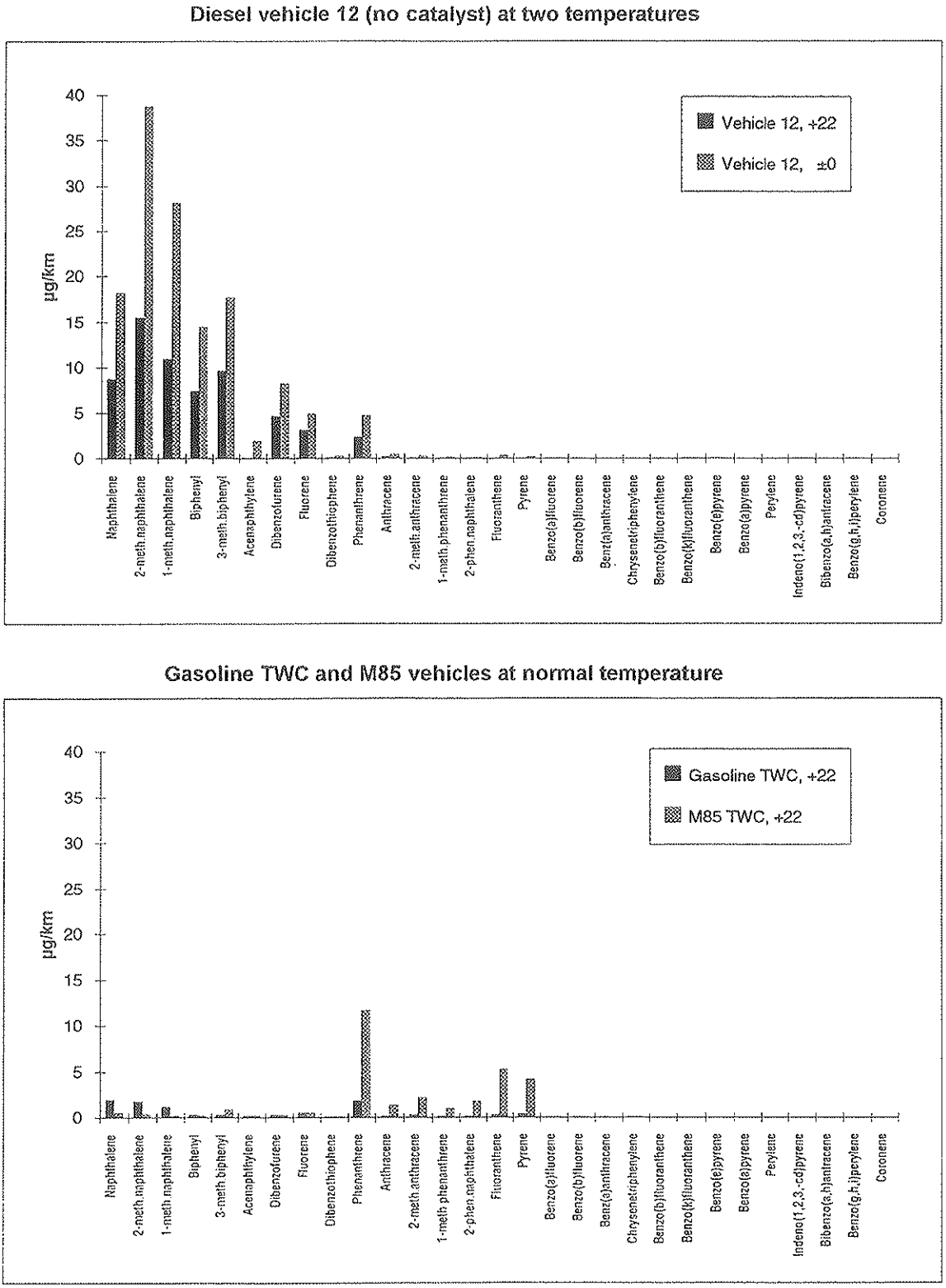



Figure 54. Semivolatile PAH emissions from vehicle 12 at +22 and ±0 °C. A gasoline TWC and an FFV vehicle on M85 were used as reference at + 22 °C (lower picture).

Figure 54 illustrates the results of the semivolatile PAH compounds. In this case the most of the compounds found were the lightest ones, primarily 2-ringed hydrocarbons. The influence of falling temperature seems to be greater on the semivolatile than on the particulate phase.

The distribution of the semivolatile components from the gasoline vehicle, which was measured for reference, concentrates on the lightest compounds from Naphthalene to Pyrene. The overall level is much lower than from the diesel vehicle. Phenantrene seems to be an exception: the level is about equal for both diesel and gasoline vehicles.

The semivolatile PAH compounds found from the FFV vehicle using M85 fuel showed that the M85 fuel emits some semivolatile compounds that are hardly not at all found from either diesel or gasoline vehicles. The dominating compound is the 3-ringed Phenantrene, and the 4-ringed compounds Fluoranthene and Pyrene are found in a scale of 5 µg/km.

The sum of the 29 PAH compounds illustrated in Figures 53 and 54 are given in Table 13. The results from the diesel vehicle 12 are shown at two temperatures and the reference results from the gasoline vehicle and the FFV vehicle on M85 are shown at normal temperature.

Table 13. Sum of the 29 PAH compounds illustrated in Figures 53 and 54.

| | | | |
|---|---|---|---|
| Particulate PAH<br>Filter sampling<br><br>µg/km | diesel | +22 °C | 18 |
| | | ±0 °C | 19 |
| | gasoline | +22 °C | 1.4 |
| | M85 | +22 °C | N/A |
| Semivolatile PAH<br>PUF sampling<br><br>µg/km | diesel | +22 °C | 63 |
| | | ±0 °C | 139 |
| | gasoline | +22 °C | 10 |
| | M85 | +22 °C | 31 |

The sum results show, that the particulate PAH emissions from the diesel vehicle are fairly independent of temperature, while the semivolatile PAH results increase considerably when the temperature is lowered.

In terms of particulate PAH emissions, the gasoline vehicle shows much lower results than diesel. The gasoline vehicle emitted mostly the heaviest compounds measured. The total sum of all measured 29 particulate PAH compounds showed a result of only 1.4 µg/km for the gasoline vehicle. The corresponding value for diesel was 18 µg/km.

In the case of semivolatile PAH emissions both diesel and gasoline vehicles emitted mostly the lightest compounds. The level from the diesel vehicle was about six times higher than from the gasoline vehicle at normal temperature.

## 23. DISCUSSION

The most efficient way to reduce emissions from vehicles equipped with Otto type engines is to introduce three way catalyst technology. In normal ambient temperatures the TWC technology will reduce emissions some 80...90 %. However, the gap in emissions between non-catalyst and TWC vehicles becomes smaller with falling temperature. At -20 °C the CO and HC emissions from a TWC vehicle are only about 50 % lower than those form a non-catalyst vehicle over the FTP test. The reason for this is that most of the CO and HC emissions are generated before catalyst light-off.

It is possible to reduce the emissions from both non-catalyst and TWC vehicles by changing the gasoline composition. In general, the addition of oxygenated compounds reduces CO emissions. The maximum emission reductions in regulated components that can be achieved with fuel modifications are on the order of 20 %. The same is true for most unregulated components, eg. benzene.

Diesel engine equipped passenger cars are rather common in Europe. The diesel engine always runs in lean-burn mode, and therefore the effect of ambient temperature on diesel vehicle emissions is rather limited. At normal ambient temperature diesel vehicles compete very well with TWC gasoline vehicles in the case of CO and HC, and are superior in this respect at low temperatures. However, the $NO_x$ emissions of diesel vehicles are rather high.

Table 14 and Figure 55 summarize the regulated emissions at +22 and -7 °C for the vehicles tested at VTT. The lowest and highest emission values for each technology are presented. The emission benefits that can be achieved by switching to an alternative fuel are, in general, smaller than those found when going from a non-catalyst vehicle to a TWC vehicle. The differences between all fuel alternatives using TWC technology are rather limited. The emissions of CO are clearly reduced with alternative fuels, especially with gaseous fuels. Although natural gas gives the highest total HC emissions, most of these are non-toxic methane. The diesel gives equivalent or even lower CO and HC values than TWC technology, but higher $NO_x$ emissions.

The M85 engine used for Part One produced very high CO and HC (measured by FID) emissions at low-temperature. However, three of four FFV's tested for Part Two performed rather well on M85 at -7 °C, and in general had lower emissions than they did when fueled with gasoline.

Of the four FFV's tested, vehicle 6 performed better than 5 and 7 on both gasoline and M85. The regulated emissions of vehicle 6 were surprisingly low even at -7 °C, and the vehicle met the new low-temperature CO emission limit by a clear margin. Vehicle 7 also meets this new emission limit. Vehicle 5 had high emissions at +22 °C, and was excluded from Figure 55, because this vehicle was a very early stage prototype and its emissions were out of range of an up-to-date FFV vehicle. The other protoype FFV vehicle (vehicle 8) gave even lower results than vehicle 6, and its values were about the lowest ever measured at VTT for a vehicle using a liquid fuel. However, this vehicle did not start at -7 °C on M85.

Table 15 and Figure 56 summarize the average values of the unregulated emissions (including formaldehyde) at +22 and -7 °C. The components dealt with here are 1,3-butadiene, benzene, formaldehyde and methanol. Figure 56 clearly indicates that the biggest improvements in the emissions of 1,3-butadiene, benzene and formaldehyde can be achieved by using catalyst technology. However, the emissions of 1,3-butadiene and benzene are reduced at all temperatures using alternative fuels instead of gasoline.

Table 14. Summary of regulated components, lowest / highest values (illustrated in Fig. 55).

| +22 °C FTP Composite [g/km] | CO | HC | $NO_x$ |
|---|---|---|---|
| Gasoline w/o cat. | 5.32 / 12.6 | 1.06 / 1.48 | 1.93 / 3.35 |
| Gasoline | 0.86 / 2.08 | 0.08 / 0.10 | 0.20 / 0.43 |
| M85 | 0.20 / 1.43 | 0.03 / 0.06 | 0.04 / 0.19 |
| LPG | 0.71 / 1.07 | 0.09 / 0.14 | 0.10 / 0.21 |
| CNG | 0.32 / 0.48 | 0.21 / 0.61 | 0.06 / 0.19 |
| Diesel | 0.08 / 0.40 | 0.05 / 0.14 | 0.40 / 0.94 |
| **-7 °C FTP Composite [g/km]** | **CO** | **HC** | **$NO_x$** |
| Gasoline w/o cat. | 10.3 / 18.1 | 1.43 / 2.41 | 2.13 / 2.70 |
| Gasoline | 3.27 / 6.75 | 0.30 / 0.50 | 0.09 / 0.22 |
| M85 | 2.56 / 4.19 | 0.39 / 0.86 | 0.06 / 0.07 |
| LPG | 1.17 / 1.49 | 0.19 / 0.23 | 0.20 / 0.29 |
| CNG | 0.51 / 0.58 | 0.39 / 0.89 | 0.13 / 0.20 |
| Diesel | 0.13 / 0.72 | 0.07 / 0.18 | 0.45 / 1.05 |

Table 15. Summary of unregulated components, average values (illustrated in Fig. 56).

| +22 °C FTP Composite [mg/km] | 1,3-butadiene | benzene | formaldehyde | methanol |
|---|---|---|---|---|
| Gasoline w/o cat. | 11.8 | 55 | 43 | 0 |
| Gasoline | 0.6 | 4.7 | 2.5 | 0 |
| M85 | <0.5 | 1.5 | 5.8 | 79 |
| LPG | <0.5 | <0.5 | <2 | 0 |
| CNG | <0.5 | 0.6 | <2 | 0 |
| Diesel | 1 | 1.5 | 12 | 0 |
| **-7 °C FTP Composite [mg/km]** | **1,3-butadiene** | **benzene** | **formaldehyde** | **methanol** |
| Gasoline w/o cat. | 10 | 69 | 44 | 0 |
| Gasoline | 1.7 | 18 | 2.6 | 0 |
| M85 | 0.5 | 11 | 23 | 810 |
| LPG | <0.5 | 1.1 | <2 | 0 |
| CNG | <0.5 | 0.9 | <2 | 0 |
| Diesel | 1.6 | 1.9 | 16 | 0 |

