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On exhaust emissions from petrol-fuelled passenger cars at low ambient temperatures

Juhani Laurikko

VTT Energy

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puh. vaihde (09) 4561, faksi 456 4374

Statens tekniska forskningscentral (VTT), Bergsmansvägen 5, PB 2000, 02044 VTT
tel. växel (09) 4561, fax 456 4374

Technical Research Centre of Finland (VTT), Vuorimiehentie 5, P.O.Box 2000, FIN–02044 VTT, Finland
phone internat. +358 9 4561, fax +358 9 456 4374

VTT Energia, Energian käyttö, Biologinkuja 3–5, PL 1601, 02044 VTT
puh. vaihde (09) 4561, faksi (09) 460 493

VTT Energi, Energiandvändning, Biologgränden 3–5, PB 1601, 02044 VTT
tel. växel (09) 4561, fax (09) 460 493

VTT Energy, Energy Use, Biologinkuja 3–5, P.O.Box 1601, FIN–02044 VTT, Finland
phone internat. + 358 9 4561, fax + 358 9 460 493

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ABSTRACT

The study at hand deals with regulated and unregulated exhaust emissions from petrol-fuelled cars at low ambient temperatures with present-day or near-future exhaust after treatment systems. The subject has been investigated at VTT over a decade and this report compiles data from various sub-studies carried out between the years 1993 - 1997. Each one of them viewed different aspects of the phenomenon, like determining the low-temperature response of today's new cars employing three-way catalytic converters or assessing the long-term durability and the influence of vehicle mileage upon the low-temperature emissions performance.

Within these studies, together more than 120 cars of model years from 1990 to 1997 have been tested. Most of them were normal, in-service vehicles with total mileages differing between only a few thousand kilometres for new cars up to 80,000 km or even more for the in-use vehicles. Both the US FTP75 and the European test cycle have been employed, and the ambient temperatures ranged from the baseline (+22 °C) down to ± 0 °C, –7 °C and in some cases even to –20 °C.

The studies attested that new cars having today's advanced emissions control systems produced fairly low levels of emissions when tested in conditions designated in the regulations that are the basis of the current new-vehicle certification. However, this performance was not necessarily attained at ambient temperatures that were below the normative range. Fairly widespread response was recorded, and cars having almost equal emissions output at baseline could produce largely deviating outcomes in low-temperature conditions.

On average, CO and HC emissions increased by a factor of five to 10, depending on the ambient temperature and vehicle type. However, emissions of NO_X were largely unaffected. Apart from these regulated emissions, many unregulated species were also determined, either by using traditional sampling and chromatography methods or on-line, employing the latest FTIR technology. Overall, the levels of these emissions were also mostly elevated at subnormal temperatures.

Total vehicle mileage seemed not to affect cold-start emissions (CO and HC) at low temperatures. Nor did the overall durability of the emission control system appear to be worse in cold-climate conditions typical for Finland. The deterioration of the emissions performance in the tested vehicles either closely followed the average trend defined by the normal, assigned deterioration factors or was even lesser.

The conclusions of this report underline the necessity of a separate low-temperature test in order to really effectively curb real-world emissions. Standards at normal temperature are no more effective alone, but need to be accompanied with additional requirements for good performance also in conditions closer to the everyday use, which comprises many cold-starts even in low ambient temperature conditions.

PREFACE

Today the white areas in geographical maps have totally vanished, because needle-sharp satellite images are readily available of almost any tract of our globe. The days of great discoveries, however, are not all gone along with the modern technology. Moreover, the development of new technology has provided us, the scientists, new worlds to chart and new challenges to conquer. Instead of exploring new lands or seas or other wonders of the nature we can also explore those new frontiers created by the growing complexity of technology itself and the consequences caused by its ever-widening applications.

Although the physical hardship of the long voyages, being on land or at sea, has now changed to the comfort of being able to make your progress without leaving your desk, similarities still exist. Although bodily present, the modern-day voyager may still, at times, mentally dwell so deep in his or hers science that it equals the absence of any ancient mariner. (This is a fact that one's family will confirm at any time). Furthermore, results from these journeys to the "great unknown" are still presented in reports and charts that are black ink on white paper. Only the elegancy of a feather pen and elaborate hand script has changed to the industry-standard typography provided by a computer and a laser printer.

Nevertheless, what is more meaningful is that the joys and prides of the early-day pioneers can still be matched. Curiosity, search for something new has always served as the *primus motor* for any scientist or explorer, and that urge can still be rewarded. However, even the greatest urge alone is not sufficient. In the tradition of the great expeditions, a wealthy provider was necessary for funding the mission. This practice is, unfortunately, very much valid even today. To be able to carry out large-scale research efforts you need sizable funding.

For the expedition at hand, the main provider has been the Ministry of Trade and Industry (KTM) through their Energy Technology Research Programmes SIHTI and MOBILE, which are today administrated by the Technology Development Centre (TEKES). Furthermore, the Ministry of Transport and Communications, as well as the Ministry of the Environment have also granted funding in significant amounts. Even companies like Neste Oy and Kemira Metalkat Oy have participated to the mission with sizable subsidies. Some very important sub-tasks have been supported by the Vehicle Administration Agency and Tekniikan Maailma, a major consumer oriented Finnish magazine covering also the field automotive technology. The rest of the necessary resources, especially heavy investments in equipment and other facilities have become from my employer, Technical Research Centre of Finland (VTT). This would be the rightful opportunity to

thank the representatives of all these organizations that have contributed to the successful fulfilment of the task. Their conviction to the justification of our work has been outstanding. I can only hope that we have been able to accomplish all the expectations vested to our endeavour.

Furthermore, my gratitude goes here also to all those people that have personally contributed to this work. I have developed many international contacts along the course of the work with people working concurrently in the same field. This network has been invaluable in coordinating the work and targeting it to topics not covered by other research groups. Fruitful have also been the various talks with my colleagues and co-workers, especially Dr. Nils-Olof Nylund. For him I owe also perhaps the greatest word of gratitude for his efforts in giving me the last necessary push in providing me the possibility to switch temporarily out of the daily work routine and devote myself to the completion of this work.

However, help is needed not only in directing the endeavour and tutoring the leader, but also to support the effort physically. Like our former counterparts, the old explorers, who used kulis or kikujus or whatever local native people to carry their heavy loads of equipment and reserve, we, the modern-day scientists, rely on our colleagues and co-workers. They carry out the numerous test runs and provide us with complex analysis necessary to obtain the matrix of information on which our conclusions are based on. However, instead of thinking them only as conveyer of the load, I would prefer to think them as my sherpas, guides that know their field and not only carry the load for you, but walk you safely through the rough terrain, sometimes even marking your footsteps in advance, not to let you fall into the stealthy pitfalls that are sneaking all the way along the path.

In saying this, my gratitude goes first to Mr. Erkki Virtanen and Mr. Reijo Mikkola, for their hard work in driving the cars thru the various tests and sometimes really suffering physically from the bitter cold caused by those low ambient conditions. Furthermore, Mr. Markku Ikonen has been an invaluable resource in compiling and calculating the test results. Providing the necessary knowledge for the task of challenging perhaps the greatest unknown, the unregulated emissions, has been Ms. Maija Lappi with her colleagues Ms. Päivi Koponen and Mr. Pekka Piimäkorpi, who had been carrying out the tedious but highly appreciated work in sampling and chromatograph analysis. Last but not least, I would like to thank Mr. Riku Vihavainen, for setting-up and operating the FTIR and post-processing the sometimes stupendous amounts of data collected within the various sub-tasks in this exercise. All of these people and the rest of my co-workers at VTT Energy's Engine Technology Group I greet with words of gratitude for being such a good and supportive team.

Precision and accuracy are essential words in the world of science, which is exact. Human being, however, is not, and for him or her, vivid imagination and an intricate plot may be of greater importance. Therefore, the plainness and straightforwardness of this kind of a report may be hard to bear. But to make it easier for a reader to digest, it could be pictured like a map, a first-hand sketch of a yet uncharted borderland, because that is how I actually saw it, when writing it. The technology of catalytic converters and other exhaust gas aftertreatment devices was the mainland and the exertion of this technology to its outer limits, far beyond the well-optimized conditions, was the new frontier zone. However, as those conditions are very relevant in real-world driving, the expedition to conquer this hostile territory was extremely important for the future efforts in the field of exhaust emission control.

Now, let the journey begin.

Espoo, November 28, 1997.

Juhani Laurikko

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APPENDICES

1 Summary and outlook to the emissions legislation

2 Details of the tested vehicles

3 Fuel specifications

4 Calculation procedures for exhaust emissions

5 Statistical variations in the measurement results

6 Instantaneous concentrations and emission rates

LIST OF SYMBOLS AND ABBREVIATIONS

Symbols

C	corrected concentration of the component
C_e	concentration of the component in exhaust sample
C_d	concentration of the component in dilution air sample
C_{CO2}	concentration of CO_2 in exhaust sample
C_{CO}	concentration of CO in exhaust sample
C_{HC}	concentration of HC in exhaust sample
C_{SHC}	corrected concentration of the HC species
C_{SHC}	corrected concentration for HC species
C_{SHCe}	concentration of the HC species in exhaust sample
C_{SHCd}	concentration of the HC species in dilution air sample
C_{SC}	corrected concentration of a carbonyl species
C_{SCe}	concentration of a carbonyl species in exhaust sample
C_{SCd}	concentration of a carbonyl species in dilution air sample
C_S	concentration of the species in DNPH sample liquid, in [mg/l]
$CO_{2,T}$	instantaneous CO_2 concentration in diluted sample
$CO_{2,B}$	background CO_2 concentration in dilution air sample
$CO_{2, Exh}$	instantaneous CO_2 concentration in raw exhaust
C_{poll}	concentration of the pollutant
DF	deterioration factor
Df	dilution factor
d_n	driven distance during bag $_n$ collection, n = 1, 2, 3
Θ_{eng}	equivalence ratio (fuel-to-air) of the engine combustion
Θ_{exh}	equivalence ratio of the exhaust gases
H	absolute humidity in test cell
kH	humidity correction factor, only for NO_X
m	emission in bag sample

m_n	emission for bag $_n$ n = 1, 2, 3
m_{poll}	mass emission of the pollutant
m_{HC}	emission of a given hydrocarbon species
m_{SC}	emission of a speciated carbonyl compound
M_{SHC}	molecular weight of the HC species
P_a	barometric pressure
P_d	saturated water vapour pressure in test cell temperature
R_a	relative humidity in test cell, in [%]
ρ	density for the given component
ρ_{poll}	density of the pollutant
ΣM_{ECE}	total test result for EC test
ΣM_{FTP}	total test result for FTP test
t_{bag}	sampling time per bag
T	temperature in test cell
T_S	temperature of the DNPH sample liquid, in [°C]
V_C	volume of the extracted DNPH sample liquid, in [ml]
V_{exh}	volume flow rate of exhaust
$V_{exh, CVS}$	average sample flow rate (volume) in CVS
$V_{exh, dill}$	sample amount per bag
V_L	volume of the exhaust for DNPH sample, in [dm^3]
V_{mix}	diluted exhaust volume (from CVS); corrected to NTP
Y_{ct}	cold transient phase of the US FTP75 driving schedule, Bag 1
Y_{hs}	hot stabilized phase of the US FTP75 driving schedule, Bag 2
Y_{ht}	hot transient phase of the US FTP75 driving schedule, Bag 3

Abbreviations

AFR	Air-to-fuel ratio
CAA	Clean Air Act (in United States), adopted in 1970
CAAA	Clean Air Act Amendments (in United States), made in 1977 (CAAA'77) and 1990 (CAAA'90).
CARB	Californian Air Resources Board
cpsi	cells per square inch
EFTA	European Free Trade Association
EGR	Exhaust gas recirculation
EHC	Electrically heated catalytic converter
EPA	Environmental Protection Agency (of the United States)
EUDC	(European) Extra-Urban Driving Cycle
FTIR	Fourier-Transform Infra Red (principle of operation)
GRPE	Group of Rapporteurs on Pollution and Energy (expert group under WP.29 of UNECE)
LEV	Low-Emission Vehicle (Certification class in the Californian LEV-programme)
NAAQS	National Ambient Air Quality Standards (in United States)
NEDC	New European Driving Cycle (ECE15+EUDC)
NMHC	non-methane hydrocarbons
NMOG	non-methane organic gases
MIR	maximum incremental reactivity (ozone forming potential)
MPFI	Multi-point fuel injection
MTBE	methyl-tertier-butyl ether (fuel oxygenate)
MVEG	Motor Vehicle Emissions Group (of EC)
OEM	original equipment (car) manufacturer
OICA	Organization International Constructeurs Automobile
PFI	Port fuel injection
PTC	positive thermal control (resistive intake air heater)

SAI	secondary air injection
SI	spark ignition (otto engine)
TAME	tertier-amyl-methyl ether (fuel oxygenate)
TLEV	Transitory Low-Emission Vehicle (Certification class in the Californian LEV-programme)
total HC	all (volatile) hydrocarbon species present in exhaust
TWC	Three-way (catalytic) converter
ULEV	Ultra-Low Emission Vehicle (Certification class in the Californian LEV-programme)
UN/ECE	United Nation's Economic Commission of Europe
US	the United States of America
ZEV	Zero-Emission Vehicle (Certification class in the Californian LEV-programme)

1 INTRODUCTION

The connection between motor vehicle exhausts and urban air pollution was established in the late 1950's. Shortly after that, cars were identified as a major source of emissions and the issue soon became strictly regulated [1]. Since the early start in mid-1960's, limit values for emissions, which new motor vehicles need to comply with, have been tightening on a progressive pace for about three decades now, and today they cover most of the world market. An update of the present legislative situation and an outlook to the near-term future is given in Chapter 3 and in Appendix 1.

Notwhitstanding, the industry has been equally successful in lowering the level of the harmful constituents found in the exhausts to meet the ever-increasing stringency of the regulations. Major contribution to this effort has come from the concept of catalytic exhaust aftertreatment introduced in mid-1970's. In its present form, the three-way catalytic converter, it has now become a standard issue in new petrol-fuelled cars. Its impact has been quite substantial, since such a system is able in normal operating conditions to convert more than 90 % of the primary pollutants – carbon monoxide, various unburned hydrocarbons and oxides of nitrogen – into less harmful form, mainly N_2, CO_2 and water vapour. Apart from presenting the latest incarnation of the catalyst technology, Chapter 3 will review some of the most novel concepts in terms of lowering the exhaust emissions.

Test procedures have an essential role in these regulations, and the setting of a limit value for any exhaust constituent has always needed in parallel a description of the procedure, how this emission is to be measured. To curb the emissions really effectively, these test procedures should be related to the actual conditions of vehicle use as closely as possible, because achieving low emissions in these regulatory tests is usually the primary target in the design of any emission control system. If the test conditions do not match real-world situations, non-optimum performance and higher emissions in normal, everyday driving are expected.

However, since the conditions and manners of vehicle use are so varied, the tests could only include a narrow subset of all the real-world options. Furthermore, because the whole legislative process has been an evolutive one, all the consequent procedures have, when defining the test conditions, copied the guidelines laid down in the first Californian rules, announced in 1964. Therefore, test conditions, like the range of ambient temperature in which the tests are performed, have remained more or less the same, although e.g. the driving schedules have over the years been diversified and modified many times to reflect actual use better.

The problem was not so evident in the early ages of catalyst-equipped cars, because they were at first mainly used in areas with warm or mild climatic conditions. Then the warm up was fast enough and system performance was deemed acceptable. However, the ever-widening use of catalyst-equipped cars has brought them to areas of a colder climate, as well. Furthermore, research work has shown that in most of the countries substantial part of the total distance travelled with passenger cars is also accumulated from very short trips. Typically, about 40 % of all trips are below 5 km, which is much less than the distance covered by the current standardized driving cycles. In such situations, the engine and its associated emission control systems operate most of their total usage time below the optimum running temperature. This will lead to inferior emissions performance, because in spite of its high efficiency in fully warmed-up mode, the operation of a catalytic converter is highly dependent on temperature and exhaust composition.

For reasons later elaborated in Chapter 2, no conversion reactions will take place, if temperatures inside the converter do not raise above a threshold value called "light-off" temperature, which is usually somewhere from 250 to 300 °C. Before this level is reached, or even after that, if the exhaust composition does not match the desired balance between the pollutants, the catalytic system functions inefficiently, if at all. The emissions are then essentially on the same engine-out level as without any aftertreatment device.

As Chapter 2 will also point out, this inadequacy was first recognized in the early studies [2] - [9], made in the United States (of America), and later ascertained by the US EPA in their large-scale investigation in the late 1980's [10]. This study was spurred by the fact that notwhitstanding the wide use of catalytic converters, the ambient air quality standard for carbon monoxide was constantly violated in the wintertime on areas with a cold climate. A valid distrust was, therefore, placed upon the effectiveness of the legislation to control real-world emissions. Furthermore, pressure has been raising concurrently towards altering these conditions, either by lowering the traditional temperature range (from +20 to +30 °C), or better yet, by defining a separate low-temperature test. Subsequently, the outcome of this study led the EPA to amend the Federal certification procedures to include an additional low-temperature test with a separate limit value for carbon monoxide. Rules were released in 1992, and gradually phased in starting from 40 % compliance for the model year 1994 to full implementation for the model year 1996.

As described in Chapter 2, similar deliberation is now underway in the European Union, as well. A common position between the Council and the Commission has already been reached in June 1997, to include a low-temperature test into the future amendments of the directive covering car emissions. This has been deemed necessary, because typical real-world ambient temperatures prevailing in the European countries, where cars with catalytic emission control are used today, are

well below this range defined in the present-day regulations.

Because of the alleged deficiency associated with the use of cars equipped with three-way catalytic emission control in low ambient temperature conditions, a mission was initiated at VTT in 1985 to assess the emissions performance of current-technology vehicles. This testing of emissions behaviour beyond the normative conditions was judged necessary, because at that time Finland was, along with the other Nordic countries, contemplating the implementation of an emission legislation similar to that of the United States, which would mean that all new cars would be equipped with catalytic converters. Should this technology fail to work efficiently in cold conditions, the act would be highly uneconomical and no real-world emission reductions would be expected. Earlier work, which is discussed in Chapter 2, was deemed non-representative in the European context, because it has dealt only with cars designed for the North-American market.

The experiments described in this report are a part of that mission. The work comprises several sub-studies of elements felt to have importance as for either causing high levels of emissions or describing the performance of a typical design. Bearing these objectives in mind the main aims of the work described here were set to be:

1) to address different aspects of the emissions performance of petrol-fuelled passenger cars representing present-day emission control technology in low ambient temperature conditions.

2) to make an attempt to constitute average emission rates for some specific air polluting compounds as a function of ambient temperature in a fleet of typical present-day cars.

This experimental section consists of several sections. At first the target-setting and general outline of the research work is introduced in Chapter 4. It is accompanied with Chapter 5, which describes the equipment, methods and test procedures used in the experimental part.

The presentation of the results is divided into several chapters, each with a specific main topic. Chapter 6 deals with the emissions of modern TWC cars in view of different test conditions and characterizes their performance.

Chapter 7 is devoted for studies to assess how vehicle mileage affects the emissions performance, especially in cold ambient conditions.

Chapter 8 deals with unregulated emissions, (ammonia, nitrous oxide and formaldehyde) which were measured within some of the studies using an on-line analyser based on FTIR technology.

Chapter 9 describes the results for individual hydrocarbon species (C_1-C_8), which were obtained using gas chromatography analyses in a study estimating performance of different catalyst formulations.

The average levels of emissions as a function of ambient temperature are presented in Chapter 10. It summarizes the results for individual sub-studies addressed in the previous chapters.

Finally, the results are reviewed and discussed in Chapter 11 and the final conclusions are listed in Chapter 12.

2 FEATURES AFFECTING TO THE PERFORMANCE OF SI ENGINE AND TWC SYSTEM AT COLD-START

2.1 PERFORMANCE OF A SI ENGINE AT COLD-START

Cold-starting of a petrol-fuelled spark-ignition (SI) engine is a challenge, especially in low ambient temperature conditions. The reason to this is that to initiate and maintain sustainable combustion liquid fuel must be evaporated. Furthermore, a suitable, quite narrowly set air-to-fuel ratio (AFR) needs to be established in the cylinder. However, in cold conditions, the evaporation of petrol is poor and the cold surfaces inside the intake manifold and the cylinder itself induce condensation losses before the air-fuel mixture reaches the combustion chamber. Therefore, overfuelling is necessary [11].

Investigations with a single-cylinder test engine [12] have shown that depending on the ambient temperature, the excess fuel ratio can be up to five times the amount of fuel, which is necessary to maintain stoichiometric AFR in a normally running fully warmed-up engine, as seen in Figure 0. Yet, according to Figure 1, the same research data indicates that this is only an apparent AFR, as the actual, in-cylinder AFR is essentially much lower and closer to stoichiometry. This is true even during the initial start-up phase and almost independently of the ambient temperature, because the rest of the fuel is either not evaporated at all, or it is lost into those condensation losses along the way to the cylinder. However, once the engine has started, the overfilling can be reduced to a level which is some 30 to 50 % of the value needed for starting in that temperature, which is presented in Figure 1.

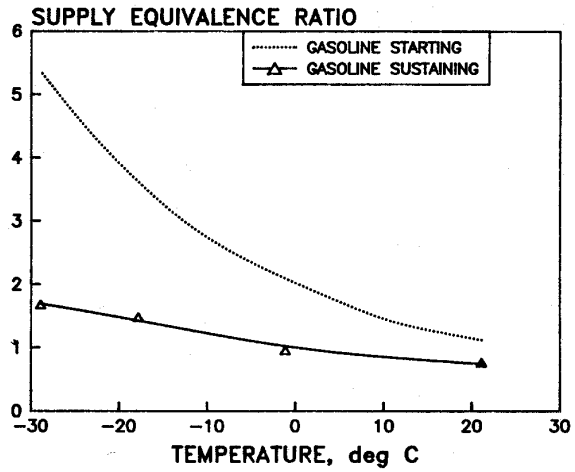

Figure 1 Supply equivalence ratio for starting and sustainable combustion with petrol at different ambient temperatures [12].

Apparently, the poor evaporation properties of petrol are the main attributes to this kind of situation, because if gaseous fuel like propane is used, the fuel supply needs not to be increased at all with lowering ambient temperatures, as shown in Figure 3.

This overfilling has several disadvantages. First, it will unduly raise fuel consumption and secondly, it will induce wear in the cylinder and piston rings by washing away the thin oil film on the cylinder walls. Perhaps the most aggravating defect is, however, the high emission rate of unburned hydrocarbons and CO. This is caused by unvaporized and thus noncombusted fuel escaping the tailpipe and locally very rich AFR in the combustion chamber causing excess CO formation.

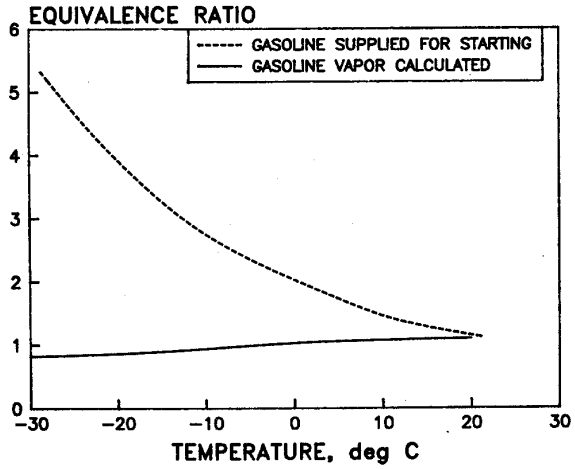

Figure 2 Calculated petrol equilibrium vapour equivalence ratio values at the supply equivalence ratio for starting [12].

For aforementioned reasons, overfuelling or enrichment, as it is also called, should always be kept to a minimum level. On the other hand, enrichment needs to be sufficient to keep the engine from stumping and stalling during the warm-up ride, as this is something that is most likely to annoy the driver very much. Therefore, the engineers responsible for determining the enrichment strategy are often confronted with a dilemma: which one of these demands is more important. As long as no strict demands for emissions specifically in low ambient temperature conditions are placed upon, the choice will most likely favour good driveability, even if it induces higher fuel consumption, as well.

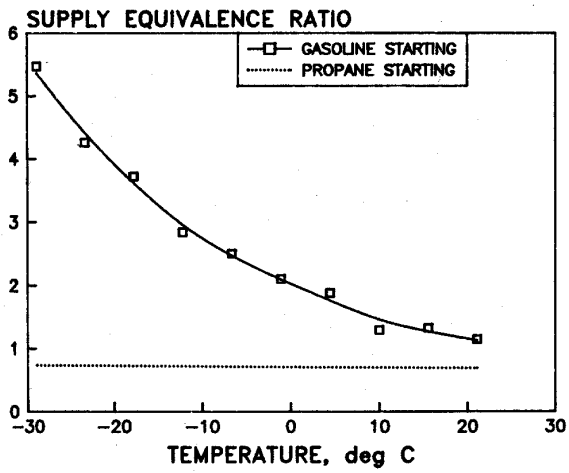

Figure 3 Supply equivalence ratio values for starting with petrol and propane [12].

The current trend in mixture preparation brought along with the catalytic converter technology has duly helped this situation, as injecting the fuel into the intake manifold very close to the intake valve effectively lowers these condensation losses and reduces the need for heavy overfilling. However, in

the interest of evaporative emission control the fuel's vapour pressure, a measure of its evaporation performance, has been constantly lowered during the past decade. Therefore, some of this advantage in fuel delivery technology is lost.

2.2 OUTLINE OF THE FACTORS AFFECTING COLD-START PERFORMANCE IN CATALYTIC SYSTEMS

A SI engine fitted with TWC system is at cold-start like any SI engine just discussed, with the exception that the performance of the catalytic system and its interaction with the engine brings added complication to the situation. Figure 4 makes an attempt to present most of the relevant parameters and design features that, according to literature and the authors practical experience, affect cold-start emission performance.