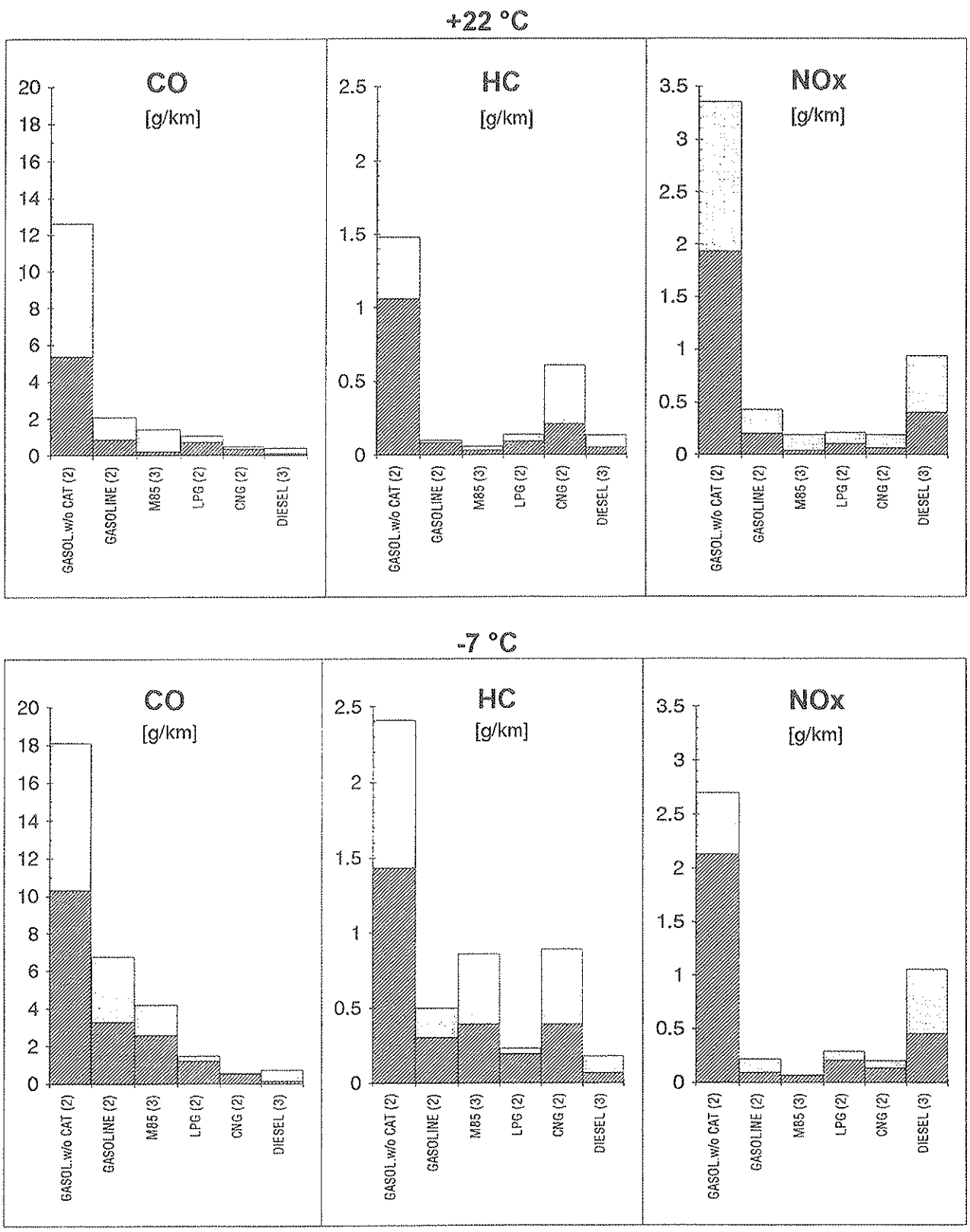



Figure 55. Summary of regulated emissions.

## SUMMARY OF UNREGULATED COMPONENTS

AVERAGE VALUES (n:o of vehicles) FTP COMPOSITE

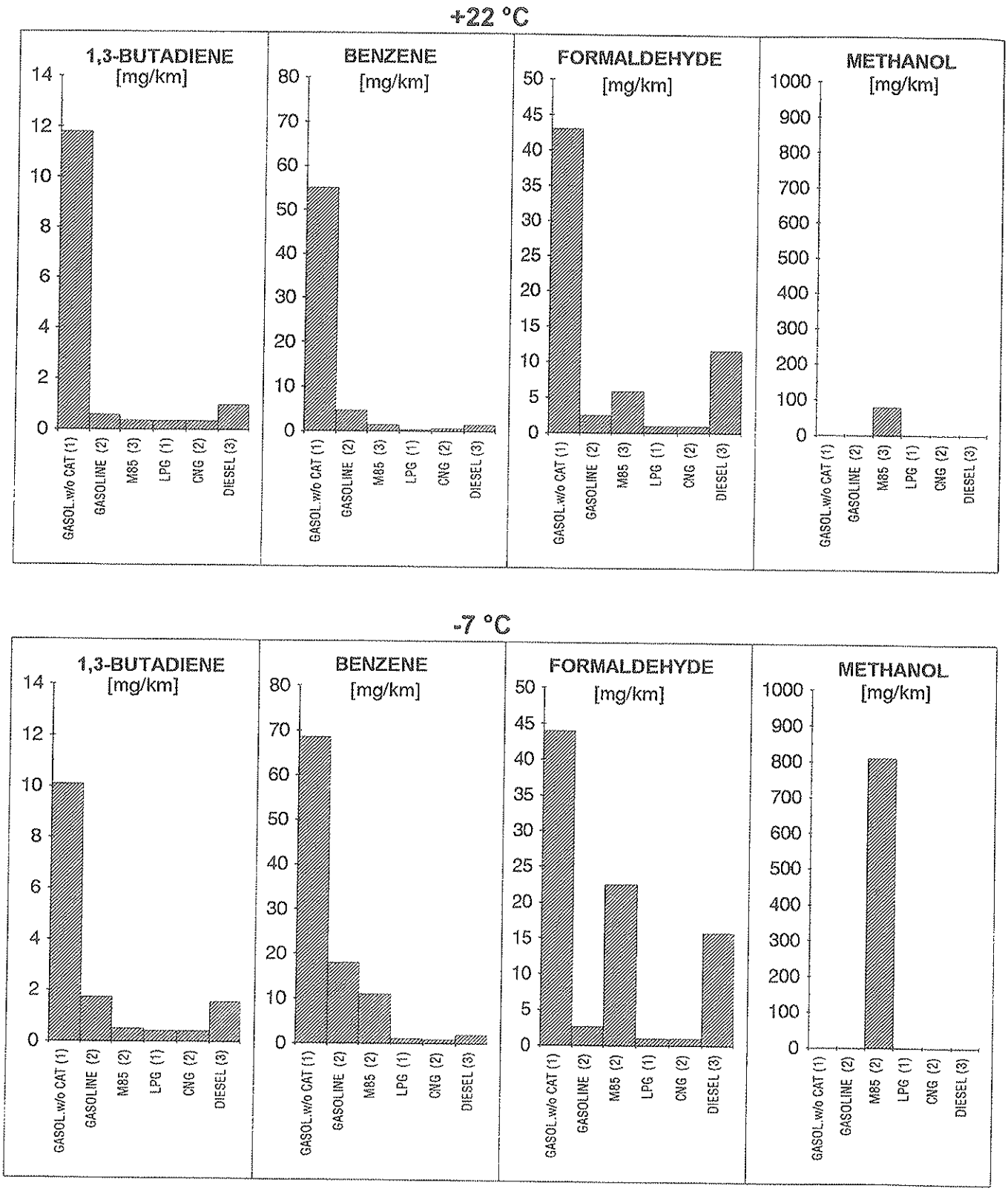



Figure 56. Summary of unregulated emissions.

For FFV's 5 and 6 the formaldehyde emission values at +22 °C were close to the LEV (Low Emission Vehicle) limit value set by California. Formaldehyde values for vehicle 7 were 50 %, and for vehicle 8 only about 20 % of the limit value 10 mg/km. On average the formaldehyde emissions of the FFV's were some two times higher than those from the gasoline vehicles at +22°C. This, however, changes dramatically at -7 °C. The formaldehyde emissions of the FFV's increase by a factor of 5 to roughly 25 mg/km, whereas the formaldehyde emissions of the gasoline vehicles are unaffected by temperature.

With FFV's 5 and 6 the emissions of unburned methanol were high, ranging from 120 to 1600 mg/km depending on vehicle and temperature. The methanol emissions from vehicle 7 were a little lower, and those from vehicle 8 considerably lower (30 mg/km at the lowest). The FID instrument used for normal HC measurements clearly underestimated unburned methanol. All the alcohol vehicles tested performed significantly better than the M85 engine tested in Part One.

The diesel vehicles give 1,3-butadiene values equivalent to gasoline vehicles, and benzene emissions close to AMF vehicles. The formaldehyde emissions of diesel vehicles are rather high, and exceed Californian limit values.

Measurements of PAH components were conducted on one diesel, one TWC gasoline and one FFV vehicle. Compared to gasoline, the total PAH emissions of the diesel vehicle were some 12 (particulate phase) to 6 (semivolatile phase) times higher at +22 °C. The FFV vehicle running on M85 gave PAH results of 3 times higher than gasoline (semivolatile phase).

As in Part One, the engines on gaseous fuels gave by far the lowest overall regulated and unregulated emissions (with the exception of the prototype flex fuel vehicle 8). The vehicles tested had up-to-date gaseous fuel injection systems, and the emissions were more or less independent of temperature. The total HC emissions of the CNG vehicles were high, but 90 % of the total HC value is methane.

With the dedicated CNG vehicle (11) the HC emissions were considerably lower than with the retrofitted system (vehicle 10). This was attributed to the fact that the catalytic converter in vehicle 11 was optimized for CNG. Practically no harmful unregulated components were found in the exhaust of the vehicles on gaseous fuels. An example of emission results with different fuels is presented in Table 16. For each fuel the vehicle with lowest overall emissions is chosen.

Table 16. Example of emission results with each of the tested fuels.

| +22 °C / -7 °C | | HC-gasoline | M85 | LPG | CNG | Diesel |
|---|---|---|---|---|---|---|
| Regulated emissions [g/km] | CO | 0.86 / 3.3 | 0.57 / 2.6 | 0.71 / 1.2 | 0.48 / 0.58 | 0.09 / 0.15 |
| | HC | 0.09 / 0.50 | 0.05 / 0.86 | 0.14 / 0.23 | 0.21 / 0.39 | 0.06 / 0.08 |
| | $NO_x$ | 0.20 / 0.09 | 0.04 / 0.06 | 0.21 / 0.29 | 0.06 / 0.13 | 0.45 / 0.45 |
| Unregu-lated- emiss. [mg/km] | Benzene | 3.2 / 22 | 1.4 / 12 | <0.5 / 1.1 | 0.9 / <0.5 | 0.9 / 1.6 |
| | 1,3-butadiene | <0.5 / 1.6 | <0.5 / 0.6 | <0.5 / <0.5 | <0.5 / <0.5 | <0.5 / <0.5 |
| | Formaldehyde | <2 / <2 | 11 / 31 | <2 / <2 | <2 / <2 | 5 / 8 |
| | Methanol | 0 / 0 | 124 / 1113 | 0 / 0 | 0 / 0 | 0 / 0 |
| vehicle | | 4 | 6 | 10 | 11 | 14 |

Prior to starting Annex V it was thought that alcohol fueled vehicles would have very high low-temperature CO and HC emissions. Such a conclusion could also be drawn from the results of Part One, Engine Tests. However, the FFV's tested for Part Two showed regulated emissions equal to or lower than those from gasoline vehicles at all temperatures. Even the formaldehyde emissions of the FFV's at normal ambient temperature were moderate, but they increased with falling temperature.

Unburned methanol, especially at low temperatures, is a problem with M85. A value of 1600 mg/km must be considered unacceptable. However, the emissions of both formaldehyde and unburned methanol can be controlled with proper engine management and catalyst technology. The lowest common testing temperature for all FFV's was ±0 °C. Formaldehyde emissions at this temperature varied from 4 to 26 mg/km, i.e. by a factor of 6. For unburned methanol the corresponding figures were 101 to 1303 mg/km, i.e. a factor 13.

If methanol were included in the regulated components of alcohol vehicles also at low temperature, this would clearly drive technology forward. Measuring only CO emission at -7 °C does not give a true picture of the emission performance of FFV's - formaldehyde and methanol emissions should be included.

Today's advanced gasoline vehicles must be considered rather clean. M85 can give lower emissions in warm conditions, but the emission of unburned methanol must be controlled. Natural gas and LPG are inherently clean fuels which, using up-to-date engine technology, give low emissions in all conditions.

The diesel vehicles perform rather well regarding CO and HC emissions, and also low-temperature emission performance in general. The $NO_x$ emissions are higher than with TWC technology. The PAH emissions of the diesel are high compared to other fuels.

Better analysis tools, including biological tests, are needed to fully evaluate the health effects of the different fuel and technology alternatives. The study at hand demonstrates that comparing different fuel alternatives using only regulated emissions can lead to wrong conclusions. One should keep in mind that the standardized emission tests were originally designed to evaluate different vehicles using a standardized test fuel. The greater the variations in fuel chemistry and engine operating principles are, the greater is also the need for sophisticated emission measurement technologies.

# APPENDICES

| Vehicle | Type | Fuel Management | Fuels used | No of cylinders | Displace-ment [ l ] | Model Year | Odo-meter [km] | Origin |
|---|---|---|---|---|---|---|---|---|
| 1 | pass. car | carburettor, automatic choke | gasoline | 4 | 1.4 | 1990 | 24000 | Japanese |
| 2 | pass. car | MPFI without catalyst | gasoline | 4 | 2.0 | 1990 | 84000 | European |
| 3 | pass. car | MPFI with catalyst | gasoline | 4 | 2.0 | 1992 | 39000 | European |
| 4 | pass. car | MPFI with catalyst, second. air injection | gasoline | 4 | 2.3 | 1994 | 21000 | Nordic |
| 5 | pass. car | MPFI with catalyst | gasoline, M50, M85, E85 | 4 | 2.3 | 1993 | 14000 | Nordic |
| 6 | pass. car | MPFI with catalyst | gasoline, M50, M85 | 4 | 1.8 | 1992 | 5500 | European |
| 7 | pass. car | MPFI with catalyst | gasoline, M50, M85 | 4 | 2.5 | 1994 | 8500 | American |
| 8 | pass. car | MPFI with heated cat., second. air injection | gasoline, M50, M85 | 4 | 2.3 | 1993 | 6000 | Nordic |
| 9 | pass. car | dual MPFI with catalyst | gasoline LPG | 4 | 2.0 | 1993 | 8000 | European |
| 10 | van | dual MPFI with catalyst | gasoline LPG, CNG | 4 | 2.0 | 1993 | 17000 | European |
| 11 | van | MPFI with catalyst | CNG | 8 | 5.2 | 1994 | 2100 | American |
| 12 | pass. car | DIESEL, IDI without catalyst | 3 types of diesel fuel | 4 | 1.9 *) | 1995 | 12000 | European |
| 13 | pass. car | DIESEL, IDI oxid. catalyst, turbo | 3 types of diesel fuel | 4 | 1.9 *) | 1995 | 5500 | European |
| 14 | pass. car | DIESEL, DI, oxid. cat. turbo, intercooler | 3 types of diesel fuel | 4 | 1.9 *) | 1995 | 7500 | European |