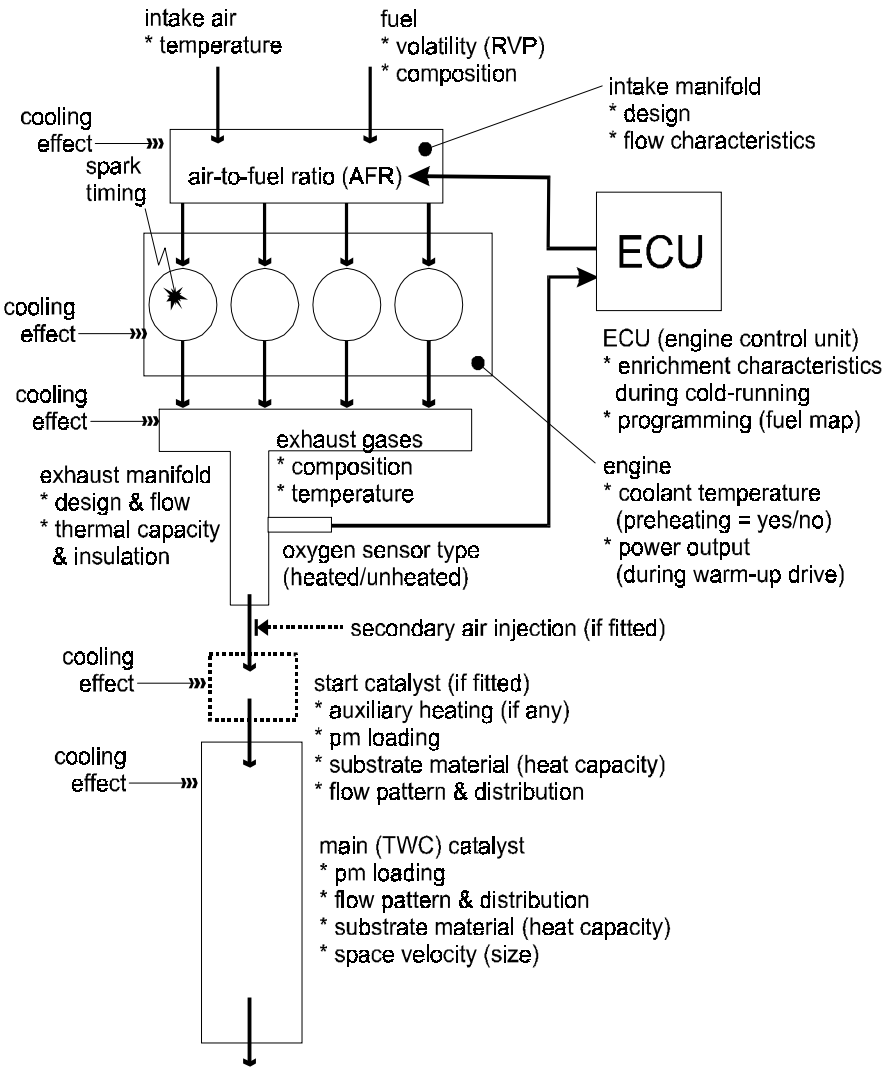

Figure 4 Parameters affecting the performance of a catalytic (TWC) emissions control system after a cold-start in low ambient temperature conditions.

As one can see, there are a great number of things that can attribute to either good or poor behaviour of the engine and the aftertreatment system in low ambient temperature conditions. Some are specific to a catalyst-equipped system, but many of them are generally applicable to all petrol-fuelled SI engines. Most of the main features will be discussed below, but some, like fuel composition or specific attributes of intake manifold designs and injector positioning or spray characteristics, are not touched here. However, they are also very important points, and should not be neglected.

At cold-start, intake air temperature, as well as coolant temperature, are both affected by the ambient temperature. The characteristics of the fuel, mainly evaporation rate (expressed as e.g. Reid vapour pressure, RVP) determines, how much fuel can be evaporated at this given ambient air temperature. Intake manifold design, flow characteristics and the type of fuel injection (manifold or port or direct in-cylinder) determine the losses of this evaporated portion before the charge enters the cylinder. Even cold combustion chamber walls can, furthermore, adversely affect the situation while still condensating some of the evaporated fuel. Therefore, the apparent air-to-fuel ratio (AFR), which is calculated on net intake air mass and fuel feed, can be very different to what the actual, in-cylinder AFR is at the point of ignition.

The spark timing has an effect not only to the composition of the exhaust gases, but also to their temperature at the time of exhaust valve opening. Late ignition will raise the temperature, but also affects to the HC content [11]. This feature is sometimes even desireable. Especially, if the exhaust manifold has a low thermal capacity and low heat losses, late ignition timing during the warm-up running can be used for heating up the catalytic converter. Using secondary air injection (SAI) will further enhance the heating effect, when the exhaust composition is biased towards high HC (and maybe even high CO) content, because of the exothermic reactions in the converter. The latter feature, however, is not effective before the catalyst has reached light-off temperature.

The characteristics of the catalytic converters, both in main and in start-up catalyst, if one is fitted to the system, can attribute to the conversion performance in two ways. Precious metal (pm) loading and type will affect to the light-off temperature and hence to the conversion rate. Furthermore, attributes like substrate material and its heat capacity, exhaust flow distribution within the converter, as well as heat transfer from the exhaust gases to the converter bed will inflict to the time, how the unit (or units) is heated-up.

Figures 5 and 6 illustrate the influence of pm-loading and Pt/Rh ratio to the light-off performance of a three-way catalytic converter. Furthermore, Figure 7 illustrates the influence of the substrate wall thickness and cell density to the light-off temperature.

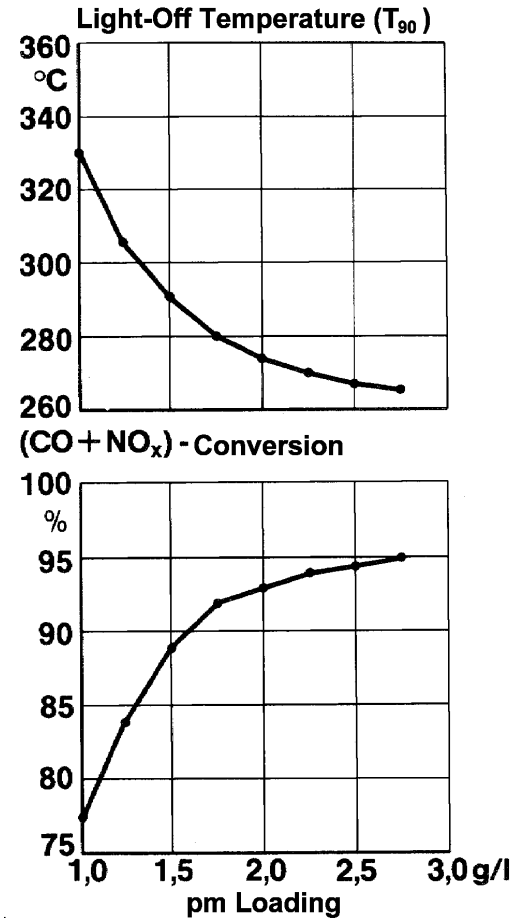

Figure 5 The influence of precious metal loading on the light-off temperature and conversion in a three-way catalyst (TWC) [13].

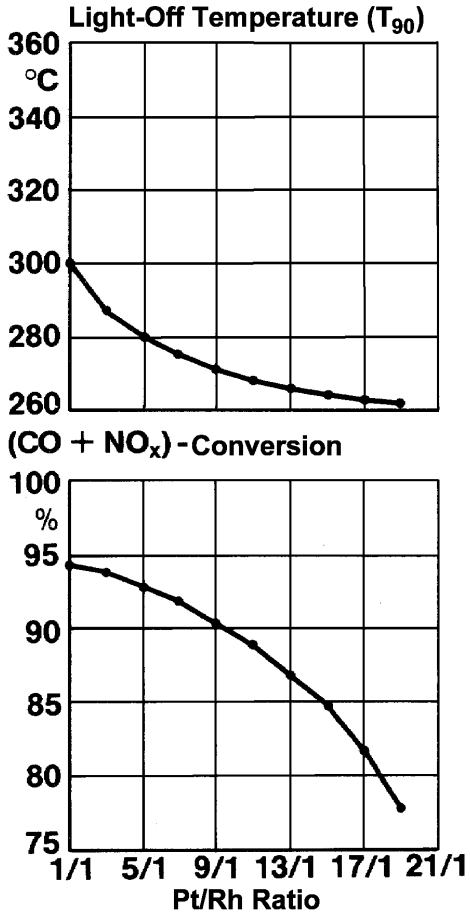

Figure 6 The influence of platinum (Pt) to Rhodium (Rh) ratio on the light-off temperature and conversion efficiency in a three-way catalyst (TWC) [13].

According to Figure 5, increasing the amount of pm-group metals applied to the substrate, often called as loading, will enhance the activity of the converter. It shall also lower its light-off temperature expressed as T_{90}, which means the temperature, where conversion ratio exceeds 90 %. It will, however, also substantially increase the cost of the converter, as the pm-metals used for exhaust catalysis are very expensive.

Furthermore, according to Figure 1, raising the share of platinum (Pt) over the amount of Rhodium (Rh), both typical in three-way catalysts, lowers the T_{90} temperature, but simultaneously lowers also the overall conversion efficiency ($CO+NO_x$). Hence, a careful balancing is called for.

Finally, as one can see in Figure 2, increasing the wall thickness, as well as cell density, which both strongly affect to the thermal capacity of the system, will increase the necessary temperature for conversion to start.

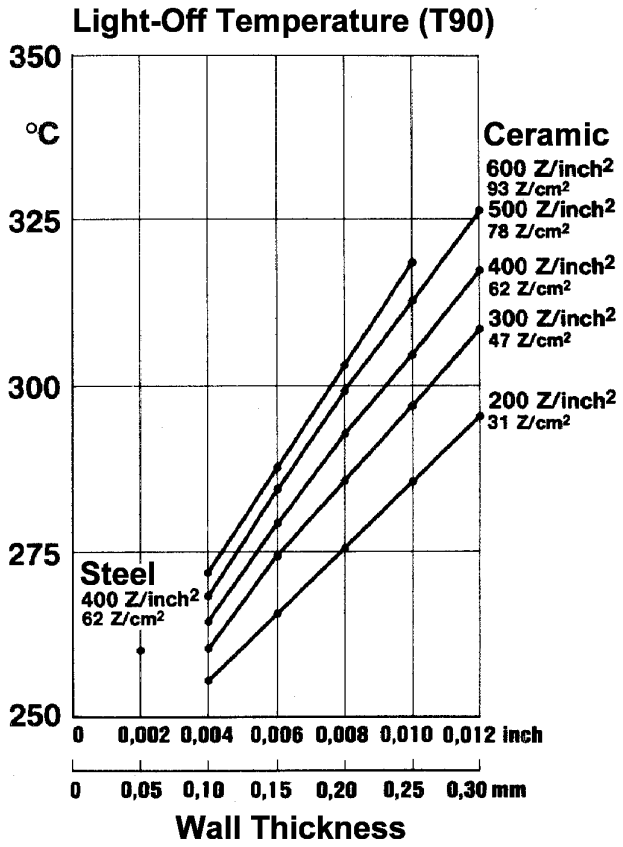

Figure 7 The influence of substrate material, wall thikness and cell density to the light-off temperature (T_{90}) in a three-way catalytic converter. [13].

All these figures, taken from [13], are only an example of the interaction of the parameters, and does not reflect the performance of the very latest technology. Therefore, they must be regarded as indicative only. Recent research and development efforts have e.g. brought new, thin-wall ceramic substrate materials and converters with higher cell densities to the marketplace [14]. Thus, the difference to steel-based substrates has probably narrowed down. However, similar work has been going on also on metallic converters [15], [16], which has enhanced their performance, as well.

During the initial running after a cold-start, the engine, even if it is fitted with an oxygen sensor and closed-loop AFR control mandated by the three-way catalyst, will run net rich with no feedback to the engine control unit (ECU) from the oxygen sensor. This is the situation mainly for two reasons. At first, the oxygen sensor will not give any useful signal, because it has, like the catalytic converter itself, a certain operating temperature threshold. Therefore, its signal is neglected, before stable operating temperature is reached. Fitting the sensor with an electrical heating element will quicken this warm-up and aid to a faster engagement.

However, the engine may still not be able to run on any leaner, closer-to-the-stoichiometric AFR, even if the oxygen sensor may have reached operating point, and could be used for closed-loop mixture control at near-stoichiometric AFR range. This kind of engine performance may be endowed to slow warm-up of the coolant with due effect to both intake manifold and combustion chamber wall temperatures, which subsequently affect to the condensation losses within the air-fuel charge.

Engine power output during warm-up running may, according to some sources like [17], not be a decisive factor, because it appears that the heat losses, which warm-up the engine and coolant, are not strongly dependant on engine power output, but remain at a sufficient level even at low loads. Furthermore, it may not be attributable to a fast warm-up to run the engine on high load during the initial warm-up drive, but to remain at lower loads, where the net exhaust output is also lower because of throttling. Thus, less unwanted exhaust emissions should occur, as well. Moreover, preheating the coolant prior to the cold-start has a substantial, positive effect. (*This feature will be discussed further in 3.2.6*)

2.3 OPERATION OF A THREE-WAY CATALYST SYSTEM IN COLD-START CONDITIONS

As it is quite well known, a three-way catalyst (TWC) emission control system operates most efficiently, if both of the following key conditions are fulfilled:

- adequate operating temperature; i.e. converter temperature above 300 °C
- an air-to-fuel ratio (AFR) close to stoichiometry (lambda=1)

The first requirement is a very basic one, because the rates of the conversion reactions are highly dependent on temperature (see Figure 8). Temperatures from 300 to 350 °C are considered as a threshold for efficient conversion to start. This temperature, already referred as $T_{90,}$ is often called also "light-off" temperature, because the conversion reactions are exothermic in nature, and once started, they will heat up the converter quite efficiently.

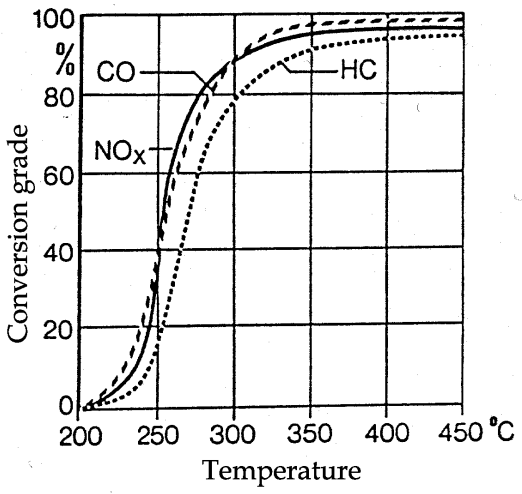

Figure 8 Conversion efficiencies in a TWC as a function of exhaust temperature [18].