*) same base engine in all diesel vehicles

## GASOLINES:

| | | | | | Summer qualities | | | Winter qualities | | |
|---|---|---|---|---|---|---|---|---|---|---|
| FUEL CODE | a | b | c | d | e2 | e3 | e4 | e2 | e3 | e4 |
| Density 15 °C, kg/l | 0,737 | 0,741 | 0,753 | 0,758 | 0,750 | 0,749 | 0,747 | 0,744 | 0,736 | 0,740 |
| Reid vapour pressure, kPa | 89 | 68 | 64 | 65 | 82 | 83 | 85 | 94 | 95 | 96 |
| Distillation, °C | | | | | | | | | | |
| IBP | 25 | | 30 | 30 | 30 | 31 | 30 | | | |
| 10 %-vol | 37 | | 48 | 48 | 45 | 45 | 48 | | | |
| 50 %-vol | 95 | | 90 | 104 | 88 | 73 | 90 | | | |
| 90 %-vol | 154 | | 156 | 165 | 160 | 159 | 156 | | | |
| FBP | 191 | | 195 | 204 | 203 | 201 | 195 | | | |
| E70 | | 26,6 | 32,4 | 26,9 | 39,4 | 43,7 | 47,7 | 42,4 | 49,2 | 47,7 |
| E180 | | 96,2 | 97,5 | 96,1 | 96,6 | 97,1 | 97,0 | 96,9 | 97,4 | 97,0 |
| Sulphur content, mg/kg | 217 | 264 | 222 | 104 | 310 | 346 | 356 | 410 | 490 | 340 |
| oxygenates | none | 13 w-% ETBE | 11 w-% MTBE | 10,7 w-% MTBE | 7,2 w-% EtOH | 9,4 w-% EtOH | 12,3 w-% EtOH | 7,2 w-% EtOH | 9,8 w-% EtOH | 12,3 w-% EtOH |

## METHANOL BLENDS:

Technical grade methanol blended with commercial Finnish oxygenated winter grade gasoline

## ETHANOL BLENDS:

Dehydrated ethanol blended with commercial Finnish oxygenated winter grade gasoline

**LPG:** Commercial LPG used in the Netherlands (70% propane, 30% butane).

**CNG:** Vehicle 10: Commercial CNG used in the Netherlands ($CH_4$= 81%, $N_2$= 10%, $CO_2$= 4%, $C_2H_6$= 4%)

Vehicle 11: Commercial Russian CNG used in FInland ($CH_4$ > 98%)

## DIESEL:

| FUEL | | | MK1 | CEC RF-03-A-84 |
|---|---|---|---|---|
| Density | | kg/l | 0.810 | 0.838 |
| Viscosity at +40 °C | | $mm^2/s$ | 1.84 | 2.6 |
| Cetane number | | | 53.0 | 51 |
| Cetane index | | | 52.9 | 51.7 |
| Distillation | 50 % | °C | 229 | 269 |
| | 90 % | °C | 258 | 323 |
| | FBP | °C | 280 | 351 |
| CFPP | | °C | < -40 | -14 |
| Sulphur content | | ppm | < 10 | 300 |

| Veh. code | Fuel code | Temp °C | CO g/km | HC g/km | NMHC g/km | NOx g/km |
|---|---|---|---|---|---|---|
| 1 | a | +20 | 9.62 | 1.48 | - | 3.03 |
| 1 | a | -7 | 18.1 | 2.41 | - | 2.44 |
| 1 | a | -20 | 20.0 | 3.27 | - | 2.63 |
| 1 | e2 | +20 | 7.64 | 1.46 | - | 2.88 |
| 1 | e2 | -7 | 13.9 | 2.05 | - | 2.60 |
| 1 | e2 | -20 | 19.3 | 2.87 | - | 2.64 |
| 1 | e3 | +20 | 5.67 | 1.34 | - | 3.15 |
| 1 | e3 | -7 | 13.7 | 2.09 | - | 2.64 |
| 1 | e3 | -20 | 18.8 | 2.69 | - | 2.62 |
| 1 | e4 | +20 | 5.32 | 1.31 | - | 3.35 |
| 1 | e4 | -7 | 11.4 | 1.83 | - | 2.70 |
| 1 | e4 | -20 | 16.0 | 2.67 | - | 2.54 |
| 2 | a | +22 | 12.6 | 1.35 | 1.30 | 1.93 |
| 2 | a | ±0 | 13.8 | 1.32 | 1.27 | 1.99 |
| 2 | a | -7 | 15.9 | 1.60 | 1.54 | 2.18 |
| 2 | a | -20 | 19.8 | 2.14 | 2.05 | 2.15 |
| 2 | b | +22 | 7.88 | 1.14 | 1.10 | 2.06 |
| 2 | b | ±0 | 12.3 | 1.45 | 1.39 | 2.16 |
| 2 | b | -7 | 13.3 | 1.52 | 1.46 | 2.13 |
| 2 | b | -20 | 16.5 | 2.07 | 1.98 | 2.18 |
| 2 | c | +22 | 6.99 | 1.06 | 1.03 | 2.33 |
| 2 | c | ±0 | 10.2 | 1.29 | 1.25 | 2.44 |
| 2 | c | -7 | 10.3 | 1.43 | 1.38 | 2.32 |
| 2 | c | -20 | - | - | - | - |
| 2 | d | +22 | 6.85 | 1.14 | 1.11 | 2.17 |
| 2 | d | ±0 | 9.44 | 1.36 | 1.32 | 2.32 |
| 2 | d | -7 | 10.9 | 1.51 | 1.46 | 2.33 |
| 2 | d | -20 | - | - | - | - |
| 3 | a | +22 | 2.08 | 0.10 | 0.08 | 0.43 |
| 3 | a | ±0 | 5.23 | 0.21 | 0.19 | 0.18 |
| 3 | a | -7 | 6.75 | 0.32 | 0.29 | 0.16 |
| 3 | a | -20 | 11.7 | 0.74 | 0.69 | 0.17 |
| 3 | b | +22 | 1.21 | 0.08 | 0.07 | 0.38 |
| 3 | b | ±0 | 4.78 | 0.22 | 0.20 | 0.22 |
| 3 | b | -7 | 6.51 | 0.33 | 0.30 | 0.22 |
| 3 | b | -20 | 11.3 | 0.82 | 0.77 | 0.23 |
| 3 | c | +22 | 1.08 | 0.09 | 0.07 | 0.36 |
| 3 | c | ±0 | 3.99 | 0.19 | 0.17 | 0.23 |
| 3 | c | -7 | 6.08 | 0.30 | 0.27 | 0.21 |
| 3 | c | -20 | - | - | - | - |
| 3 | d | +22 | 1.15 | 0.10 | 0.08 | 0.29 |
| 3 | d | ±0 | 3.97 | 0.20 | 0.18 | 0.16 |
| 3 | d | -7 | 5.86 | 0.34 | 0.31 | 0.14 |
| 3 | d | -20 | - | - | - | - |

| Veh. code | Fuel code | Temp °C | CO g/km | HC g/km | NMHC g/km | OMHCE g/km | NOx g/km |
|---|---|---|---|---|---|---|---|
| 4 | a | +22 | 0.86 | 0.09 | 0.07 | - | 0.20 |
| 4 | a | ±0 | 2.28 | 0.31 | 0.28 | - | 0.12 |
| 4 | a | -7 | 3.27 | 0.50 | 0.46 | - | 0.09 |
| 4 | a | -20 | 9.24 | 1.65 | 1.57 | - | 0.11 |
| 5 | M/E0 | +20 | 4.35 | 0.98 | - | - | 0.25 |
| 5 | M/E0 | ±0 | 6.75 | 1.50 | - | - | 0.33 |
| 5 | M/E0 | -7 | 8.77 | 2.15 | - | - | 0.34 |
| 5 | E85 | +20 | 2.80 | 0.37 | - | - | 0.27 |
| 5 | E85 | ±0 | 4.70 | 0.90 | - | - | 0.23 |
| 5 | E85 | -7 | 5.89 | 1.41 | - | - | 0.29 |
| 5 | M50 | +20 | 3.53 | 0.57 | - | - | 0.29 |
| 5 | M50 | ±0 | 7.94 | 1.66 | - | - | 0.40 |
| 5 | M50 | -7 | 6.44 | 1.16 | - | - | 0.40 |
| 5 | M85 | +20 | 2.63 | 0.36 | - | - | 0.28 |
| 5 | M85 | ±0 | 4.17 | 0.71 | - | - | 0.43 |
| 5 | M85 | -7 | 4.53 | 1.02 | - | - | 0.27 |
| 6 | M0 | +22 | 1.59 | 0.11 | 0.09 | - | 0.12 |
| 6 | M0 | +7 | 1.82 | 0.16 | 0.14 | - | 0.04 |
| 6 | M0 | ±0 | 2.58 | 0.23 | 0.21 | - | 0.06 |
| 6 | M0 | -7 | 4.20 | 0.37 | 0.34 | - | 0.08 |
| 6 | M50 | +22 | 0.98 | 0.07 | 0.06 | 0.10 | 0.24 |
| 6 | M50 | +7 | 2.41 | 0.17 | 0.15 | 0.23 | 0.12 |
| 6 | M50 | ±0 | 3.13 | 0.25 | 0.23 | 0.34 | 0.14 |
| 6 | M50 | -7 | 4.17 | 0.45 | 0.42 | 0.61 | 0.11 |
| 6 | M85 | +22 | 0.57 | 0.05 | 0.04 | 0.11 | 0.04 |
| 6 | M85 | +7 | 1.44 | 0.17 | 0.16 | 0.37 | 0.09 |
| 6 | M85 | ±0 | 1.79 | 0.35 | 0.34 | 0.70 | 0.15 |
| 6 | M85 | -7 | 2.56 | 0.86 | 0.84 | 1.36 | 0.06 |
| 7 | M0 | +22 | 2.74 | 0.15 | 0.12 | - | 0.08 |
| 7 | M0 | +7 | 3.87 | 0.25 | 0.22 | - | 0.07 |
| 7 | M0 | ±0 | 5.56 | 0.32 | 0.28 | - | 0.07 |
| 7 | M0 | -7 | 6.33 | 0.44 | 0.41 | - | 0.07 |
| 7 | M50 | +22 | 2.25 | 0.11 | 0.09 | 0.12 | 0.07 |
| 7 | M50 | +7 | 3.29 | 0.17 | 0.15 | 0.20 | 0.06 |
| 7 | M50 | ±0 | 4.02 | 0.20 | 0.18 | 0.24 | 0.05 |
| 7 | M50 | -7 | 4.81 | 0.26 | 0.23 | 0.31 | 0.06 |
| 7 | M85 | +22 | 1.43 | 0.06 | 0.05 | 0.10 | 0.06 |
| 7 | M85 | +7 | 2.07 | 0.13 | 0.12 | 0.22 | 0.08 |
| 7 | M85 | ±0 | 3.21 | 0.25 | 0.23 | 0.41 | 0.07 |
| 7 | M85 | -7 | 4.19 | 0.39 | 0.37 | 0.62 | 0.07 |

| Veh. code | Fuel code | Temp °C | CO g/km | HC g/km | NMHC g/km | OMHCE g/km | NOx g/km |
|---|---|---|---|---|---|---|---|
| 8 | M0 | +22 | 0.41 | 0.05 | 0.04 | - | 0.12 |
| 8 | M0 | +7 | 1.40 | 0.14 | 0.12 | - | 0.10 |
| 8 | M0 | ±0 | 2.41 | 0.23 | 0.20 | - | 0.09 |
| 8 | M0 | -7 | 2.83 | 0.40 | 0.36 | - | 0.10 |
| 8 | M50 | +22 | 0.29 | 0.04 | 0.03 | 0.05 | 0.11 |
| 8 | M50 | +7 | 0.50 | 0.09 | 0.07 | 0.10 | 0.13 |
| 8 | M50 | ±0 | 0.85 | 0.11 | 0.09 | 0.13 | 0.17 |
| 8 | M50 | -7 | 1.32 | 0.22 | 0.19 | 0.26 | 0.24 |
| 8 | M85 | +22 | 0.20 | 0.03 | 0.02 | 0.04 | 0.19 |
| 8 | M85 | +7 | 0.24 | 0.05 | 0.04 | 0.07 | 0.26 |
| 8 | M85 | ±0 | 1.27 | 0.10 | 0.08 | 0.15 | 0.19 |
| 8 | M85 | -7 | MF | MF | MF | MF | MF |
| 9 | a | +22 | 0.81 | 0.13 | - | - | 0.16 |
| 9 | a | +7 | - | - | - | - | - |
| 9 | a | ±0 | 3.17 | 0.29 | - | - | 0.20 |
| 9 | a | -7 | - | - | - | - | - |
| 9 | LPG | +22 | 1.07 | 0.09 | - | - | 0.10 |
| 9 | LPG | +7 | 0.68 | 0.07 | - | - | 0.18 |
| 9 | LPG | ±0 | 0.95 | 0.09 | - | - | 0.15 |
| 9 | LPG | -7 | 1.49 | 0.19 | - | - | 0.20 |
| 10 | a | +22 | 1.97 | 0.36 | 0.31 | - | 0.21 |
| 10 | a | +7 | 4.12 | 0.52 | 0.47 | - | 0.30 |
| 10 | a | ±0 | 5.16 | 0.58 | 0.53 | - | 0.29 |
| 10 | a | -7 | 6.26 | 0.81 | 0.75 | - | 0.27 |
| 10 | LPG | +22 | 0.71 | 0.14 | 0.10 | - | 0.21 |
| 10 | LPG | +7 | 1.06 | 0.15 | 0.11 | - | 0.26 |
| 10 | LPG | ±0 | 0.88 | 0.13 | 0.10 | - | 0.24 |
| 10 | LPG | -7 | 1.17 | 0.23 | 0.18 | - | 0.29 |
| 10 | CNG | +22 | 0.32 | 0.61 | 0.05 | - | 0.19 |
| 10 | CNG | +7 | 0.49 | 0.71 | 0.07 | - | 0.19 |
| 10 | CNG | ±0 | 0.52 | 0.74 | 0.07 | - | 0.17 |
| 10 | CNG | -7 | 0.51 | 0.89 | 0.09 | - | 0.20 |
| 11 | CNG | +22 | 0.48 | 0.21 | 0.02 | - | 0.06 |
| 11 | CNG | +7 | 0.41 | 0.21 | 0.01 | - | 0.09 |
| 11 | CNG | ±0 | 0.45 | 0.24 | 0.03 | - | 0.10 |
| 11 | CNG | -7 | 0.58 | 0.39 | 0.08 | - | 0.13 |