The latter criterion is attributed to the fact that a three-way converter normally operates without supplementary air, i.e. only using the oxygen contained in the exhaust itself. Thus, the composition of the exhaust gases needs to have a good balance between components needing oxidizing (CO, HC) and reducing reactions (NO_X), because, as Figure 9 shows, the efficiency of these main reactions are somewhat counteractive over the air-to-fuel range.

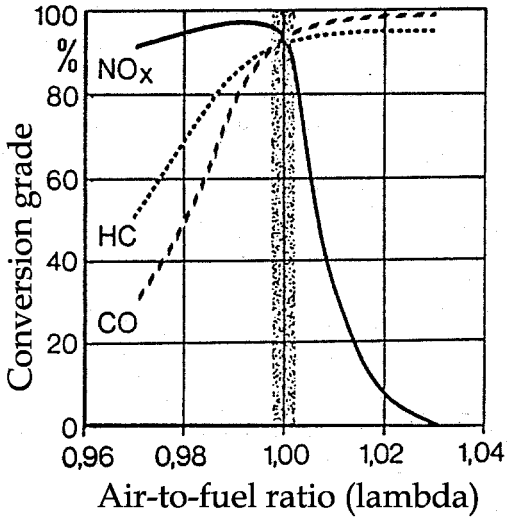

Figure 9 Conversion grades for CO, HC and Nox as a function of AFR. [18].

Furthermore, because according to Figure 11, exhaust composition is highly dependent on the amount of fuel in the combustion air, this translates to the beforesaid conditions, i.e. near stoichiometric conditions. The closer to lambda=1 the AFR is, the better. Usually the target-range with the allowable tolerance band, the so called "lambda-window", for AFR is referred to be from 0.997 to 1.003. It is also shown in Figure 9 as a shaded area, where all the three main conversions are at their best.

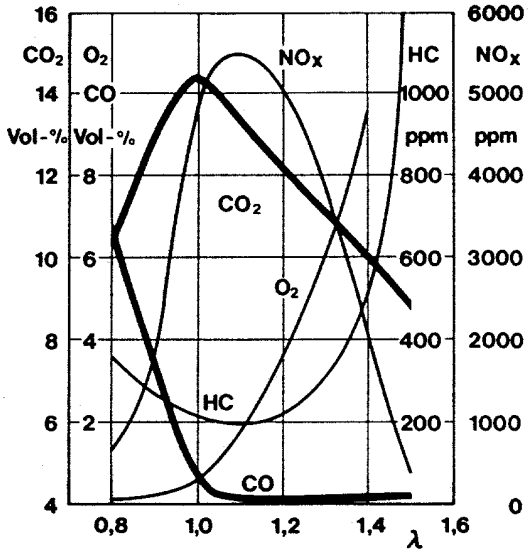

Figure 10 Exhaust composition as a function of air excess ratio over stoichiometry (lambada) [18].

However, as already discussed, in the event of a cold-start in ambient temperatures below +20 °C, both of these constraints have to be bent, if not totally broken. In that kind of conditions the catalyst bed temperature is, of course, well below light-off temperature. Furthermore, for the reasons already discussed in a previous section (2.1), the AFR is also way off the desired range. Not only because more fuel has to be fed into the engine to ensure that the effective AFR in the cylinder near the spark plug is kept within the limits for ignition and stable combustion, but also because the mixture often also very inhomogeneous. This brings local AFR to a very rich region and causes excessive CO formation during combustion. Furthermore, the "wall-wetting" effect of cold cylinder and manifold surfaces increases the emission of unburnt hydrocarbons (HC), as well [11].

Because, for aforementioned reasons, both of the basic rules for efficient converter performance are broken, a TWC equipped car produces during a cold-start probably as much harmful emissions as its former, non-catalyst counterpart. Without undue generalization, this is also the "rule-of-thumb" for the first few kilometres of the driving. The latter of the facts, the enrichment, may have even stronger influence on the operation than the low catalyst bed temperatures. This is so, because after the engine has started, exhaust temperatures are nearly non-dependent of ambient conditions, thus the heat flux from the exhausts to the converter is almost equal even at low temperature conditions.

Furthermore, a decline of 40 °C in ambient temperature, and subsequently the start-point for the catalyst warm-up, i.e. from +20 to -20 °C, means only a 10 % decrease, if we consider the target-level for converter bed temperature to be around 400 °C. However, when the engine and coolant temperatures are in question, the target is some 80 °C for normal, non-hesitant operation. Here, the same kind of drop in ambient temperature means some 50 % increase, and consequently 50 % longer time to reach that target level, as the warm-up characteristics of the coolant and the engine are also almost independent of the ambient temperature. Figure 11 illustrates this dispute.

This "theory" corroborates with the experience that in most of the cases catalyst bed temperature has raised well above the light-off level long before the coolant temperature has reached the point, at which the enrichment of the air-fuel mixture is no longer needed, and stoichiometric operation is possible with due effect on converter performance. Engine coolant temperature and its implications to the enrichment seem, therefore, to have much greater influence on the conversion efficiency in cold ambient conditions than converter temperature or design or even pm loading).

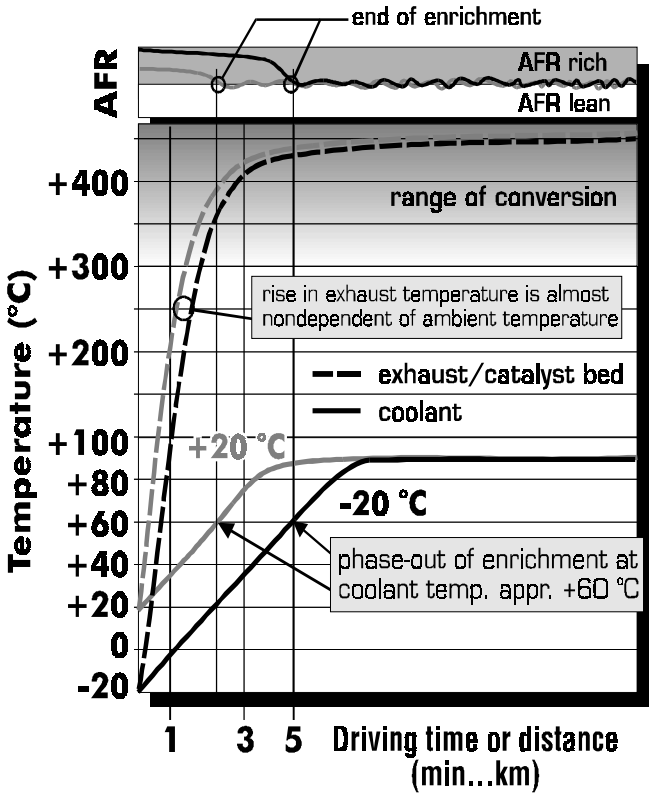

Figure 11 Schematic representation of air-to-fuel ratio (AFR), exhaust and coolant temperatures after a cold start at normal (+20 °C) ambient temperature.

However, after the engine and the converter have both reached their normal operating conditions, the performance of the exhaust aftertreatment is almost independent of ambient temperature, and very low emission levels can be attained. Unfortunately, in many of the cases the driver has reached his or her destination at the same time as this occurs, because typical trip lengths in urban driving tend to be only around 3 to 5 km, which is in many cases about the same distance needed to warm-up the engine and reach low pollution levels, if the ambient temperature lies within the region of -7 to -15 °C. The effect of emission control system is then much derated from the levels quoted for regulatory tests run in normal ambient temperatures.

2.4 EARLIER RESEARCH WORK ON THE SUBJECT

2.4.1 The pioneering studies

Consequently, the adverse effect of cold operating conditions to the emissions of petrol fuelled engines, as well as to the performance of their associated emission controls has been investigated and reported by many authors in the literature. This early, pioneering work has been reported in, e.g. [3] - [9]. It has addressed the problem in view of the typical technology of that era. A multitude of different options from a carburetted non-catalyst to a fully closed-loop controlled MPFI system with a three-way catalyst were available to fulfill the rather lenient regulatory requirements of that time.

The main conclusions of this early work, which has already been addressed by the author in [19] and [20], were, that lowering the ambient temperature gives rise to emissions, especially CO and HC. Even NO_X emission may be affected, but generally it behaves contrary to the other two, because a rich-running engine usually produces less oxides of nitrogen than what it does if a stoichiometric or lean mixture setting is used. Overall the sophistication of the emission control system seemed to increase the vehicle's sensitivity to low ambient temperatures, the non-catalyst versions being least affected.

2.4.2 The studies by the US EPA

Though this early work had already established a basic understanding of the phenomenon, a kind of landmark study in this field, however, has been the work that the US EPA carried out in 1987 prior to its promulgation of the Cold-Temperature CO Regulation. It was published, among other reports, by Larson in [10]. Although the previous work had already covered many technologies, this study, was the most comprehensive, covering altogether some 180 vehicles. Of these, the majority was representing typical 1980's passenger cars in the North-

American market, but to provide the necessary cross-section of the on-road vehicle fleet, some vehicles from the 1970's were also included into the test fleet, as well as even a couple from the pre-regulatory and pre-catalyst era on the 1960's.

Overall, this study corroborated most of the results from the early work. Figures 12 and 13, based on data taken from [10], show, how five to nearly sixfold increase in CO and HC emissions were encountered for the test fleet, on average, in the first phase of the FTP75 driving schedule (Y_{ct}=Bag 1), but the combined, full FTP result was less affected.

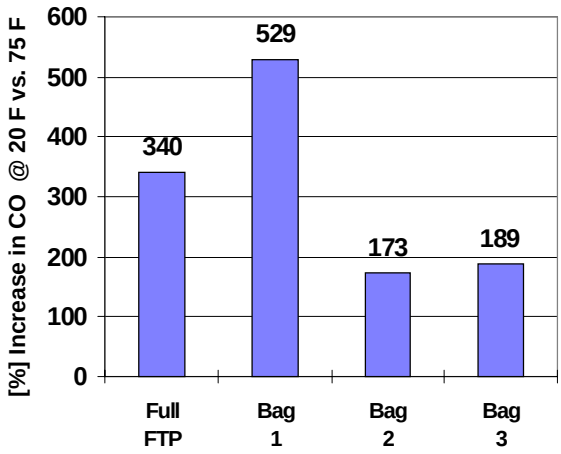

Figure 12 Relative increace in CO emissions; 20 °F vs. 75 °F according to [10].

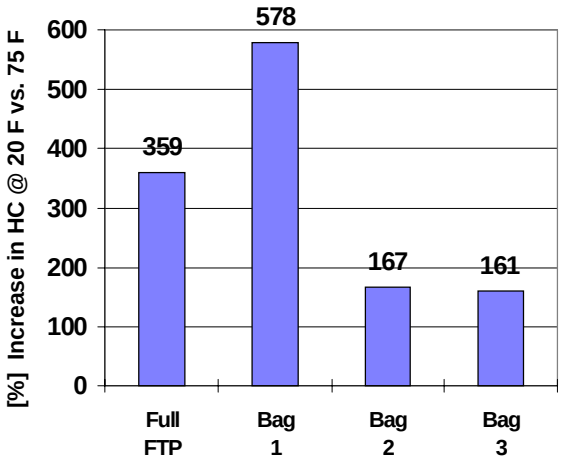

Figure 13 Relative increase in HC emissions; 20 °F vs. 75 °F according to [10].

A comparison of the performance of different fuel delivery systems was also included in the report. Figures 14 and 15 illustrate the combined, full FTP results broken down to sub-fleets according to the fuel system in the vehicle.

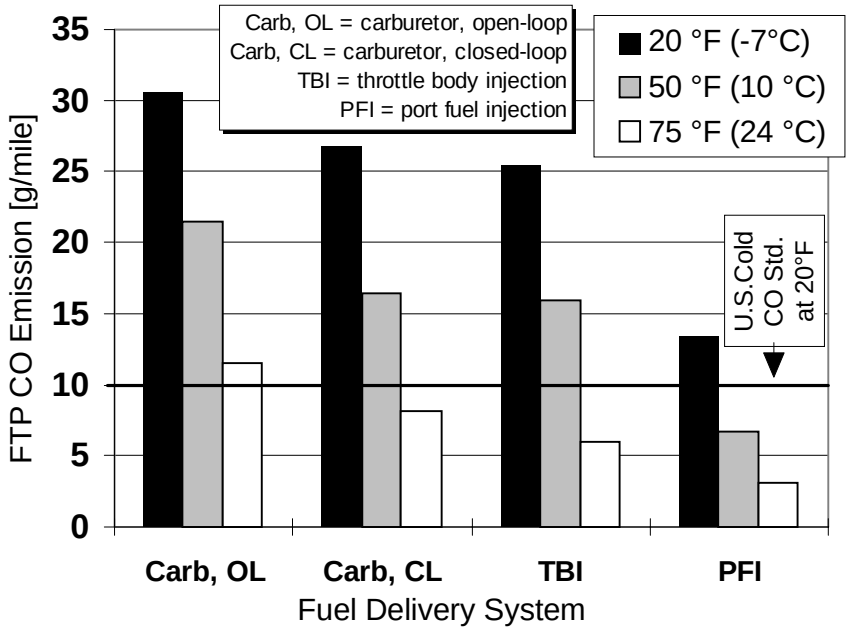

Figure 14 FTP CO emissions for different fuel delivery systems in various ambient temperatures; according to [10].