- = not measured

MF = vehicle malfunction

| Veh. code | Fuel code | Temp °C | CO g/km Bag1 | CO g/km Bag2 | CO g/km Bag3 | HC g/km Bag1 | HC g/km Bag2 | HC g/km Bag3 | NOx g/km Bag1 | NOx g/km Bag2 | NOx g/km Bag3 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | a | +20 | 18.4 | 8.34 | 5.42 | 1.91 | 1.47 | 1.20 | 2.61 | 3.04 | 3.31 |
| 1 | a | -7 | 51.7 | 10.7 | 6.64 | 5.55 | 1.69 | 1.42 | 1.44 | 2.63 | 2.83 |
| 1 | a | -20 | 69.0 | 7.74 | 6.84 | 9.26 | 1.85 | 1.51 | 1.29 | 2.99 | 2.95 |
| 1 | e2 | +20 | 16.3 | 6.44 | 3.35 | 1.84 | 1.45 | 1.20 | 2.53 | 2.82 | 3.23 |
| 1 | e2 | -7 | 44.6 | 6.81 | 3.89 | 4.14 | 1.61 | 1.30 | 1.58 | 2.78 | 3.03 |
| 1 | e2 | -20 | 70.9 | 6.23 | 5.20 | 7.75 | 1.74 | 1.36 | 1.23 | 3.00 | 3.02 |
| 1 | e3 | +20 | 13.4 | 4.27 | 2.44 | 1.60 | 1.36 | 1.12 | 2.76 | 3.14 | 3.45 |
| 1 | e3 | -7 | 45.4 | 6.25 | 3.79 | 4.37 | 1.61 | 1.27 | 1.49 | 2.89 | 3.03 |
| 1 | e3 | -20 | 72.3 | 4.58 | 5.55 | 7.13 | 1.58 | 1.45 | 1.21 | 2.98 | 3.00 |
| 1 | e4 | +20 | 14.1 | 3.54 | 2.04 | 1.66 | 1.31 | 1.02 | 2.82 | 3.47 | 3.50 |
| 1 | e4 | -7 | 40.3 | 4.44 | 2.84 | 3.50 | 1.50 | 1.19 | 1.64 | 2.94 | 3.06 |
| 1 | e4 | -20 | 61.6 | 4.09 | 4.48 | 7.23 | 1.59 | 1.29 | 1.23 | 2.87 | 2.90 |
| 2 | a | +22 | 18.7 | 12.8 | 7.62 | 1.67 | 1.37 | 1.06 | 2.16 | 1.59 | 2.42 |
| 2 | a | ±0 | 29.9 | 11.0 | 6.88 | 2.24 | 1.18 | 0.88 | 2.34 | 1.59 | 2.49 |
| 2 | a | -7 | 33.9 | 13.1 | 7.83 | 2.84 | 1.41 | 1.01 | 2.43 | 1.80 | 2.74 |
| 2 | a | -20 | 46.4 | 14.7 | 9.17 | 4.65 | 1.65 | 1.19 | 2.18 | 1.80 | 2.78 |
| 2 | b | +22 | 13.0 | 7.53 | 4.68 | 1.37 | 1.19 | 0.87 | 2.45 | 1.67 | 2.51 |
| 2 | b | ±0 | 27.3 | 9.99 | 5.41 | 2.47 | 1.30 | 0.94 | 2.49 | 1.73 | 2.71 |
| 2 | b | -7 | 30.2 | 10.3 | 6.36 | 2.70 | 1.31 | 1.02 | 2.54 | 1.70 | 2.66 |
| 2 | b | -20 | 39.9 | 12.1 | 7.39 | 4.73 | 1.52 | 1.10 | 2.38 | 1.81 | 2.74 |
| 2 | c | +22 | 11.7 | 6.66 | 4.05 | 1.41 | 1.02 | 0.87 | 2.73 | 1.91 | 2.82 |
| 2 | c | ±0 | 22.8 | 8.13 | 4.67 | 2.08 | 1.18 | 0.90 | 2.88 | 1.93 | 3.07 |
| 2 | c | -7 | 25.3 | 7.23 | 4.58 | 2.73 | 1.18 | 0.90 | 2.83 | 1.82 | 2.89 |
| 2 | c | -20 | - | - | - | - | - | - | - | - | - |
| 2 | d | +22 | 11.6 | 6.42 | 4.02 | 1.41 | 1.18 | 0.87 | 2.61 | 1.77 | 2.61 |
| 2 | d | ±0 | 22.8 | 6.88 | 4.26 | 2.31 | 1.21 | 0.93 | 2.72 | 1.89 | 2.82 |
| 2 | d | -7 | 25.0 | 8.27 | 5.26 | 2.79 | 1.28 | 0.98 | 2.70 | 1.90 | 2.84 |
| 2 | d | -20 | - | - | - | - | - | - | - | - | - |
| 3 | a | +22 | 5.35 | 1.07 | 1.54 | 0.35 | 0.02 | 0.06 | 0.69 | 0.28 | 0.52 |
| 3 | a | ±0 | 23.9 | 0.40 | 0.28 | 1.00 | 0.00 | 0.02 | 0.25 | 0.08 | 0.32 |
| 3 | a | -7 | 31.0 | 0.45 | 0.40 | 1.44 | 0.03 | 0.04 | 0.27 | 0.07 | 0.26 |
| 3 | a | -20 | 54.7 | 0.51 | 0.50 | 3.46 | 0.02 | 0.04 | 0.28 | 0.05 | 0.30 |
| 3 | b | +22 | 3.84 | 0.49 | 0.59 | 0.30 | 0.02 | 0.03 | 0.54 | 0.23 | 0.53 |
| 3 | b | ±0 | 21.7 | 0.40 | 0.27 | 0.98 | 0.02 | 0.02 | 0.29 | 0.09 | 0.40 |
| 3 | b | -7 | 29.9 | 0.40 | 0.38 | 1.48 | 0.02 | 0.03 | 0.30 | 0.12 | 0.35 |
| 3 | b | -20 | 52.5 | 0.64 | 0.44 | 3.83 | 0.04 | 0.04 | 0.36 | 0.09 | 0.37 |
| 3 | c | +22 | 12.6 | 0.20 | 0.18 | 1.82 | 0.02 | 0.04 | 0.22 | 0.05 | 0.14 |
| 3 | c | ±0 | 17.4 | 0.55 | 0.38 | 0.83 | 0.03 | 0.03 | 0.30 | 0.14 | 0.36 |
| 3 | c | -7 | 27.9 | 0.44 | 0.37 | 1.38 | 0.02 | 0.03 | 0.29 | 0.08 | 0.39 |
| 3 | c | -20 | - | - | - | - | - | - | - | - | - |
| 3 | d | +22 | 3.58 | 0.51 | 0.56 | 0.35 | 0.03 | 0.06 | 0.47 | 0.16 | 0.38 |
| 3 | d | ±0 | 17.7 | 0.37 | 0.46 | 0.87 | 0.02 | 0.03 | 0.23 | 0.10 | 0.23 |
| 3 | d | -7 | 26.3 | 0.52 | 0.53 | 1.54 | 0.02 | 0.04 | 0.23 | 0.05 | 0.22 |
| 3 | d | -20 | - | - | - | - | - | - | - | - | - |
| 4 | a | +22 | 3.66 | 0.09 | 0.17 | 0.30 | 0.03 | 0.03 | 0.30 | 0.10 | 0.30 |
| 4 | a | ±0 | 10.2 | 0.20 | 0.17 | 1.33 | 0.03 | 0.04 | 0.27 | 0.04 | 0.16 |
| 4 | a | -7 | 15.0 | 0.20 | 0.18 | 2.30 | 0.02 | 0.03 | 0.17 | 0.05 | 0.11 |
| 4 | a | -20 | 43.4 | 0.29 | 0.39 | 7.75 | 0.05 | 0.05 | 0.22 | 0.06 | 0.12 |
| 5 | M/E0 | +20 | 14.6 | 1.39 | 2.22 | 4.34 | 0.03 | 0.23 | 0.36 | 0.20 | 0.25 |
| 5 | M/E0 | ±0 | 28.4 | 0.99 | 1.31 | 6.95 | 0.03 | 0.15 | 0.32 | 0.38 | 0.25 |
| 5 | M/E0 | -7 | 38.3 | 0.83 | 1.51 | 9.86 | 0.04 | 0.33 | 0.50 | 0.33 | 0.25 |
| 5 | E85 | +20 | 9.56 | 0.59 | 1.84 | 1.27 | 0.03 | 0.34 | 0.32 | 0.22 | 0.32 |
| 5 | E85 | ±0 | 20.4 | 0.29 | 1.14 | 4.06 | 0.05 | 0.11 | 0.27 | 0.22 | 0.23 |
| 5 | E85 | -7 | 26.5 | 0.35 | 0.82 | 6.35 | 0.09 | 0.17 | 0.33 | 0.25 | 0.31 |
| 5 | M50 | +20 | 12.7 | 0.65 | 2.12 | 2.38 | 0.03 | 0.24 | 0.34 | 0.28 | 0.27 |
| 5 | M50 | ±0 | 35.1 | 0.57 | 1.37 | 7.47 | 0.07 | 0.28 | 0.40 | 0.41 | 0.37 |
| 5 | M50 | -7 | 28.5 | 0.51 | 1.04 | 5.13 | 0.03 | 0.30 | 0.38 | 0.38 | 0.46 |
| 5 | M85 | +20 | 9.63 | 0.45 | 1.48 | 1.49 | 0.05 | 0.10 | 0.37 | 0.25 | 0.25 |
| 5 | M85 | ±0 | 17.6 | 0.37 | 1.22 | 3.22 | 0.02 | 0.09 | 0.49 | 0.39 | 0.46 |
| 5 | M85 | -7 | 20.2 | 0.28 | 0.77 | 4.73 | 0.05 | 0.07 | 0.48 | 0.18 | 0.28 |

| Veh. code | Fuel code | Temp °C | CO g/km Bag1 | CO g/km Bag2 | CO g/km Bag3 | HC g/km Bag1 | HC g/km Bag2 | HC g/km Bag3 | NOx g/km Bag1 | NOx g/km Bag2 | NOx g/km Bag3 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 6 | M0 | +22 | 2.48 | 1.27 | 1.53 | 0.28 | 0.06 | 0.07 | 0.18 | 0.09 | 0.12 |
| 6 | M0 | +7 | 8.35 | 0.15 | 0.10 | 0.72 | 0.02 | 0.01 | 0.13 | 0.02 | 0.02 |
| 6 | M0 | ±0 | 12.0 | 0.13 | 0.07 | 1.04 | 0.02 | 0.01 | 0.13 | 0.03 | 0.05 |
| 6 | M0 | -7 | 19.2 | 0.36 | 0.11 | 1.66 | 0.04 | 0.02 | 0.19 | 0.07 | 0.04 |
| 6 | M50 | +22 | 4.10 | 0.13 | 0.23 | 0.31 | 0.01 | 0.01 | 0.41 | 0.16 | 0.27 |
| 6 | M50 | +7 | 11.1 | 0.19 | 0.10 | 0.78 | 0.02 | 0.01 | 0.28 | 0.06 | 0.13 |
| 6 | M50 | ±0 | 14.6 | 0.16 | 0.10 | 1.17 | 0.01 | 0.00 | 0.24 | 0.04 | 0.24 |
| 6 | M50 | -7 | 19.4 | 0.20 | 0.13 | 2.07 | 0.02 | 0.01 | 0.28 | 0.04 | 0.12 |
| 6 | M85 | +22 | 1.81 | 0.26 | 0.19 | 0.21 | 0.01 | 0.01 | 0.12 | 0.02 | 0.03 |
| 6 | M85 | +7 | 5.95 | 0.30 | 0.19 | 0.80 | 0.01 | 0.00 | 0.12 | 0.08 | 0.09 |
| 6 | M85 | ±0 | 8.08 | 0.19 | 0.05 | 1.64 | 0.01 | 0.00 | 0.29 | 0.07 | 0.20 |
| 6 | M85 | -7 | 11.8 | 0.16 | 0.14 | 4.11 | 0.02 | 0.00 | 0.15 | 0.02 | 0.09 |
| 7 | M0 | +22 | 3.36 | 2.38 | 2.94 | 0.31 | 0.09 | 0.12 | 0.26 | 0.02 | 0.05 |
| 7 | M0 | +7 | 11.4 | 1.87 | 1.91 | 0.83 | 0.09 | 0.11 | 0.21 | 0.03 | 0.06 |
| 7 | M0 | ±0 | 19.4 | 1.90 | 1.95 | 1.15 | 0.10 | 0.10 | 0.18 | 0.03 | 0.07 |
| 7 | M0 | -7 | 24.3 | 1.23 | 2.26 | 1.57 | 0.14 | 0.13 | 0.17 | 0.02 | 0.08 |
| 7 | M50 | +22 | 3.24 | 1.92 | 2.13 | 0.25 | 0.07 | 0.07 | 0.24 | 0.01 | 0.05 |
| 7 | M50 | +7 | 10.5 | 1.31 | 1.53 | 0.60 | 0.06 | 0.05 | 0.15 | 0.02 | 0.06 |
| 7 | M50 | ±0 | 13.6 | 1.21 | 2.02 | 0.79 | 0.05 | 0.06 | 0.12 | 0.02 | 0.06 |
| 7 | M50 | -7 | 17.9 | 1.04 | 1.91 | 1.05 | 0.04 | 0.06 | 0.15 | 0.02 | 0.05 |
| 7 | M85 | +22 | 3.03 | 0.90 | 1.21 | 0.21 | 0.02 | 0.03 | 0.19 | 0.02 | 0.03 |
| 7 | M85 | +7 | 7.19 | 0.58 | 1.00 | 0.54 | 0.02 | 0.02 | 0.28 | 0.03 | 0.04 |
| 7 | M85 | ±0 | 12.6 | 0.78 | 0.63 | 1.11 | 0.02 | 0.02 | 0.22 | 0.03 | 0.03 |
| 7 | M85 | -7 | 17.8 | 0.45 | 0.92 | 1.80 | 0.02 | 0.02 | 0.23 | 0.03 | 0.04 |
| 8 | M0 | +22 | 0.95 | 0.34 | 0.13 | 0.14 | 0.02 | 0.02 | 0.32 | 0.03 | 0.14 |
| 8 | M0 | +7 | 5.46 | 0.43 | 0.16 | 0.57 | 0.03 | 0.01 | 0.22 | 0.03 | 0.16 |
| 8 | M0 | ±0 | 10.5 | 0.36 | 0.20 | 1.05 | 0.03 | 0.01 | 0.21 | 0.03 | 0.12 |
| 8 | M0 | -7 | 13.0 | 0.24 | 0.11 | 1.69 | 0.10 | 0.02 | 0.21 | 0.04 | 0.13 |
| 8 | M50 | +22 | 0.81 | 0.19 | 0.10 | 0.12 | 0.02 | 0.02 | 0.30 | 0.02 | 0.14 |
| 8 | M50 | +7 | 2.04 | 0.10 | 0.10 | 0.29 | 0.05 | 0.03 | 0.39 | 0.02 | 0.15 |
| 8 | M50 | ±0 | 3.71 | 0.11 | 0.09 | 0.47 | 0.02 | 0.02 | 0.58 | 0.02 | 0.14 |
| 8 | M50 | -7 | 6.18 | 0.05 | 0.06 | 0.99 | 0.03 | 0.02 | 0.74 | 0.10 | 0.15 |
| 8 | M85 | +22 | 0.62 | 0.11 | 0.06 | 0.09 | 0.02 | 0.01 | 0.50 | 0.04 | 0.24 |
| 8 | M85 | +7 | 0.99 | 0.04 | 0.06 | 0.19 | 0.02 | 0.02 | 0.58 | 0.13 | 0.28 |
| 8 | M85 | ±0 | 5.42 | 0.18 | 0.18 | 0.44 | 0.01 | 0.01 | 0.32 | 0.11 | 0.24 |
| 8 | M85 | -7 | MF | MF | MF | MF | MF | MF | MF | MF | MF |
| 9 | a | +22 | 3.44 | 0.09 | 0.19 | 0.49 | 0.04 | 0.04 | 0.34 | 0.11 | 0.13 |
| 9 | a | +7 | - | - | - | - | - | - | - | - | - |
| 9 | a | ±0 | 14.6 | 0.16 | 0.25 | 1.26 | 0.03 | 0.04 | 0.45 | 0.14 | 0.13 |
| 9 | a | -7 | - | - | - | - | - | - | - | - | - |
| 9 | LPG | +22 | 2.28 | 0.42 | 1.39 | 0.27 | 0.02 | 0.09 | 0.17 | 0.09 | 0.06 |
| 9 | LPG | +7 | 2.08 | 0.34 | 0.28 | 0.17 | 0.03 | 0.06 | 0.29 | 0.17 | 0.10 |
| 9 | LPG | ±0 | 2.81 | 0.37 | 0.67 | 0.30 | 0.02 | 0.08 | 0.29 | 0.12 | 0.10 |
| 9 | LPG | -7 | 4.97 | 0.17 | 1.35 | 0.65 | 0.02 | 0.17 | 0.37 | 0.15 | 0.17 |
| 10 | a | +22 | 6.38 | 0.79 | 0.84 | 0.91 | 0.18 | 0.27 | 0.28 | 0.20 | 0.18 |
| 10 | a | +7 | 16.5 | 0.95 | 0.75 | 1.66 | 0.20 | 0.28 | 0.65 | 0.18 | 0.26 |
| 10 | a | ±0 | 21.2 | 1.00 | 0.91 | 1.98 | 0.19 | 0.27 | 0.58 | 0.18 | 0.27 |
| 10 | a | -7 | 26.4 | 1.08 | 0.87 | 2.77 | 0.30 | 0.31 | 0.43 | 0.20 | 0.27 |
| 10 | LPG | +22 | 2.12 | 0.21 | 0.60 | 0.31 | 0.07 | 0.14 | 0.36 | 0.16 | 0.20 |
| 10 | LPG | +7 | 2.82 | 0.24 | 1.27 | 0.40 | 0.05 | 0.14 | 0.41 | 0.25 | 0.18 |
| 10 | LPG | ±0 | 2.77 | 0.25 | 0.66 | 0.40 | 0.04 | 0.09 | 0.36 | 0.21 | 0.23 |
| 10 | LPG | -7 | 3.91 | 0.31 | 0.74 | 0.75 | 0.07 | 0.13 | 0.48 | 0.25 | 0.20 |
| 10 | CNG | +22 | 0.77 | 0.13 | 0.35 | 0.78 | 0.57 | 0.58 | 0.21 | 0.19 | 0.19 |
| 10 | CNG | +7 | 1.18 | 0.21 | 0.51 | 1.02 | 0.61 | 0.67 | 0.23 | 0.17 | 0.19 |
| 10 | CNG | ±0 | 1.40 | 0.24 | 0.39 | 1.23 | 0.61 | 0.60 | 0.20 | 0.15 | 0.20 |
| 10 | CNG | -7 | 1.51 | 0.17 | 0.40 | 1.51 | 0.76 | 0.65 | 0.22 | 0.19 | 0.21 |
| 11 | CNG | +22 | 1.06 | 0.34 | 0.33 | 0.32 | 0.17 | 0.21 | 0.10 | 0.03 | 0.08 |
| 11 | CNG | +7 | 0.77 | 0.34 | 0.27 | 0.36 | 0.15 | 0.22 | 0.20 | 0.03 | 0.10 |
| 11 | CNG | ±0 | 0.93 | 0.39 | 0.21 | 0.41 | 0.17 | 0.22 | 0.24 | 0.03 | 0.13 |
| 11 | CNG | -7 | 1.75 | 0.30 | 0.22 | 0.60 | 0.29 | 0.40 | 1.87 | 0.03 | 1.01 |

- = not measured
MF = vehicle malfunction

| Veh. code | Fuel code | Temp °C | Methane CH4 mg/km | Ethylene C2H4 mg/km | Acetylene C2H2 mg/km | Ethane C2H6 mg/km | Propylene C3H6 mg/km | Propane C3H8 mg/km | Isobutene C4H8 mg/km | 1,3-Butadiene C4H6 mg/km | Isopentane C5H12 mg/km | Benzene C6H6 mg/km | Toluene C7H8 mg/km | Xylene C8H10 mg/km |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | a | +22 | 52 | 106 | 74 | 16 | 52 | 1.9 | 9.2 | 12 | 65 | 68 | 144 | 129 |
| 2 | a | ±0 | 54 | 97 | 73 | 13 | 46 | 1.7 | 8.1 | 10 | 52 | 64 | 140 | 144 |
| 2 | a | -7 | 64 | 108 | 84 | 7.2 | 51 | 1.7 | 9.0 | 11 | 60 | 77 | 173 | 178 |
| 2 | a | -20 | 91 | 134 | 119 | 18 | 64 | 2.1 | 11 | 12 | 84 | 104 | 239 | 252 |
| 2 | b | +22 | 35 | 86 | 56 | 12 | 42 | 3.8 | 6.7 | 9.2 | 58 | 56 | 113 | 89 |
| 2 | b | ±0 | 58 | 100 | 86 | 13 | 48 | 1.5 | 7.5 | 12 | 50 | 72 | 142 | 149 |
| 2 | b | -7 | 62 | 105 | 85 | 14 | 49 | 1.8 | 7.3 | 12 | 54 | 79 | 160 | 168 |
| 2 | b | -20 | 85 | 129 | 107 | 16 | 59 | 1.6 | 8.7 | 14 | 72 | 104 | 219 | 225 |
| 2 | c | +22 | 33 | 81 | 56 | 9.0 | 38 | <0.5 | 5.9 | 13 | 52 | 54 | 103 | 105 |
| 2 | c | ±0 | 43 | 91 | 66 | 11 | 42 | 6.3 | 6.2 | 8.7 | 41 | 60 | 128 | 141 |
| 2 | c | -7 | 45 | 92 | 68 | 11 | 42 | 1.0 | 6.1 | 9.2 | 50 | 63 | 141 | 154 |
| 2 | c | -20 | - | - | - | - | - | - | - | - | - | - | - | - |
| 2 | d | +22 | 30 | 78 | 51 | 10 | 39 | <0.5 | 5.5 | 13 | 51 | 42 | 115 | 114 |
| 2 | d | ±0 | 41 | 90 | 64 | 11 | 44 | <0.5 | 6.0 | 11 | 54 | 50 | 139 | 150 |
| 2 | d | -7 | 48 | 91 | 70 | 11 | 44 | <0.5 | 6.2 | 8.1 | 46 | 55 | 151 | 158 |
| 2 | d | -20 | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | a | +22 | 17 | 6.8 | 3.6 | 1.8 | 3.7 | <0.5 | 0.6 | 0.7 | 7.1 | 5.9 | 10 | 9.1 |
| 3 | a | ±0 | 21 | 17 | 10 | 2.8 | 8.6 | <0.5 | 1.7 | 1.2 | 13 | 13 | 29 | 31 |
| 3 | a | -7 | 28 | 22 | 14 | 3.7 | 11 | <0.5 | 2.1 | 1.7 | 13 | 18 | 40 | 43 |
| 3 | a | -20 | 46 | 40 | 26 | 5.6 | 19 | 0.7 | 4.1 | 4.1 | 30 | 33 | 85 | 80 |
| 3 | b | +22 | 13 | 5.8 | 2.7 | 1.8 | 3.0 | <0.5 | 0.5 | 0.5 | 13 | 4.4 | 9.1 | 1.6 |
| 3 | b | ±0 | 24 | 17 | 14 | 2.7 | 8.2 | <0.5 | 1.4 | 1.2 | 10 | 14 | 30 | 26 |
| 3 | b | -7 | 31 | 24 | 15 | 3.9 | 11 | <0.5 | 1.8 | 1.7 | 12 | 18 | 40 | 38 |
| 3 | b | -20 | 51 | 44 | 27 | 6.1 | 19 | 0.6 | 3.7 | 4.4 | 28 | 40 | 95 | 98 |
| 3 | c | +22 | 12 | 4.9 | 2.2 | 1.6 | 2.7 | <0.5 | <0.5 | 0.7 | 4.9 | 5.0 | 11 | 9.2 |
| 3 | c | ±0 | 21 | 14 | 6.7 | 2.4 | 6.8 | <0.5 | 1.2 | 1.2 | 9.3 | 12 | 21 | 19 |
| 3 | c | -7 | 27 | 21 | 13 | 3.2 | 9.4 | <0.5 | 1.7 | 1.7 | 12 | 17 | 34 | 31 |
| 3 | c | -20 | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | d | +22 | 15 | 6.2 | 2.3 | 2.1 | 3.5 | <0.5 | <0.5 | 0.7 | 5.3 | 4.9 | 30 | 17 |
| 3 | d | ±0 | 17 | 14 | 6.8 | 2.6 | 7.2 | 0.7 | 1.1 | 1.0 | 8.3 | 10 | 27 | 32 |
| 3 | d | -7 | 26 | 22 | 11 | 3.5 | 11 | <0.5 | 1.8 | 1.9 | 12 | 15 | 45 | 41 |
| 3 | d | -20 | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | a | +22 | 17 | 3.0 | 3.1 | 2.2 | 1.8 | <0.5 | <0.5 | <0.5 | 3.9 | 3.2 | 7.6 | 8.7 |
| 4 | a | ±0 | 28 | 8.6 | 8.4 | 4.0 | 4.3 | <0.5 | 1.0 | 1.1 | 13 | 13 | 40 | 46 |
| 4 | a | -7 | 36 | 14 | 13 | 3.5 | 6.3 | <0.5 | 1.5 | 1.6 | 21 | 22 | 67 | 69 |
| 4 | a | -20 | 77 | 49 | 46 | 6.9 | 19 | 1.0 | 4.7 | 5.4 | 72 | 65 | 190 | 154 |
| 6 | M0 | +22 | 18 | 5.7 | 2.1 | 2.8 | 3.5 | <0.5 | <0.5 | 0.5 | 8.0 | 9.4 | 14 | 23 |
| 6 | M0 | +7 | 16 | 9.1 | 6.0 | 2.4 | 4.8 | <0.5 | 0.9 | 1.3 | 9.4 | 10 | 23 | 24 |
| 6 | M0 | ±0 | 18 | 12 | 8.4 | 2.3 | 6.0 | <0.5 | 1.3 | 1.6 | 10 | 13 | 32 | 34 |
| 6 | M0 | -7 | 28 | 19 | 12 | 3.3 | 8.6 | <0.5 | 1.9 | 2.4 | 15 | 22 | 49 | 56 |
| 6 | M50 | +22 | 11 | 3.0 | 2.4 | <0.5 | 1.4 | <0.5 | <0.5 | <0.5 | 5.9 | 3.2 | 8.9 | 11 |
| 6 | M50 | +7 | 16 | 6.4 | <0.5 | 0.6 | 3.0 | <0.5 | 0.6 | 0.7 | 5.5 | 7.0 | 17 | 19 |
| 6 | M50 | ±0 | 19 | 11 | 5.9 | 0.9 | 4.1 | <0.5 | 0.8 | 1.0 | 6.8 | 10 | 24 | 26 |
| 6 | M50 | -7 | 27 | 15 | 10 | 1.2 | 5.8 | <0.5 | 1.1 | 1.4 | 11 | 17 | 40 | 42 |
| 6 | M85 | +22 | 7.2 | 0.9 | <0.5 | <0.5 | 0.5 | <0.5 | <0.5 | <0.5 | 2.0 | 1.4 | 5.0 | 6.1 |
| 6 | M85 | +7 | 10 | 2.9 | <0.5 | <0.5 | 1.3 | <0.5 | <0.5 | <0.5 | 2.4 | 3.4 | 7.6 | 8.6 |
| 6 | M85 | ±0 | 13 | 4.6 | <0.5 | <0.5 | 2.1 | <0.5 | <0.5 | <0.5 | 3.4 | 5.6 | 13 | 15 |
| 6 | M85 | -7 | 23 | 7.8 | <0.5 | 0.5 | 3.0 | <0.5 | 0.6 | 0.6 | 5.4 | 12 | 26 | 30 |