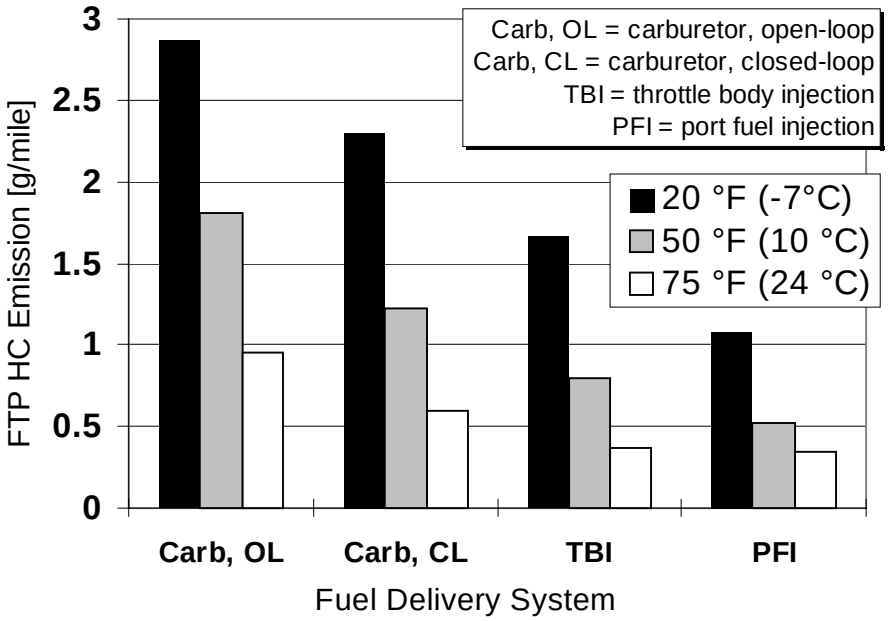

Figure 15 FTP HC emissions for different fuel delivery systems in various ambient temperatures; according to [10].

The challenge that the upcoming cold-temperature CO standard, which was later set on 10 g/mile, posed to even the best of the cars of that period, can be seen in Figure 14. The standard is indicated there, and it shows that the averages in all of the sub-fleet are exceeding it, some even quite substantially.

Furthermore, Figures 16 and 17 give the same kind of presentation on the basis of the emissions measured in Bag 1, which is collected from the first phase (Y_{ct}) of the FTP75 driving cycle.

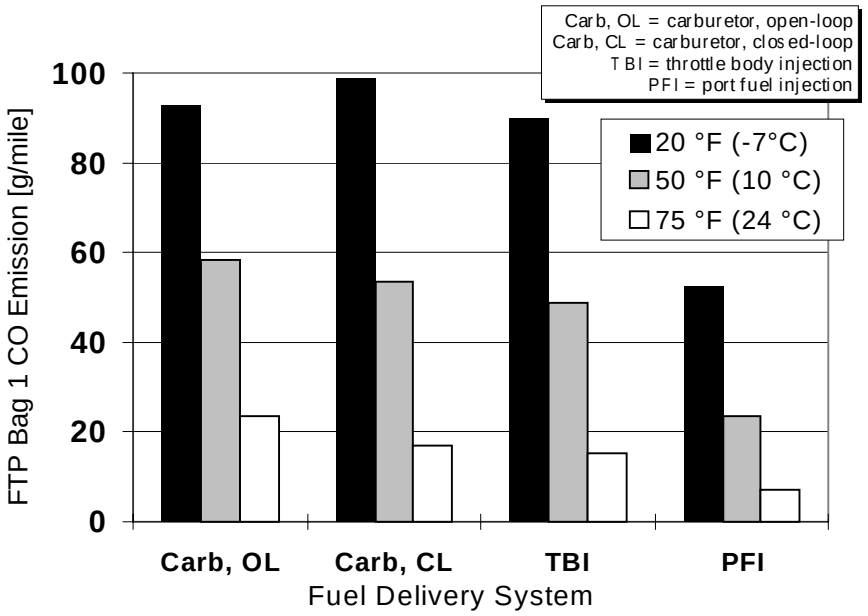

Figure 16 FTP Bag 1 CO emissions for different fuel delivery systems in various ambient temperatures; according to [10].

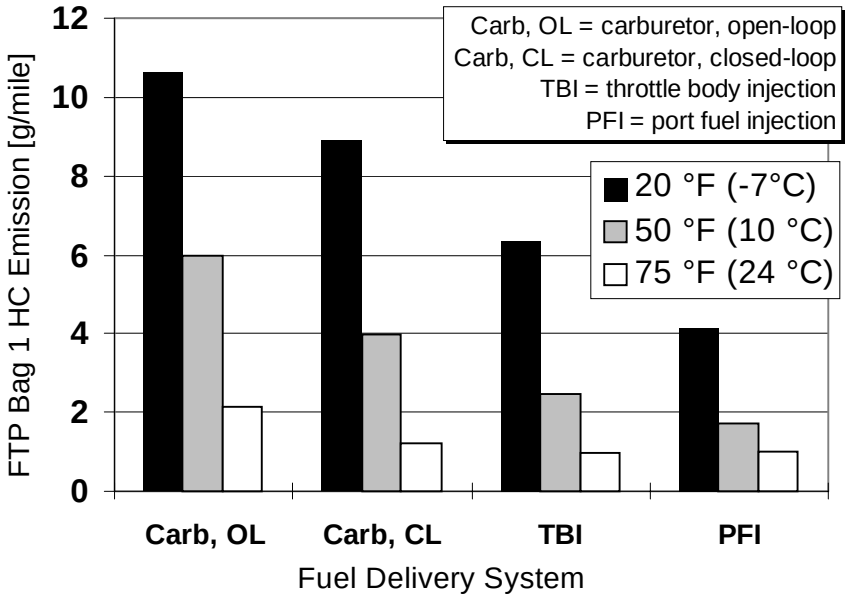

Figure 17 FTP Bag 1 HC emissions for different fuel delivery systems in various ambient temperatures; according to [10].

As can be seen from these Figures, CO emissions levels in bag 1 are least affected by the fuel system, but HC emissions, both total FTP and bag 1, show dependence. A sophisticated fuel delivery seems to be an advantage, because port-fuel injected (PFI) cars have the lowest HC emissions. The difference in temperature response, however, was much larger in terms of CO, and the gradient from 75 °F (+24 °C) to 20 °F (-7 °C) was largest in cars with PFI systems.

The response of the different fuel delivery systems to the lowering of the ambient temperature is more clearly seen in Figures 18 and 19, which show the results in relative scale, normalized to the level measured at 75 °F (+24 °C). This leads to a conclusion that vehicles with more sophisticated fuel delivery, and thus also apparenly less-polluting ones at normal conditions, are more susceptible to the effects of low ambient temperatures.

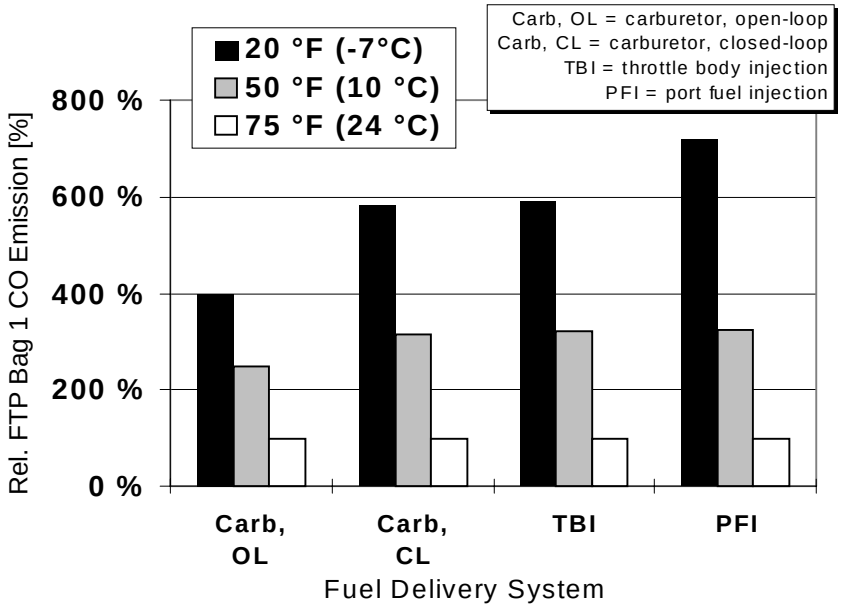

Figure 18 Ambient temperature response as relative CO emissions in FTP Bag 1 for different fuel delivery systems; according to [10].

Therefore, the trend towards lower emissions at normal temperatures does not necessarily mean that low emissions level is attained in cold conditions, as well. However, in case of HC, PFI systems, being the most favoured option in today's TWC cars, seem to have a clear advantage over the more simple fuel metering systems.

Since the cold-temperature CO standard became implemented into the US certification requirements, the EPA has not reported any special case studies.
Although the certification values could be used to assess the performance of the current model year vehicles, such studies have not, at least to the author's knowledge, been published.

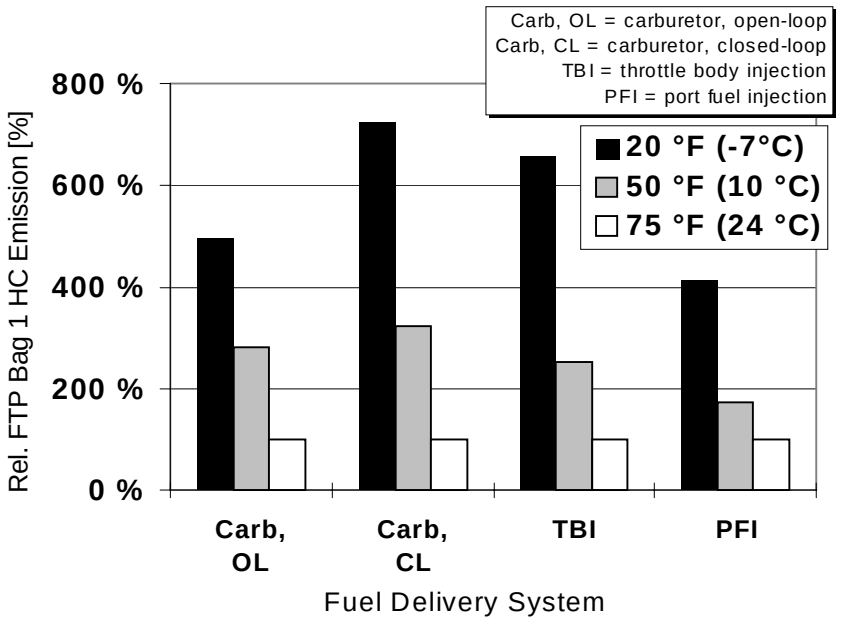

Figure 19 Ambient temperature response as relative HC emissions in FTP Bag 1 for different fuel delivery systems; according to [10].

2.4.3 VROM/TNO Studies

Of the latest studies on the subject, worth mentioning is also work funded by the Dutch Ministry of the Environment (VROM) and carried out at the TNO institute in the Netherlands. Results of this work have been reported by Rijekboer et Havenith in [21]. Their work has, together with the co-Nordic studies discussed in this report, provided basic data on the cold-start emissions performance of European vehicles using European driving schedule. Furthermore, it has in many ways laid down the fundamentals for the European deliberations for cold-temperature standard and test procedure (see 2.2.2).

Significant part of the work is summarized in Figure 20, which shows CO, HC and NO_X emissions as a function of ambient temperature for a large number of petrol fuelled vehicles measured in connection with the Dutch in-use compliance programme. In these tests the European urban driving cycle, i.e. ECE15 cycle was used. As the graphs show, CO and HC emissions seem to increase with falling ambient temperature at almost the same magnitude. About fivefold emissions are measured at 0 °C, compared with the level reached in the normal ambient temperature range, i.e. above +20 °C. This is in about the same order of magnitude that previous studies, using FTP75 driving cycle, have reported. Furthermore, the study did not find NO_X emissions to be affected, overall, by the ambient conditions.

The Dutch study included also some preliminary work on the possible technologies to control the excess emissions due to the cold-start at low temperature.

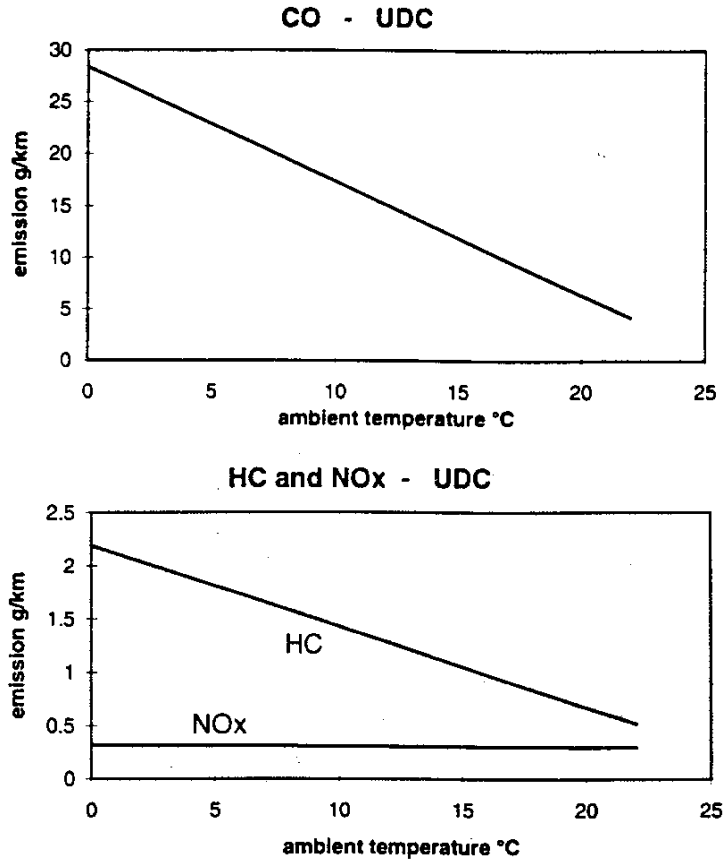

Figure 20 CO, HC and N0$_x$ emissions as a function of ambient temperature in a fleet of Dutch vehicles [21].

The options explored were secondary air injection (SAI), warming-up the intake air by thermally controlled resistor (PTC) and a heat accumulator (*see 3.2.6 for further details*), which warms-up the engine coolant. Figure 21 gives results for these tested options at -7 °C.

As seen in Figure 21, intake air heating was the most efficient option, but the heat accumulator was almost as efficient. Furthermore, secondary air injection showed on both vehicles quite good HC control, but much poorer CO performance as the warm-up devices.

2.4.4 Other European Studies

Two recent studies on the subject have been published in 1997. Swedish work on the effect of preheating was reported in [22] (see also 4.6.3). It was the last update in the long line of Swedish research work previously described, e.g. in [23] and [24].

The subject has been evaluated and judged to be significant even in Poland. This work was reported in [25] with some experimental results of Polish cars.

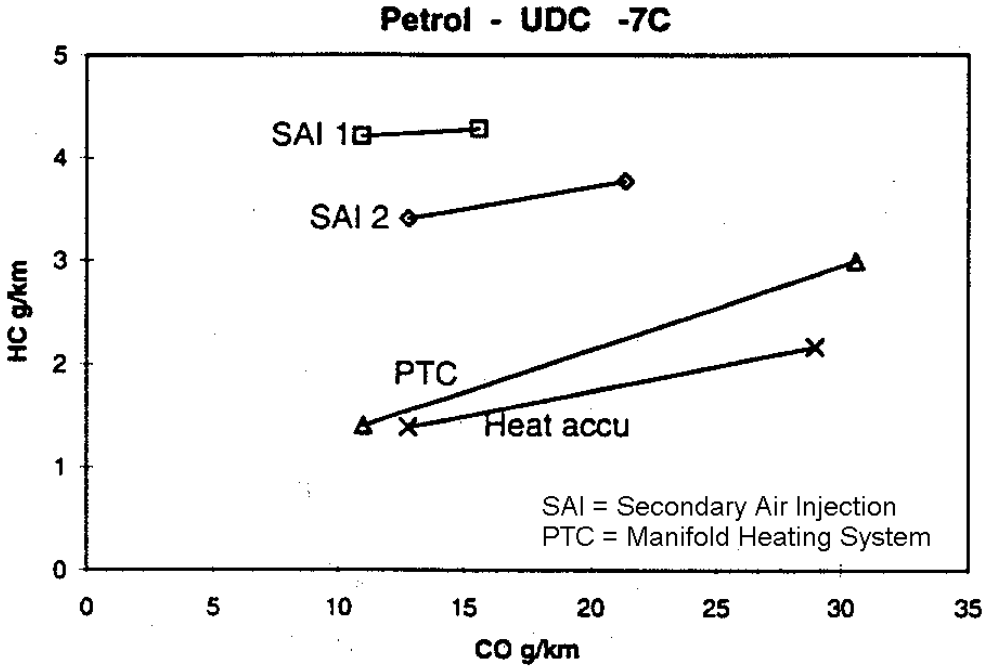

Figure 21 CO and HC emissions at 7 °C for cars using different cold-start emissions ambatement technologies [21].

3 OUTLOOK TO THE LEGISLATION AND EMISSION CONTROL TECHNOLOGY

3.1 SPECIAL REQUIREMENTS FOR EMISSION PERFORMANCE AT LOW AMBIENT TEMPERATURES

3.1.1 The role of test procedure and ambient conditions

Since the early days of emission regulation, the setting of a standard for any exhaust constituent has always been accompanied with a well-defined description, how this emission is to be measured. Like in any game with rules, it was also soon realized that these regulatory requirements and good performance in the normative tests will become the primary target for the design. Therefore, these test procedures should be related to the actual conditions of vehicle use as closely as possible. However, since the conditions and manners of vehicle use are so varied, the tests could only include a narrow subset of all the real-world options. Furthermore, because the whole legislative process has been an evolutive one, all the subsequent procedures have in test conditions copied or at least closely followed the guidelines set by their first incarnation, the Californian rules announced in 1964.

Driving patterns, which describe how the vehicle is to be operated during an emissions test, have been revised and updated many times to better reflect the traffic conditions of the particular era, area or market, where the regulations are intended to be implemented. However, test conditions, like the range of ambient temperature in which the tests are performed, have remained more or less the same. The problem was not so evident in the early ages of catalyst-equipped cars, because they were at first mainly used in areas with warm or mild climatic conditions, where the warm up was fast enough and system performance was deemed acceptable.

Only recently separate procedures to address emissions performance at lower temperatures than the traditional lower bound of the normative conditions (+20 °C) has been introduced, at first in the United States (of America) and now in the European Union, as well.

These low-temperature tests have become necessary, because typical real-world ambient temperatures prevailing in countries, where cars with catalytic emission control are used today, are well below this range defined in the regulations. Furthermore, research work around the world has shown that in most of the countries substantial part of the total distance travelled with passenger cars is accumulated from very short trips. In such conditions, the engine and its associated emission control systems operate most of their total usage time below the

normal running temperature. This will lead to inferior emissions performance, because notwhitstanding its high efficiency in fully warmed-up mode, the operation of a catalytic converter is highly dependent on temperature and exhaust composition.

3.1.2 United States (of America)

This inadequacy was first recognized in the early studies [2] ... [9], made in the United States, and later ascertained by the US EPA in their large-scale investigation in the late 1980's [10]. This study, which results were already reviewed in detail in 2.3, was spurred by the fact that notwhitstanding the wide use of catalytic converters, the ambient air quality standard for carbon monoxide (CO) was almost constantly violated in the wintertime on areas with a cold climate. A valid distrust was, therefore, placed upon the effectiveness of the legislation to control real-world emissions, and pressure began raising towards altering test procedures, either by lowering the traditional temperature range, or better yet, by defining a separate low-temperature test.

Subsequently, the outcome of this study led the EPA to amend the Federal certification procedures in 1992 to include a separate, low ambient temperature cold-start test performed at 20 °F (app. -7 °C) with a limit value for CO emission (10 g/mile = 6.2 g/km). This addition [26] to the type approval requirements, applicable to all petrol-fuelled light-duty vehicles, has already been fully phased in. It started from a 40 % compliance for model year 1994 and went on to a 60 % coverage for 1995, with full 100 % implementation for model years 1996 vehicles, both passenger cars and light-duty trucks.

3.1.3 Sweden

From the European countries Sweden is presently the only one that has any special requirements for low-temperature emissions performance. Although Sweden is currently a member of the European Union and, therefore, compelled to follow the EU directives in matters like emissions regulations, it has a special scheme for environmental classification of motor vehicles (and fuels, as well) that contain extra requirements. Normal vehicles complying with the current directives are in environmental class 3 (C.3). In addition, there are two voluntary classes, C.2 and C.1. For passenger cars (L1 vehicles), C.2 is based on current US standards for model year 1994. The most stringent class (C.1) is essentially the same as Californian TLEV standard, but includes even the aforementioned US Federal requirement for cold-temperature CO, being 10 g/mile in an FTP75 test at 20 °F. This has been translated to 6.2 g/km at -7 °C in SI units. A somewhat more relaxed standard (7.5 g/km) for cold-temperature CO is, however, applied to light-duty trucks and vans in environmental class 1 (L2 and L3 vehicles).

3.1.4 European Union

Even in Europe, the adverse effect of cold start and low operating temperatures on the performance of current emission control systems has been recognized. Valid distrust was placed upon the effectiveness of the legislation to control real-world emissions, because areas of a cold climate include not only the Nordic countries but other areas, as well. Meteorological statistics show that beyond northern Europe, temperatures below 0 °C prevail frequently from December to February also in a fairly large area including Germany, Eastern Europe and the alpine regions of Austria, Switzerland, Italy and France.

Discussions about the role of low ambient temperature and the possible option of defining an additional low temperature test started in Europe almost concurrently with the introduction of the aforementioned US procedures. This debate underwent within the framework of both of the bodies responsible for the evolution of European emission regulations, these being the Group of Rapporteurs on Pollution and Energy (GRPE) of the Working Part 29 (WP.29), set up under the Inland Transport Committee (ITC) of UN/ECE, and the Motor Vehicle Emissions Group (MVEG), the ad hoc working group of the European Commission on the subject of motor vehicle emissions.

Governmental expert groups in Sweden, Finland and the Netherlands, as well as the automotive industry through its collaborative organization (ACEA) have all been working to produce data on which the test procedure and prospective standards could be based. As a result of this, by the end of year 1995, a draft of a cold temperature (-7 °C) test procedure was developed, and the discussion of emission standards was initiated.

However, in the assessment of the goals and key issues for future emission standards within the European Community, the priority level of cold ambient test and standard was lowered. This target-setting, which was primarily based on the modelling studies of ambient air quality in some major European cities[1] performed as part of the European Auto/Oil[2] -research initiative, did not present the effect of cold-starts as relevant. Mainly, because at low temperatures, the emissions of CO and HC are increased, which combination did not seem to have any critical influence on air quality in these cities. Moreover, emissions of HC and NO_x in high temperatures together with the high-intensity UV radiation conditions were identified as the core of the pollution problem. These, as is well known, are the main precursors for ozone (O_3), which was the critical pollutant in most of the

[1] Athens, Milan, Lyon, Madrid, London, Cologne, The Hague.

[2] Cooperative research initiative between the Commission of the European Union and the European automotive and oil industry.

urban environments within the chosen control group. Therefore, the issue of cold-testing assumed a much lower priority level in the agenda. Eventually, the initiative of a low-temperature test was not included at all in the European Commission's proposal for future emission standards for passenger cars submitted to the Council in June 1996.

Notwhitstanding, immediately following this decision, speculations arose, that if any of the capitals of the Nordic countries had been among the group, the result would probably have been slightly different, as the basis of introducing the American cold-temperature test was the EPA study showing abnormally high ambient CO levels encountered in many US cities that have "real winter weather", like Denver in Colorado. This happened, though nearly all cars on the road in North-America are catalyst-equipped.

Furthermore, the matter was reinstated by the initiatives from some member countries in the Council's Environment Working Group during the preliminary discussions for the upcoming Parliament review. The debate was backed-up by further contributions from these member states showing that if the case was not for CO, the adverse effect of low ambient temperature to the emissions of unburnt hydrocarbons would seriously affect urban air quality. In addition, it was ascertained by the same parties that the inclusion of a low-temperature test with limit values for HC, would be a cost-effective measure towards lowering the hydrocarbon emission over the whole European Union, not just in the northern member states. The effect of such a procedure with appropriate limit values was estimated to be equal to the effect of the new limit values set for the normal ambient conditions.

The matter then underwent serious discussion during the winter and spring of 1997 in the Environment Working Group of the Council. As a final result in the meeting at the end of June 1997, a Common Position between the Council and the Commission was reached to include separate low-temperature test and performance requirements in the upcoming amendment of the directive 70/220/EEC. The matter is, however, still under Parliaments review, and because sufficient lead time is necessary for the inclusion of such a major entry, decisions are pending, whether these regulations will become effective for the year 2000, or are their implementation postponed to the year 2002.

3.2 SHORT REVIEW OF THE LATEST EMISSION CONTROL TECHNOLOGY

3.2.1 General Target-setting

The target-setting for the design and performance of systems and devices used for emission control is generally based on the emission standards of the regulations

applicable to that area, where the vehicle is expected to be marketed. As already mentioned, the most challenging of present-day regulations are the Californian Low-emission vehicle standards. However, the Californian market is only some 10 % of the total world market, even if it is by far the greatest one of any of the US states. Therefore, the US EPA's recent initiative, the National Low-Emission Vehicle Program, announced in June 1997, is creating a much-welcomed widening of that market. Furthermore, Step III of the regulations in the European Union more or less equals both of these US programmess in stringency (*see Appendix 1 for details*). Therefore, it will again vastly add market size and leverage for such low-emission passenger cars and other light-duty motor vehicles in the beginning of the next millennium. Manufacturers are evidently taking note on that and are outlining their strategies and designing their future emission control systems keeping the Californian LEV regulations very much as their primary target.

Based on even the near-future standards and test procedure modifications presented in the aforementioned chapter, it has become apparent that the basic three-way catalyst system with a single catalytic converter and the closed- loop control of the air-to-fuel ratio with an oxygen sensor and electronic fuel injection will no more be sufficient to meet future demands. This is even more true, if testing in lower ambient temperatures is added into the list of certification and type approval requirements. Therefore, the main emphasis for future applications lies in very quick and effective operation of the emission control systems right after a cold-start. This is the case, as most of the emissions, especially hydrocarbons, are released during the first few minutes, when the converter bed temperature is low and the exhaust composition is imbalanced regarding effective three-way catalyst operation. New technologies or modification to those already employed are, therefore, called for, and already a number of technologies have been proposed, which were claimed to offset most of the cold-start effect. However, these were mainly targeted to meet the ultra-low hydrocarbon emission standards in normal ambient conditions, and not necessarily to curb emissions occurring after a "real" cold start at a low, subzero ambient temperature. In the following section, some of these technologies will be discussed, and their relevance to lower also subzero cold-start emissions shall be estimated.