- = not measured

| Veh. code | Fuel code | Temp °C | Methane CH4 mg/km | Ethylene C2H4 mg/km | Acetylene C2H2 mg/km | Ethane C2H6 mg/km | Propylene C3H6 mg/km | Propane C3H8 mg/km | Isobutene C4H8 mg/km | 1,3-Butadiene C4H6 mg/km | Isopentane C5H12 mg/km | Benzene C6H6 mg/km | Toluene C7H8 mg/km | Xylene C8H10 mg/km |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7 | M0 | +22 | 25 | 6 | 2.0 | 3.8 | 3.7 | <0.5 | 0.8 | 0.5 | 11 | 11 | 15 | 12 |
| 7 | M0 | +7 | 30 | 12 | 5.5 | 4.4 | 6.2 | <0.5 | 1.0 | 1.1 | 15 | 17 | 31 | 32 |
| 7 | M0 | ±0 | 35 | 16 | 7.3 | 5.0 | 7.2 | 0.8 | 1.9 | 1.6 | 17 | 21 | 35 | 39 |
| 7 | M0 | -7 | 27 | 22 | 10 | 4.6 | 9.0 | 0.5 | 1.9 | 1.9 | 21 | 26 | 46 | 45 |
| 7 | M50 | +22 | 18 | 2.4 | 1.5 | 0.8 | 1.8 | 1.5 | 1.3 | <0.5 | 9.1 | 6.6 | 9.1 | 7.7 |
| 7 | M50 | +7 | 21 | 6.0 | 3.1 | 1.2 | 2.6 | <0.5 | 1.1 | <0.5 | 10 | 10 | 15 | 12 |
| 7 | M50 | ±0 | 25 | 7.9 | 4.9 | 1.1 | 3.6 | <0.5 | 0.6 | 0.6 | 10 | 11 | 20 | 17 |
| 7 | M50 | -7 | 27 | 11 | 5.5 | 1.4 | 4.0 | <0.5 | 0.7 | 0.6 | 10 | 14 | 26 | 22 |
| 7 | M85 | +22 | 10 | 0.8 | 0.9 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | 4.2 | 2.0 | 3.5 | 4.1 |
| 7 | M85 | +7 | 11 | 2.0 | 1.3 | <0.5 | 0.7 | <0.5 | <0.5 | <0.5 | 5.2 | 3.6 | 6.4 | 6.8 |
| 7 | M85 | ±0 | 16 | 3.9 | 2.1 | <0.5 | 1.3 | <0.5 | <0.5 | <0.5 | 5.9 | 6.4 | 11 | 10 |
| 7 | M85 | -7 | 23 | 6.0 | 3.2 | 0.6 | 1.8 | <0.5 | <0.5 | <0.5 | 7.0 | 10 | 20 | 17 |
| 8 | M0 | +22 | 11 | 1.0 | 0.6 | 0.7 | 0.7 | <0.5 | <0.5 | <0.5 | 5.0 | 3.0 | 6.0 | 10 |
| 8 | M0 | +7 | 18 | 6.2 | 1.9 | 1.3 | 3.0 | <0.5 | <0.5 | 1.6 | 7.4 | 12 | 21 | 22 |
| 8 | M0 | ±0 | 27 | 12 | 3.0 | 2.4 | 5.3 | <0.5 | 0.9 | 0.9 | 11 | 23 | 36 | 38 |
| 8 | M0 | -7 | 35 | 16 | 6.3 | 4.3 | 6.7 | <0.5 | 1.2 | 1.3 | 12 | 30 | 48 | 44 |
| 8 | M50 | +22 | 10 | 0.7 | <0.5 | <0.5 | <0.5 | <0.5 | 0.7 | <0.5 | 4.8 | 1.8 | 3.7 | 5.3 |
| 8 | M50 | +7 | 16 | 1.6 | 0.8 | <0.5 | 0.8 | <0.5 | 1.2 | <0.5 | 9.1 | 4.8 | 7.8 | 8.2 |
| 8 | M50 | ±0 | 19 | 3.2 | 1.2 | 0.6 | 1.5 | <0.5 | <0.5 | <0.5 | 6.2 | 8.9 | 15 | 13 |
| 8 | M50 | -7 | 28 | 8.2 | 3.6 | 1.0 | 3.0 | <0.5 | 0.7 | 0.5 | 9.0 | 17 | 26 | 20 |
| 8 | M85 | +22 | 7.7 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | 3.7 | 1.0 | 1.7 | 3.9 |
| 8 | M85 | +7 | 11 | 0.6 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | 3.3 | 1.4 | 2.4 | 3.2 |
| 8 | M85 | ±0 | 16 | 2.2 | 0.6 | <0.5 | 0.9 | <0.5 | <0.5 | <0.5 | 0.6 | 6.2 | 8.4 | 8.6 |
| 8 | M85 | -7 | MF | MF | MF | MF | MF | MF | MF | MF | MF | MF | MF | MF |
| 10 | a | +22 | 41 | 10 | 4.1 | 3.2 | 4.5 | <0.5 | 2.0 | 0.7 | 29 | 28 | 46 | 18* |
| 10 | a | +7 | 49 | 20 | 11 | 4.8 | 7.9 | 0.6 | 3.9 | 1.4 | 37 | 38 | 70 | 23* |
| 10 | a | ±0 | 54 | 24 | 15 | 5.1 | 10 | 0.7 | 4.8 | 1.5 | 40 | 43 | 83 | 24* |
| 10 | a | -7 | 59 | 31 | 18 | 6.4 | 14 | 0.8 | 6.4 | 2.6 | 54 | 54 | 118 | 32* |
| 10 | LPG | +22 | 32 | 3.7 | 1.2 | 2.5 | 2.2 | 68 | <0.5 | <0.5 | 2.5 | <0.5 | 0.7 | 14* |
| 10 | LPG | +7 | 43 | 4.7 | 2.1 | 3.0 | 3.5 | 92 | <0.5 | <0.5 | 2.3 | 0.6 | 1.5 | 18* |
| 10 | LPG | ±0 | 33 | 4.9 | 1.0 | 3.1 | <0.5 | 78 | <0.5 | <0.5 | 2.4 | 1.0 | 2.4 | 16* |
| 10 | LPG | -7 | 49 | 5.6 | 2.9 | 3.3 | 5.4 | 127 | 0.7 | <0.5 | 2.9 | 1.1 | 3.3 | 31* |
| 10 | CNG | +22 | 561 | 0.6 | <0.5 | 22 | <0.5 | 4.5 | <0.5 | <0.5 | 2.3 | <0.5 | 0.6 | 2.3* |
| 10 | CNG | +7 | 642 | 1.2 | <0.5 | 26 | <0.5 | 5.2 | <0.5 | <0.5 | 2.3 | 0.9 | 2.0 | 2.5* |
| 10 | CNG | ±0 | 669 | 1.4 | <0.5 | 27 | <0.5 | 6.0 | <0.5 | <0.5 | 2.3 | 1.1 | 2.1 | 2.6* |
| 10 | CNG | -7 | 802 | 1.9 | <0.5 | 36 | <0.5 | 4.2 | <0.5 | <0.5 | 3.1 | 1.2 | 3.1 | 3.0* |
| 11 | CNG | +22 | 193 | 0.7 | <0.5 | 2.3 | <0.5 | <0.5 | <0.5 | <0.5 | 3.4 | 0.9 | 3.1 | 6.5 |
| 11 | CNG | +7 | 199 | 0.8 | <0.5 | 2.7 | <0.5 | <0.5 | <0.5 | <0.5 | 3.5 | 0.9 | 2.4 | 3.8 |
| 11 | CNG | ±0 | 213 | 0.7 | <0.5 | 2.7 | <0.5 | <0.5 | <0.5 | <0.5 | 3.6 | 0.5 | 5.3 | 4.2 |
| 11 | CNG | -7 | 307 | 0.7 | <0.5 | 5.1 | <0.5 | 0.6 | <0.5 | <0.5 | 1.5 | <0.5 | 3.0 | 1.6 |

MF = vehicle malfunction

* = Xylene was not measured with vehicle 10, butane (C4H10) measured instead

| Veh. code | Fuel code | Temp [°C] | MeOH [mg/km] | Form-aldehyde [mg/km] |
|---|---|---|---|---|
| 2 | c | +22 | 0 | 43 |
| 2 | a | -7 | 0 | 44 |
| 3 | a | +22 | 0 | 3.4 |
| 3 | c | +22 | 0 | <2 |
| 3 | a | -7 | 0 | 3.7 |
| 4 | a | +22 | 0 | <2 |
| 4 | a | ±0 | 0 | <2 |
| 4 | a | -7 | 0 | <2 |
| 4 | a | -20 | 0 | <2 |
| 5 | M85 | +22 | 756 | 12 |
| 5 | M85 | +7 | - | - |
| 5 | M85 | ±0 | 1303 | 14 |
| 5 | M85 | -7 | 1619 | 17 |
| 6 | M0 | +22 | 0 | 2.9 |
| 6 | M0 | +7 | 0 | 2.9 |
| 6 | M0 | ±0 | 0 | 2.8 |
| 6 | M0 | -7 | 0 | 2.9 |
| 6 | M50 | +22 | 57 | 3.4 |
| 6 | M50 | +7 | 134 | 6.1 |
| 6 | M50 | ±0 | 198 | 9.0 |
| 6 | M50 | -7 | 347 | 14 |
| 6 | M85 | +22 | 124 | 11 |
| 6 | M85 | +7 | 436 | 17 |
| 6 | M85 | ±0 | 785 | 26 |
| 6 | M85 | -7 | 1113 | 31 |
| 7 | M0 | +22 | 0 | <2 |
| 7 | M0 | +7 | 0 | <2 |
| 7 | M0 | ±0 | 0 | <2 |
| 7 | M0 | -7 | 0 | <2 |
| 7 | M50 | +22 | 27 | 2.1 |
| 7 | M50 | +7 | 67 | 3.0 |
| 7 | M50 | ±0 | 83 | 3.9 |
| 7 | M50 | -7 | 108 | 4.7 |
| 7 | M85 | +22 | 82 | 5.0 |
| 7 | M85 | +7 | 206 | 8.0 |
| 7 | M85 | ±0 | 363 | 11 |
| 7 | M85 | -7 | 507 | 14 |

| Veh. code | Fuel code | Temp [°C] | MeOH [mg/km] | Form-aldehyde [mg/km] |
|---|---|---|---|---|
| 8 | M0 | +22 | 0 | <2 |
| 8 | M0 | +7 | 0 | <2 |
| 8 | M0 | ±0 | 0 | <2 |
| 8 | M0 | -7 | 0 | <2 |
| 8 | M50 | +22 | 14 | <2 |
| 8 | M50 | +7 | 27 | <2 |
| 8 | M50 | ±0 | 39 | <2 |
| 8 | M50 | -7 | 92 | 4.5 |
| 8 | M85 | +22 | 30 | <2 |
| 8 | M85 | +7 | 50 | 4.7 |
| 8 | M85 | ±0 | 101 | 4.0 |
| 8 | M85 | -7 | MF | MF |
| 10 | a | +22 | 0 | 2.5 |
| 10 | a | +7 | 0 | 2.5 |
| 10 | a | ±0 | 0 | 2.6 |
| 10 | a | -7 | 0 | 2.3 |
| 10 | LPG | +22 | 0 | <2 |
| 10 | LPG | +7 | 0 | <2 |
| 10 | LPG | ±0 | 0 | <2 |
| 10 | LPG | -7 | 0 | <2 |
| 10 | CNG | +22 | 0 | <2 |
| 10 | CNG | +7 | 0 | <2 |
| 10 | CNG | ±0 | 0 | <2 |
| 10 | CNG | -7 | 0 | <2 |
| 11 | CNG | +22 | 0 | <2 |
| 11 | CNG | +7 | 0 | <2 |
| 11 | CNG | ±0 | 0 | <2 |
| 11 | CNG | -7 | 0 | <2 |

- = not measured
MF = vehicle malfunction

| Vehicle code | Fuel code | Temp [°C] | Form-aldehyde [mg/km] | Acet-aldehyde [mg/km] |
|---|---|---|---|---|
| 7 | M0 | +22 | 0.3 | 0.2 |
| 7 | M0 | +7 | 0.3 | 0.4 |
| 7 | M0 | ±0 | 0.4 | 0.6 |
| 7 | M0 | -7 | 0.5 | 0.7 |
| 7 | M50 | +22 | 1.4 | 0.2 |
| 7 | M50 | +7 | 1.9 | 0.3 |
| 7 | M50 | ±0 | 2.4 | 0.4 |
| 7 | M50 | -7 | 2.8 | 0.7 |
| 7 | M85 | +22 | 5.7 | <0.2 |
| 7 | M85 | +7 | 8.5 | 0.3 |
| 7 | M85 | ±0 | 14 | 0.4 |
| 7 | M85 | -7 | 16 | 0.5 |
| 8 | M0 | +22 | 0.1 | <0.2 |
| 8 | M0 | +7 | 0.1 | <0.2 |
| 8 | M0 | ±0 | 0.1 | 0.2 |
| 8 | M0 | -7 | 0.1 | 0.4 |
| 8 | M50 | +22 | 0.6 | <0.2 |
| 8 | M50 | +7 | 1.3 | <0.2 |
| 8 | M50 | ±0 | 1.3 | 0.2 |
| 8 | M50 | -7 | 4.3 | 0.3 |
| 8 | M85 | +22 | 2.3 | <0.2 |
| 8 | M85 | +7 | 5.6 | 0.2 |
| 8 | M85 | ±0 | 6.2 | 0.2 |
| 8 | M85 | -7 | MF | MF |

MF = vehicle malfunction

| Veh. code | Fuel code | Temp °C | CO g/km | HCi g/km | NOx g/km | PM g/km |
|---|---|---|---|---|---|---|
| 12 | MK1 | +22 | 0.350 | 0.051 | 0.919 | 0.052 |
| 12 | MK1 | ±0 | 0.480 | 0.097 | 1.064 | 0.064 |
| 12 | MK1 | -7 | 0.484 | 0.075 | 1.049 | 0.065 |
| 12 | MK1 | -20 | 0.687 | 0.133 | 1.009 | 0.091 |
| 12 | RME/MK1 | +22 | 0.353 | 0.052 | 0.926 | 0.053 |
| 12 | RME/MK1 | ±0 | 0.432 | 0.056 | 1.145 | 0.060 |
| 12 | RME/MK1 | -7 | 0.492 | 0.067 | 0.983 | 0.067 |
| 12 | CEC | +22 | 0.399 | 0.059 | 0.942 | 0.071 |
| 12 | CEC | ±0 | 0.501 | 0.074 | 0.977 | 0.072 |
| 12 | CEC | -7 | 0.582 | 0.091 | 1.054 | 0.076 |
| 13 | MK1 | +22 | 0.296 | 0.093 | 0.618 | 0.056 |
| 13 | MK1 | ±0 | 0.490 | 0.150 | 0.613 | 0.063 |
| 13 | MK1 | -7 | 0.524 | 0.159 | 0.604 | 0.067 |
| 13 | MK1 | -20 | 0.720 | 0.195 | 0.672 | 0.070 |
| 13 | RME/MK1 | +22 | 0.330 | 0.122 | 0.629 | 0.057 |
| 13 | RME/MK1 | ±0 | 0.515 | 0.165 | 0.631 | 0.065 |
| 13 | RME/MK1 | -7 | 0.584 | 0.168 | 0.607 | 0.067 |
| 13 | CEC | +22 | 0.402 | 0.137 | 0.637 | 0.084 |
| 13 | CEC | ±0 | 0.651 | 0.174 | 0.659 | 0.102 |
| 13 | CEC | -7 | 0.723 | 0.179 | 0.668 | 0.096 |
| 14 | MK1 | +22 | 0.079 | 0.070 | 0.449 | 0.062 |
| 14 | MK1 | ±0 | 0.080 | 0.069 | 0.494 | 0.067 |
| 14 | MK1 | -7 | 0.133 | 0.082 | 0.546 | 0.065 |
| 14 | MK1 | -20 | 0.271 | 0.128 | 0.491 | 0.098 |
| 14 | RME/MK1 | +22 | 0.094 | 0.062 | 0.453 | 0.055 |
| 14 | RME/MK1 | ±0 | 0.106 | 0.058 | 0.560 | 0.061 |
| 14 | RME/MK1 | -7 | 0.153 | 0.074 | 0.463 | 0.060 |
| 14 | CEC | +22 | 0.159 | 0.062 | 0.402 | 0.088 |
| 14 | CEC | ±0 | 0.213 | 0.065 | 0.387 | 0.099 |
| 14 | CEC | -7 | 0.260 | 0.088 | 0.454 | 0.095 |

MK1 = Swedish Environmental Class 1
RME/MK1 = Rapeseed Methyl Ester / MK1, ratio 20% / 80%
CEC = CEC RF-03-A-84 Reference Diesel

HCi = integrated total hydrocarbons

| Veh. code | Fuel code | Temp °C | CO g/km | | | HCi g/km | | | NOx g/km | | | PM g/km | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Bag1 | Bag2 | Bag3 | Bag1 | Bag2 | Bag3 | Bag1 | Bag2 | Bag3 | Bag1 | Bag2 | Bag3 |
| 12 | MK1 | +22 | 0.316 | 0.419 | 0.245 | 0.051 | 0.057 | 0.038 | 0.859 | 1.006 | 0.801 | 0.051 | 0.053 | 0.051 |
| 12 | MK1 | ±0 | 0.462 | 0.575 | 0.313 | 0.090 | 0.116 | 0.068 | 1.016 | 1.154 | 0.929 | 0.076 | 0.065 | 0.054 |
| 12 | MK1 | -7 | 0.488 | 0.569 | 0.320 | 0.099 | 0.082 | 0.045 | 1.008 | 1.126 | 0.935 | 0.094 | 0.059 | 0.053 |
| 12 | MK1 | -20 | 0.835 | 0.775 | 0.412 | 0.252 | 0.128 | 0.053 | 1.045 | 1.050 | 0.903 | 0.169 | 0.070 | 0.071 |
| 12 | RME/MK1 | +22 | 0.325 | 0.423 | 0.241 | 0.056 | 0.059 | 0.036 | 0.870 | 1.016 | 0.799 | 0.057 | 0.054 | 0.049 |
| 12 | RME/MK1 | ±0 | 0.401 | 0.517 | 0.294 | 0.077 | 0.059 | 0.035 | 1.096 | 1.240 | 1.004 | 0.088 | 0.054 | 0.050 |
| 12 | RME/MK1 | -7 | 0.485 | 0.591 | 0.310 | 0.097 | 0.069 | 0.040 | 0.946 | 1.061 | 0.864 | 0.096 | 0.063 | 0.053 |
| 12 | CEC | +22 | 0.376 | 0.473 | 0.276 | 0.065 | 0.066 | 0.041 | 0.866 | 1.041 | 0.812 | 0.075 | 0.072 | 0.064 |
| 12 | CEC | ±0 | 0.540 | 0.575 | 0.333 | 0.092 | 0.081 | 0.048 | 0.908 | 1.070 | 0.856 | 0.089 | 0.070 | 0.064 |
| 12 | CEC | -7 | 0.571 | 0.700 | 0.368 | 0.112 | 0.103 | 0.053 | 0.993 | 1.146 | 0.927 | 0.101 | 0.070 | 0.068 |
| 13 | MK1 | +22 | 0.292 | 0.328 | 0.240 | 0.101 | 0.101 | 0.071 | 0.650 | 0.630 | 0.569 | 0.063 | 0.055 | 0.055 |
| 13 | MK1 | ±0 | 0.415 | 0.630 | 0.283 | 0.158 | 0.177 | 0.094 | 0.666 | 0.614 | 0.570 | 0.084 | 0.058 | 0.058 |
| 13 | MK1 | -7 | 0.427 | 0.666 | 0.332 | 0.162 | 0.186 | 0.105 | 0.678 | 0.604 | 0.549 | 0.093 | 0.061 | 0.056 |
| 13 | MK1 | -20 | 0.493 | 0.967 | 0.427 | 0.155 | 0.243 | 0.137 | 0.846 | 0.645 | 0.590 | 0.098 | 0.063 | 0.062 |
| 13 | RME/MK1 | +22 | 0.375 | 0.355 | 0.248 | 0.135 | 0.136 | 0.084 | 0.624 | 0.650 | 0.592 | 0.066 | 0.056 | 0.053 |
| 13 | RME/MK1 | ±0 | 0.455 | 0.678 | 0.256 | 0.158 | 0.200 | 0.104 | 0.691 | 0.633 | 0.580 | 0.088 | 0.059 | 0.060 |
| 13 | RME/MK1 | -7 | 0.469 | 0.757 | 0.347 | 0.157 | 0.200 | 0.117 | 0.674 | 0.606 | 0.556 | 0.094 | 0.061 | 0.060 |
| 13 | CEC | +22 | 0.350 | 0.502 | 0.253 | 0.125 | 0.161 | 0.099 | 0.625 | 0.665 | 0.591 | 0.090 | 0.085 | 0.080 |
| 13 | CEC | ±0 | 0.543 | 0.841 | 0.375 | 0.154 | 0.207 | 0.125 | 0.723 | 0.670 | 0.592 | 0.123 | 0.103 | 0.084 |
| 13 | CEC | -7 | 0.591 | 0.919 | 0.450 | 0.167 | 0.210 | 0.131 | 0.750 | 0.672 | 0.599 | 0.129 | 0.091 | 0.082 |
| 14 | MK1 | +22 | 0.272 | 0.026 | 0.032 | 0.078 | 0.079 | 0.048 | 0.440 | 0.465 | 0.427 | 0.068 | 0.059 | 0.063 |
| 14 | MK1 | ±0 | 0.249 | 0.032 | 0.042 | 0.076 | 0.074 | 0.052 | 0.561 | 0.493 | 0.445 | 0.090 | 0.061 | 0.061 |
| 14 | MK1 | -7 | 0.449 | 0.041 | 0.069 | 0.133 | 0.078 | 0.051 | 0.667 | 0.533 | 0.480 | 0.095 | 0.057 | 0.060 |
| 14 | MK1 | -20 | 0.877 | 0.102 | 0.132 | 0.307 | 0.095 | 0.055 | 0.675 | 0.457 | 0.415 | 0.164 | 0.083 | 0.076 |
| 14 | RME/MK1 | +22 | 0.314 | 0.040 | 0.030 | 0.083 | 0.066 | 0.039 | 0.438 | 0.470 | 0.433 | 0.058 | 0.054 | 0.054 |
| 14 | RME/MK1 | ±0 | 0.316 | 0.047 | 0.059 | 0.078 | 0.059 | 0.040 | 0.656 | 0.546 | 0.514 | 0.080 | 0.056 | 0.055 |
| 14 | RME/MK1 | -7 | 0.501 | 0.051 | 0.081 | 0.130 | 0.065 | 0.047 | 0.567 | 0.456 | 0.398 | 0.089 | 0.052 | 0.053 |
| 14 | CEC | +22 | 0.458 | 0.076 | 0.088 | 0.094 | 0.061 | 0.040 | 0.389 | 0.413 | 0.391 | 0.095 | 0.083 | 0.090 |
| 14 | CEC | ±0 | 0.476 | 0.144 | 0.146 | 0.092 | 0.065 | 0.045 | 0.456 | 0.380 | 0.348 | 0.116 | 0.093 | 0.097 |
| 14 | CEC | -7 | 0.716 | 0.140 | 0.156 | 0.178 | 0.077 | 0.044 | 0.586 | 0.433 | 0.400 | 0.144 | 0.083 | 0.081 |

MK1 = Swedish Environmental Class 1
RME/MK1 = Rapeseed Methyl Ester / MK1, ratio 20% / 80%
CEC = CEC RF-03-A-84 Reference Diesel