3.2.2 Light-off converters and close-coupled systems

Traditional design, at least in a typical European small and medium-sized car, has been a single catalytic converter in an underfloor position replacing conveniently at the same time one of the exhaust silencers. This layout, however, places the converter rather far away from the engine, which is the heat source to use for heat-up the catalyst under warm-up drive after a cold-start. Therefore, if rapid heat-up is sought, a new layout is proposed involving a small-size preconverter, usually referred as "light-off converter", close to the engine or even in the exhaust

manifold and a normal main unit in traditional, underfloor position. This is not a totally novel idea, but has been used by some of the manufacturers for a few years already. It is, however, most likely that the concept will gain much wider use in the near future. Alternatively, a single main converter may be positioned very close to the engine, in a layout called “close-coupling”, for more rapid heat-up. This scheme is expected to be especially favoured among small cars. Figure 22 illustrates these different lay-out schemes.

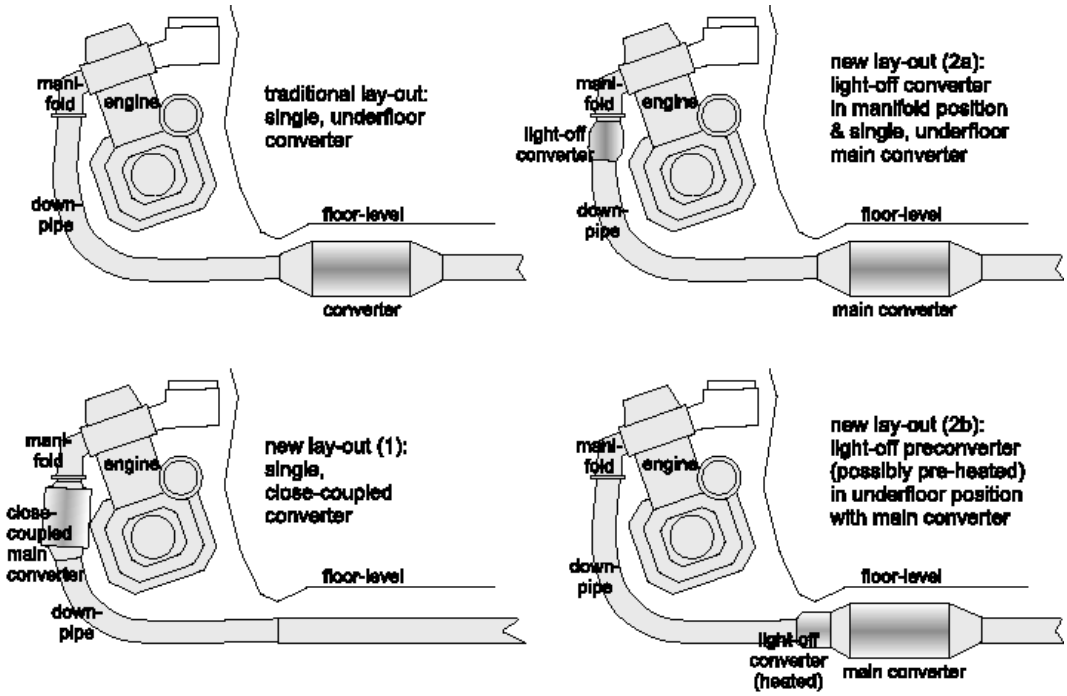

Figure 22 Optional lay-outs for advanced catalytic converter placement.

The hydrocarbon conversion, especially, will be enhanced, as a small, rapidly heating light-off converter will react quickly and start the conversion soon after the start-up. These oxidizing reactions are exothermic and, in addition to curbing harmful emissions, they will produce even more heat to warm-up the main converter. As the light-off converters are mostly used for oxidation, their favoured catalyst composition is based on palladium (Pd), as it has lower light-off temperature than platinum (Pt) [27], the oxidizing catalyst mostly used in present-day three-way converters. Furthermore, Pd has better heat resistance than Pt. This is most important, because in this kind of position, very close to the engine, exhaust temperatures can be extremely high from time to time deteriorating converter performance rapidly, if the construction is not sufficiently heat-resistant.

For the same reason metallic substrates, though they have very low thermal capacity and are thus suitable for fast heat-up, are not especially attractive in light-off or close-coupled converter applications, unless a special alloy and washcoat can be formulated [15], [16]. On the other hand, making thin-wall ceramic

honeycomb substrates that would have the same kind of characteristics as the metallic ones in terms of back pressure and thermal capacity, is not an easy task either, based on the volume of recent literature on the subject, e.g. [28] - [33].

3.2.3 Heated converters

If close-coupling the main unit or adding a preconverter is not effective enough for rapid heat-up, using a (pre)heated converter would become necessary. Several options for heat input have been listed in the literature [34] - [36] ranging from electric resistors to fuel-fired heating. Figure 23, derived from the literature [34], illustrates three main principles.

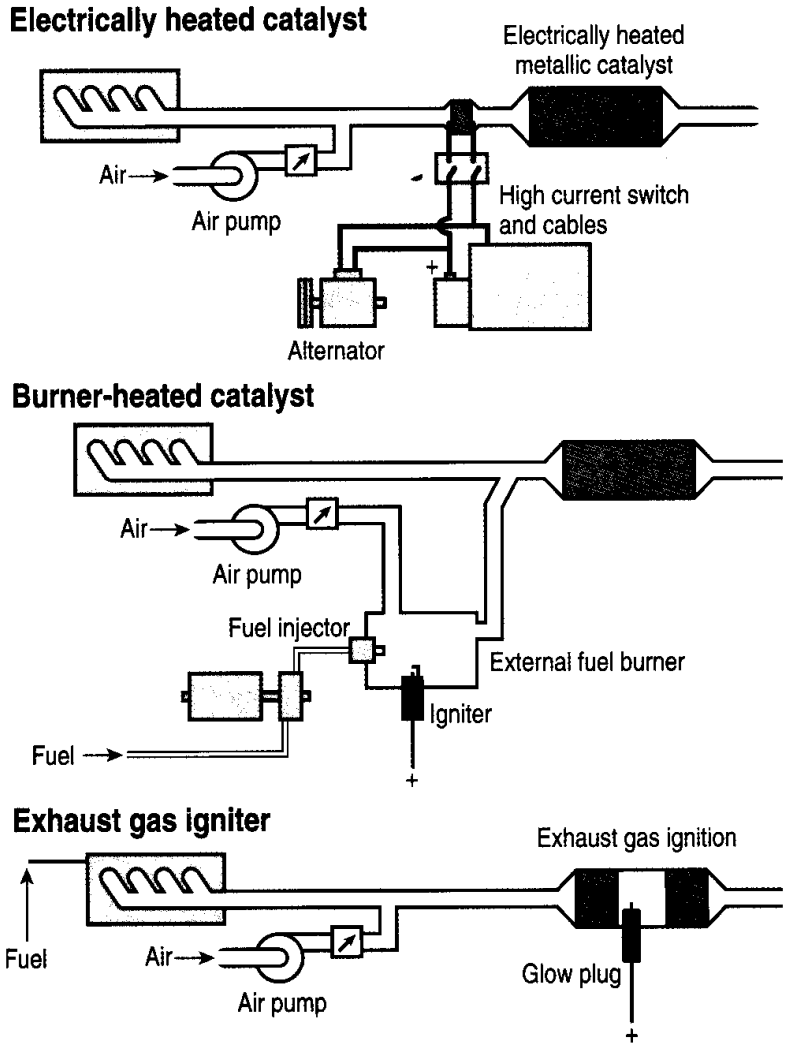

Figure 23 Schematics of the main principles of converter heating [34].

The heating can raise the bed temperature to the light-off level right after the cold-start, or even before, if preheating is used. In laboratory tests like those reported in [34] - [45], most of these systems seemed to work quite well producing very low emission levels.

Figure 24 An example of an electrically heated (pre)converter (Source: Corning Inc.)

Even their initially very high energy requirement and poor long- term durability has now been brought to acceptable levels, after more than a five- year concentrated R&D effort. Innovative features like automatic triggering of this preheating via a door switch has been introduced, but practical applications to a high-volume production model are still nonexistent. However, so far only a few experimental or small-volume cars are using such systems [46], most notable of them is probably the BMW Alpina B12 [47], [48]. As an example of current-level product design, a photograph of one EHC make is shown in Figure 25 and a schematic repsesentation in Figure 26.

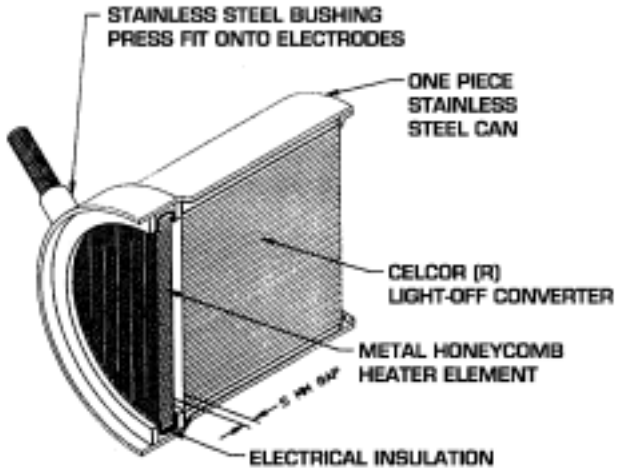

Figure 25 Schematics of an electrically heated (pre)converter (Source: Corning Inc.)

Unfortunately, the impact of and EHC upon "real" cold-starts, i.e. subzero conditions, is limited, as even the most up-to-date designs are still using so much power that their use may endanger the start of the vehicle in low ambient temperature conditions. Thus they are often made inoperative in sub-zero starts [48].

3.2.4 Other means to fast catalyst warm-up

Apart from these exotic apparel, more simple and straightforward (and thus also less costly) methods like using an air-gap insulated, thin and double-wall design in the exhaust manifold (see Figure 26) or retarding ignition and concurrently enriching air-fuel mixture has also been contemplated. The first one will help to decrease heat losses and the latter will increase the heat input into the catalyst.

Consequently, as the literature describes [49], [50], many of these items have already been taken into production, as well, especially in very large displacement engine/converter applications. They are most effective in connection with an auxiliary air-pump supplying air into the manifold (or into the preconverter), thus enabling oxidizing reactions to start as soon as the converter reaches light-off temperature, even if the exhaust composition is heavily offset due to the fuel-rich air-to-fuel ratio (AFR). The use of such supplemental air injection must, however, be terminated as soon as the engine starts to warm up and stoichiometric AFR operation mode can be attained. Otherwise, the excess oxygen will derate the conversion of nitrogen oxides to an almost nonexistent level.

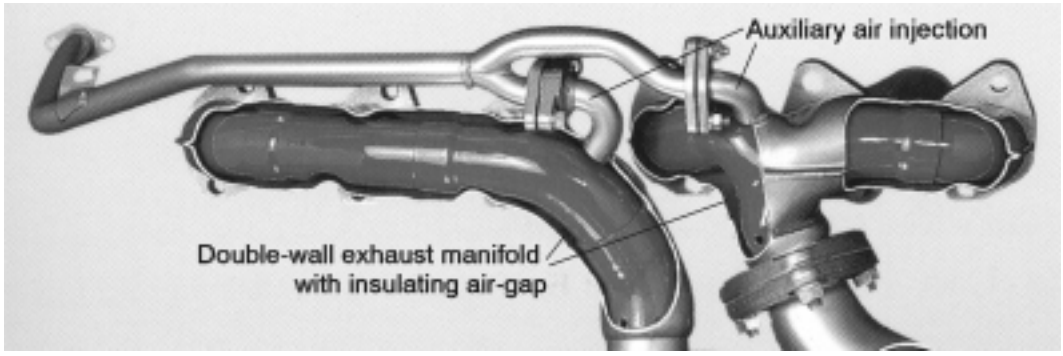

Figure 26 Double-wall exhaust manifold construction with air-gap insulation and auxiliary air input pipes (Source: Boysen AG).

3.2.5 Hydrocarbon trap systems

A totally different strategy to the auxiliary heating to provide quick converter operation was chosen, when a fairly novel concept was introduced specifically for hydrocarbon emission control. It is a device that could trap the unburned hydrocarbons so abundantly present in cold exhaust gases and delay their entry to the catalytic reactor, before it has reached its normal operating temperatures and could not convert them efficiently. At first, this kind of concept became available as parallel bypass systems, through which the low-temperature exhaust gases were routed for the first few minutes after a cold-start [51] - [53]. Later the concept matured to a device often referred with the abbreviation “ILA” (in-line adsorber), employing the same basic principle, but with much more simple construction and lessened complexity.

In its current form described in the literature, e.g. [54] - [57], ILA’s are composed from some zeolite-based adsorber material and centrally connected to a dual-brick

main catalytic converter unit. Figure 27 presents a schematical lay-out of such a system and its operation.