HCi = integrated total hydrocarbons

| Veh. code | Fuel code | Temp °C | Methane CH4 mg/km | Ethylene C2H4 mg/km | Acetylene C2H2 mg/km | Ethane C2H6 mg/km | Propylene C3H6 mg/km | Propane C3H8 mg/km | Isobutene C4H8 mg/km | 1,3-Butadiene C4H6 mg/km | Isopentane C5H12 mg/km | Benzene C6H6 mg/km | Toluene C7H8 mg/km | Xylene C8H10 mg/km |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 12 | MK1 | +22 | 0.7 | 8.2 | 0.5 | <0.1 | 2.7 | - | 0.7 | 1.1 | 0.9 | 1.1 | 0.5 | 0.7 |
| 12 | MK1 | ±0 | 1.1 | 13 | 1.3 | <0.1 | 4.8 | - | 1.3 | 1.7 | 0.9 | 1.8 | 1.0 | 0.9 |
| 12 | MK1 | -7 | 1.2 | 11 | 1.2 | 0.1 | 3.8 | - | 1.0 | 1.4 | 0.8 | 1.5 | 0.7 | 0.4 |
| 12 | MK1 | -20 | 4.3 | 17 | 2.2 | 0.3 | 5.4 | - | 1.4 | 2.0 | - | 2.8 | 1.2 | 1.8 |
| 12 | RME/MK1 | +22 | 0.9 | 8.9 | 1.0 | <0.1 | 3.0 | - | 0.8 | 1.2 | 0.8 | 1.2 | 1.0 | 0.7 |
| 12 | RME/MK1 | ±0 | 2.4 | 10 | 1.1 | 0.1 | 3.1 | - | 0.9 | 1.4 | 1.0 | 1.3 | 0.5 | 0.7 |
| 12 | RME/MK1 | -7 | 0.9 | 12 | 2.7 | <0.1 | 3.6 | - | 1.0 | 1.5 | 0.7 | 1.5 | 1.6 | 2.6 |
| 12 | CEC | +22 | 0.6 | 9.7 | 2.5 | <0.1 | 3.4 | - | 0.9 | 1.3 | 0.6 | 1.1 | 0.6 | 0.8 |
| 12 | CEC | ±0 | 0.9 | 12 | 2.9 | <0.1 | 4.1 | - | 1.1 | 1.5 | 0.6 | 1.2 | 1.1 | 1.4 |
| 12 | CEC | -7 | 1.2 | 14 | 3.6 | <0.1 | 4.9 | - | 1.3 | 1.8 | 0.8 | 1.6 | 2.8 | 5.0 |
| 13 | MK1 | +22 | 1.1 | 14 | 1.9 | 0.3 | 5.3 | - | 1.3 | 1.4 | 0.6 | 2.1 | 1.8 | 3.3 |
| 13 | MK1 | ±0 | 2.6 | 20 | 3.4 | 0.7 | 7.2 | - | 2.0 | 2.2 | 1.2 | 2.7 | 1.7 | 1.9 |
| 13 | MK1 | -7 | 3.3 | 21 | 3.6 | 0.8 | 7.9 | - | 2.1 | 2.3 | 0.6 | 2.8 | 1.7 | 2.2 |
| 13 | MK1 | -20 | 3.7 | 25 | 4.4 | 0.7 | 9.2 | - | 2.6 | 2.8 | 0.7 | 3.0 | 1.9 | 2.0 |
| 13 | RME/MK1 | +22 | 1.8 | 16 | 2.0 | 0.3 | 5.4 | - | 1.4 | 1.7 | 0.4 | 2.2 | 1.5 | 1.7 |
| 13 | RME/MK1 | ±0 | 2.4 | 21 | 3.3 | 0.8 | 7.2 | - | 2.1 | 2.4 | 0.6 | 2.6 | 1.5 | 1.2 |
| 13 | RME/MK1 | -7 | 0.9 | 24 | 3.7 | 0.8 | 7.8 | - | 2.2 | 2.7 | 0.4 | 2.8 | 1.7 | 1.1 |
| 13 | CEC | +22 | 4.8 | 21 | 4.1 | 0.3 | 3.0 | - | 5.2 | 1.3 | 1.8 | 3.0 | 2.5 | 1.8 |
| 13 | CEC | ±0 | 3.0 | 25 | 4.4 | 0.7 | 9.2 | - | 2.5 | 3.2 | 0.8 | 2.6 | 1.8 | 1.7 |
| 13 | CEC | -7 | 10 | 22 | 4.0 | 0.2 | 7.9 | - | 2.1 | 2.7 | 0.6 | 2.0 | 1.8 | 3.8 |
| 14 | MK1 | +22 | 5.2 | 3.9 | <0.1 | 0.7 | 1.2 | - | 0.2 | 0.2 | 1.1 | 0.9 | 0.9 | 1.2 |
| 14 | MK1 | ±0 | 5.0 | 4.6 | 0.4 | 0.3 | 1.3 | - | 0.2 | 0.2 | 0.7 | 1.0 | 0.5 | 0.5 |
| 14 | MK1 | -7 | 5.9 | 6.0 | 0.8 | 0.8 | 1.7 | - | 0.3 | 0.3 | 0.8 | 1.3 | 0.6 | 0.7 |
| 14 | MK1 | -20 | 7.9 | 11 | 2.3 | 1.0 | 3.2 | - | 0.7 | 0.8 | 0.7 | 2.1 | 1.4 | 1.3 |
| 14 | RME/MK1 | +22 | 5.2 | 4.5 | 0.5 | 0.8 | 1.3 | - | 0.2 | 0.3 | 0.8 | 0.9 | 0.7 | 1.0 |
| 14 | RME/MK1 | ±0 | 4.7 | 4.8 | 0.4 | 0.2 | 1.3 | - | 0.2 | 0.3 | 0.8 | 0.9 | 0.8 | 0.5 |
| 14 | RME/MK1 | -7 | 6.0 | 6.7 | 0.9 | 0.5 | 1.8 | - | 0.3 | 0.4 | 0.8 | 1.6 | 2.2 | 5.5 |
| 14 | CEC | +22 | 4.9 | 6.4 | 1.0 | 0.7 | 1.9 | - | 0.3 | 0.4 | 0.3 | 1.0 | 0.9 | 0.8 |
| 14 | CEC | ±0 | 5.4 | 7.8 | 1.0 | 0.4 | 2.2 | - | 0.5 | 0.6 | 0.5 | 1.2 | 1.0 | 1.0 |
| 14 | CEC | -7 | 5.6 | 10 | 1.8 | 0.7 | 3.0 | - | 0.7 | 0.9 | 0.6 | 1.8 | 1.7 | 2.6 |

MK1 = Swedish Environmental Class 1
RME/MK1 = Rapeseed Methyl Ester / MK1, ratio 20% / 80%
CEC = CEC RF-03-A-84 Reference Diesel

- = not measured

| Vehicle code | Fuel code | Temp [°C] | Form-aldehyde [mg/km] | Acet-aldehyde [mg/km] |
|---|---|---|---|---|
| 12 | MK1 | +22 | 7.8 | 2.7 |
| 12 | MK1 | ±0 | 14 | 5.4 |
| 12 | MK1 | -7 | 12 | 4.4 |
| 12 | MK1 | -20 | 16 | 4.0 |
| 12 | RME/MK1 | +22 | 8.5 | 3.0 |
| 12 | RME/MK1 | ±0 | 11 | 3.8 |
| 12 | RME/MK1 | -7 | 12 | 4.3 |
| 12 | CEC | +22 | 9.3 | 3.5 |
| 12 | CEC | ±0 | 13 | 4.7 |
| 12 | CEC | -7 | 14 | 5.7 |
| 13 | MK1 | +22 | 18 | 7.2 |
| 13 | MK1 | ±0 | 24 | 9.5 |
| 13 | MK1 | -7 | 24 | 11 |
| 13 | MK1 | -20 | 32 | 14 |
| 13 | RME/MK1 | +22 | 21 | 9.1 |
| 13 | RME/MK1 | ±0 | 27 | 12 |
| 13 | RME/MK1 | -7 | 26 | 12 |
| 13 | CEC | +22 | 23 | 10 |
| 13 | CEC | ±0 | 27 | 12 |
| 13 | CEC | -7 | 29 | 13 |
| 14 | MK1 | +22 | 4.1 | 1.9 |
| 14 | MK1 | ±0 | 5.6 | 2.6 |
| 14 | MK1 | -7 | 6.7 | 3.0 |
| 14 | MK1 | -20 | 12 | 6.1 |
| 14 | RME/MK1 | +22 | 5.2 | 2.3 |
| 14 | RME/MK1 | ±0 | 5.3 | 2.3 |
| 14 | RME/MK1 | -7 | 8.0 | 3.4 |
| 14 | CEC | +22 | 7.1 | 3.3 |
| 14 | CEC | ±0 | 8.4 | 3.8 |
| 14 | CEC | -7 | 9.8 | 4.6 |

MK1 = Swedish Environmental Class 1
RME/MK1 = Rapeseed Methyl Ester / MK1, ratio 20% / 80%
CEC = CEC RF-03-A-84 Reference Diesel

Appendix 7

PAH Analysis from Diesel Vehicle 12 at Two Temperatures

Gasoline TWC and FFV Vehicles for Reference

FTP Composite without Weighting Factors

| Compound µg/km | PARTICULATE PAH | | | | SEMIVOLATILE PAH | | | |
|---|---|---|---|---|---|---|---|---|
| | Diesel +22 | Diesel ±0 | Gasol. +22 | M85 +22 | Diesel +22 | Diesel ±0 | Gasol. +22 | M85 +22 |
| Naphthalene | <0.1 | <0.1 | <0.1 | - | 8.7 | 18 | 2.0 | 0.5 |
| 2-meth.naphthalene | <0.1 | <0.1 | 0.1 | - | 15 | 39 | 1.8 | 0.4 |
| 1-meth.naphthalene | <0.1 | <0.1 | <0.1 | - | 11 | 28 | 1.2 | 0.2 |
| Biphenyl | <0.1 | <0.1 | <0.1 | - | 7.4 | 14 | 0.3 | 0.2 |
| 3-meth.biphenyl | <0.1 | 0.2 | <0.1 | - | 9.6 | 18 | 0.4 | 0.9 |
| Acenaphthylene | 0.5 | <0.1 | <0.1 | - | <0.1 | 1.9 | 0.2 | 0.2 |
| Dibenzofurene | 0.2 | 0.3 | <0.1 | - | 4.7 | 8.2 | 0.4 | 0.3 |
| Fluorene | 0.3 | 0.3 | <0.1 | - | 3.1 | 4.9 | 0.6 | 0.6 |
| Dibenzothiophene | 0.2 | 0.2 | <0.1 | - | 0.1 | 0.3 | <0.1 | 0.1 |
| Phenanthrene | 5.6 | 4.4 | <0.1 | - | 2.3 | 4.7 | 1.8 | 12 |
| Anthracene | 0.6 | 0.5 | <0.1 | - | 0.2 | 0.5 | 0.2 | 1.4 |
| 2-meth.anthracene | 1.6 | 1.8 | <0.1 | - | 0.1 | 0.3 | 0.3 | 2.2 |
| 1-meth.phenanthrene | 1.3 | 1.4 | <0.1 | - | <0.1 | 0.2 | 0.2 | 1.0 |
| 2-phen.naphthalene | 0.5 | 0.5 | <0.1 | - | 0.1 | 0.1 | 0.2 | 1.8 |
| Fluoranthene | 2.3 | 2.5 | <0.1 | - | <0.1 | 0.3 | 0.3 | 5.2 |
| Pyrene | 3.5 | 3.1 | 0.1 | - | <0.1 | 0.2 | 0.4 | 4.2 |
| Benzo(a)fluorene | 0.1 | 0.3 | <0.1 | - | 0.1 | 0.1 | <0.1 | 0.1 |
| Benzo(b)fluorene | 0.2 | 0.3 | <0.1 | - | 0.1 | <0.1 | <0.1 | <0.1 |
| Benz(a)anthracene | 0.1 | 0.5 | 0.1 | - | <0.1 | <0.1 | <0.1 | <0.1 |
| Chrysenetriphenylene | 0.2 | 0.6 | 0.1 | - | <0.1 | <0.1 | <0.1 | <0.1 |
| Benzo(b)fluoranthene | 0.2 | 0.3 | 0.1 | - | 0.1 | <0.1 | <0.1 | <0.1 |
| Benzo(k)fluoranthene | 0.1 | 0.2 | 0.1 | - | <0.1 | <0.1 | <0.1 | <0.1 |
| Benzo(e)pyrene | 0.2 | 0.4 | 0.1 | - | <0.1 | <0.1 | <0.1 | <0.1 |
| Benzo(a)pyrene | 0.1 | 0.3 | 0.1 | - | <0.1 | <0.1 | <0.1 | <0.1 |
| Perylene | <0.1 | <0.1 | <0.1 | - | <0.1 | <0.1 | <0.1 | <0.1 |
| Indeno(1,2,3,-cd)pyrene | 0.1 | 0.2 | 0.1 | - | <0.1 | <0.1 | <0.1 | <0.1 |
| Bibenzo(a,h)antracene | <0.1 | <0.1 | <0.1 | - | <0.1 | <0.1 | <0.1 | <0.1 |
| Benzo(g,h,i)perylene | 0.2 | 0.3 | 0.2 | - | <0.1 | <0.1 | <0.1 | <0.1 |
| Coronene | <0.1 | <0.1 | 0.2 | - | <0.1 | <0.1 | <0.1 | <0.1 |
| **SUM** | **18** | **19** | **1.4** | **-** | **63** | **139** | **10** | **31** |

- = not measured

Published by

VTT

Vuorimiehentie 5, P.O.Box 2000, FIN–02044 VTT, Finland
Phone internat. + 358 0 4561
Telefax + 358 0 456 4374

Series title, number and report code of publication
VTT Publications 271 VTT–PUBS–271

Date
March 1996

Project number

Author(s)

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Name of project

IEA Alternative Motor Fuels, Annex V

Commissioned by

IEA Alternative Motor Fuels Agreement

Title

# Performance evaluation of alternative fuel/engine concepts. 1990–1995

## Final report including addendum of diesel vehicles

Abstract

Annex V within the IEA Agreement on Alternative Motor Fuels is the first subtask to generate new experimental data. The objective of the task is to generate information on the emission potential of alternative fuels in severe operating conditions and to evaluate new emission measurement methods. The work was carried out in three phases, Engine Tests, Vehicle Tests and Addendum of Diesel Vehicles. The work was carried out at VTT (Technical Research Centre of Finland) as a cost shared operation. Participants were Belgium (Parts Two and Three), Canada (Parts One and Two), Finland, Italy (Part One), Japan, the Netherlands, Sweden and USA. The United Kingdom also joined at the end of the Annex.

The work included 143 different vehicle/fuel/temperature combinations. FTP type emission tests were run on 14 vehicles powered with different gasoline compositions, methanol (M50 and M85), ethanol (E85), LPG, CNG and diesel. Both regulated and unregulated emission components were measured using the most up-to-date emissions measurement technology.

The results indicated, that today's advanced gasoline vehicles must be considered rather clean. Diesel is comparable with gasoline in the case of CO and HC. M85 gives low emissions in warm conditions, but unburned methanol must be controlled. Natural gas and LPG are inherently clean fuels which, using up-to-date engine technology, give low emissions in all conditions.

Activity unit

VTT Energy, Energy Use, Biologinkuja 3–5, P.O.Box 1601, FIN–02044 VTT, Finland

ISSN and series title

1235–0621 VTT PUBLICATIONS

ISBN
951–38–4929–5

Language
English

Class (UDC)
662.6/.8:621.436:53.083

Keywords
fuels, substitutes, utilization, energy, performance, evaluation, motors, diesel engines, vehicles, tests, emissions, exhaust gases, measurement

Sold by VTT Information Service
P.O. Box 2000, FIN–02044 VTT, Finland
Phone internat. + 358 0 456 4404
Fax + 358 0 456 4374

Pages
120 p. + app. 16 p.

Price group
C

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Tätä julkaisua myy

VTT TIETOPALVELU
PL 2000
02044 VTT
Puh. (90) 456 4404
Telekopio (90) 456 4374

Denna publikation säljs av

VTT INFORMATIONSTJÄNST
PB 2000
02044 VTT
Tel. (90) 456 4404
Fax (90) 456 4374

This publication is available from

VTT INFORMATION SERVICE
P.O.Box 2000
FIN–02044 VTT, Finland
Phone internat. + 358 0 456 4404
Fax + 358 0 456 4374

ISBN 951–38–4929–5 ISSN 1235–0621 UDC 662.6/.8:621.436:53.083