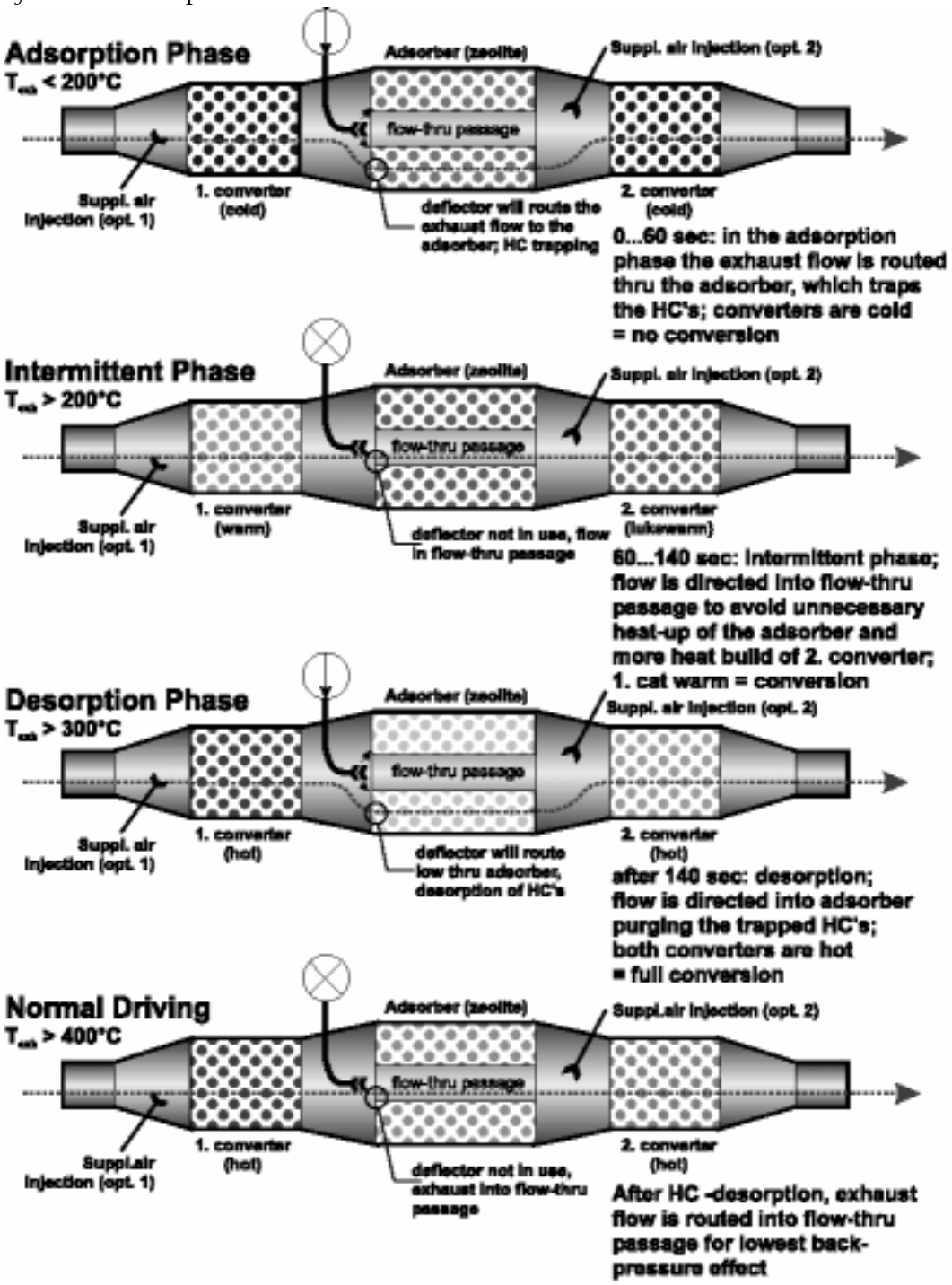

Figure 27 Schematic lay-out and operation of an in-line hydrocarbon adsorber unit.

As seen in the figure, after a cold start, when additional hydrocarbon emission control is needed, a simple but effective device called flow deflector routes the

cold (below 250 °C) exhaust gases through the adsorber material, which will trap them. Then, in a short while, when the exhaust temperature has risen and HC concentration has been subsequently decreased because of the phasing-out of the enrichment and warming-up of the front converter, the deflector is turned off and the exhaust gases are flowing freely through the passage in the adsorber heating up the latter converter, but not unduly heating up the adsorber. Not before the second converter is fully heated, will the deflector be switched on again, letting the warm exhaust gases to flow through the adsorber material and subsequently purge all the trapped hydrocarbons. In this phase, conversion reactions can be enhanced via injecting supplemental air prior to the second converter.

This air supply must, though, be turned off as soon as the trap has been purged and the engine can be run on stoichiometric AFR. With this kind of two brick construction, this cut off is, however, less critical as with single TWC converter, because the front converter, if formulated with TWC capabilities, can maintain reduction even if the second part is in oxygen-rich state. Unnecessary and unwanted NO $\rightarrow$ NO_2 oxidation may result, though, in the second converter and, therefore, shutting of the supplemental air as quickly as possible is highly advisable.

3.2.6 Engine preheating

The effects of preheating

Another method to lower cold-start emissions, is engine preheating. According to [22] - [24] and [58] - [68] it may even be the most efficient. Notwhitstanding what type of preheating is used, less enrichment is needed, if the engine has been warmed-up prior to the cold-start. Thus, CO emissions are subsequently lowered. Warmed-up engines produce also less unburnt HC emission, because of the leaner mixture setting and lower condensation losses. Furthermore, because a preheated engine reaches its operating temperatures much quicker than a non-heated one, stoichiometric operation can be engaged sooner, with due effect on converter performance.

Quite a comprehensive study on the merits (and possible demerits) of engine pre-heating to the exhaust emissions and fuel consumption is presented in [22]. The author has also reported some results from tests with an electrical block heater in [66]. Furthermore, the use of latent heat battery has also been investigated by the author at VTT Energy [67] and in other institutes, as well [64]. According to these reports, both of these heating systems are able to lower the excess CO and HC emissions at cold starts by some 40 to 80%, depending on ambient temperature and vehicle technology.

Electrical and other preheaters

The use of an electrical block heater is widespread in Nordic countries like Sweden and Finland. A recent study [58] has shown that, e.g. in Finland, more than 90% of the cars are equipped with one. However, their use is not that common, as the motorist is required to plug the heater each time he parks the car. This can sometimes be too much of a burden, as today's cars do start-up quite easily even without the preheating, which was not the case about a decade ago, when the heater was the only way to get the engine started at -20 °C or below. Furthermore, network outlets are not available everywhere, although many car owners have one at least at home. Fuel-fired heaters are perhaps most convenient, and operate quite transparently anywhere, but they are much more expensive than the simple electric devices.

Heat batteries

In the beginning of the 1990's, a novel system for engine preheating was introduced [59]. It was called latent heat storage, but it was also known as "heat battery". It was a device that stores the heat from the coolant to be used in the subsequent cold start. Therefore, it could operate totally transparently to the driver and without any external energy supply.

The first generation of heat batteries were true latent heat storage, saving the heat energy into a suitable media (e.g. barium hydroxide salt) while the engine itself cooled down. The heat was caught in the latent heat needed for melting of this salt, and released during recrystallization, when the cold coolant entered the heat storage. Thus the coolant was quickly warmed-up and was fed back with a small pump into the engine, which in a very short while (30 to 60 seconds) could then be started with much more warmed-up state.

No separate valves or by-bass passages to control the flow were needed in this system design, illustrated in Figure 28. This was due to the fact that after the heat stored in the salt had been released in the recrystallization process, the salt remained in a solid state until the coolant again reached the melting temperature of the media, which, e.g. for a barium hydroxide is 78 °C. Therefore, diverting the coolant flow to pass the heat storage was not necessary, as it did not slow down the warm up of the coolant during the initial stages of driving until near-normal operating temperatures were reached. (Depending on the engine, target value for coolant temperature is usually somewhere between 80 to 90 °C). The technology of this device and its use are further discussed also in [60] - [63].

However, due to the difficulties encountered during the field trials, this design was later abandoned, and a new design was created. The durability of the heat exchanger containing the salt seemed to be the core of the problem. Breakages in

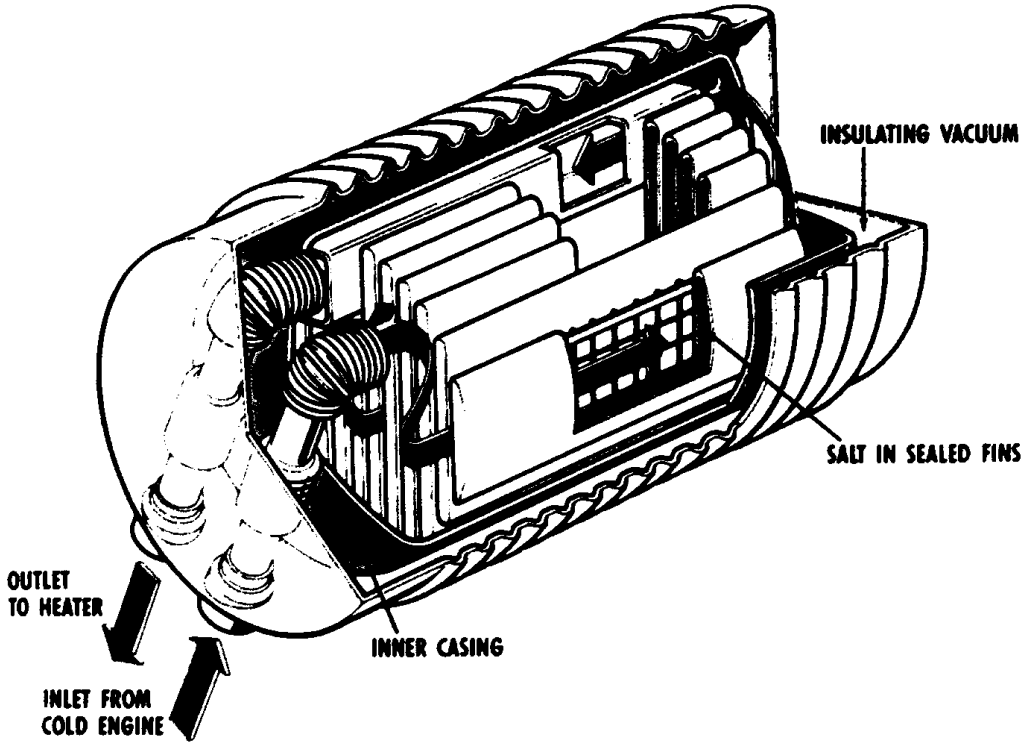

Figure 28 Latent heat storage device for engine preheating prior to a coldstart [61].

the seams of these stainless steel casings occurred, letting the hydroxide salt leak into the cooling system, where it attacked quite aggressively all aluminium parts, which are plentiful in today's cars.

Therefore, the new design, described, e.g. in [64], is now devoid of the salt and consists only of a simple well-isolated holder for coolant to keep it warm enough for a later restart. Valves, controlled by thermostats, let the hot coolant flow into the storage, when the engine is shut down. In the event of a cold start, valves are opened and by the assistance of a small circulating pump, the engine block is primed with warm coolant. Simultaneously, same amount of cold coolant is taken in. Thus, the coolant capacity needs effectively to be doubled in the presence of such a system. After this exchange, which takes about 30 seconds, the valves are shut, and the engine can be started in a considerably warmed-up state. The heat output can be up to 2.16 MWs (600 Wh), released in just a couple of minutes, which equals the effect of the use of a normal electrical block heater for about one hour.

In spite of its merits, this new system has not yet reached any widespread use. Apart from some cost issues, underhood space constraints that limit the installation in many of the modern cars are perhaps the weakest points at the moment. However, these can be avoided, if the designer accounts room for the system already at the initial stages of the design. In this manner BMW has managed to fit it in and is, as the first OEM, offering the heat battery as an option for a series-produced car, the new 500 series [65].

4 OUTLINE OF THE EXPERIMENTAL WORK

4.1 BACKGROUND AND TARGET-SETTING

The initial research already discussed in Chapter 2 has proved that the effective operation of the emission control devices is mainly attributed only to the conditions characterized by the legislation. This means that, aside some exceptions, ambient temperatures below +20 °C are not accounted for. However, conclusive evidence combining actual meteorological data and results from different traffic surveys around the world points out that substantial part of the actual driving is derived from other kind of situations and ambient conditions than those described by the regulations. Therefore, a disagreement between the real-life driving conditions and those designated in the emissions regulation exists. Furthermore, it has its implications to the alleged problems associated with the use of cars equipped with three-way catalytic emission control in low ambient temperature conditions.

Against this background a mission was initiated by VTT in 1985 to assess the emissions performance of current-technology vehicles in real-world ambient temperatures, especially those in the sub-zero range prevailing in the Nordic countries over the winter months. This testing of emissions behaviour beyond the normative conditions was judged necessary, because at that time Finland was, along with the other EFTA countries, contemplating the implementation of an emission legislation similar to that of the United States, which would mean that all new cars would be equipped with catalytic converters. Should this technology fail to work efficiently in cold conditions, the act would be highly uneconomical and no real-world emission reductions would be expected. Earlier work, which was discussed in Chapter 2, was deemed non-representative in the European context, because it has dealt only with cars designed for the North-American market.

The experiments described in this report are a part of that mission, comprising sub-studies of aspects felt to have importance in terms of either causing high amounts of emissions or affecting to the performance of a typical design. In addition, to be able to more accurately determine the inventories of different air polluting emissions contained in vehicle exhaust gases, as well as to target the future emission control initiatives more cost-effectively to address specifically the major sources of the emissions, the measurement of emissions performance of current technology vehicles was taken beyond the regulatory components.

4.2 MAIN OBJECTIVES

Based on the basic problems identified in previous chapters, the main objectives of the work described here were set to be:

1) to address different aspects of the emissions performance of petrol-fuelled passenger cars representing present-day emission control technology in low ambient temperature conditions.

2) to make an attempt to constitute average emission rates for some specific air polluting compounds as a function of ambient temperature in a fleet of typical present-day TWC cars.

These studies entailed the assessment of the effect of following main parameters presumed to affect emissions performance:

- vehicle and emission control system design
- ambient temperature level
- vehicle mileage.

The secondary task of the work extended the measurement of emissions from current-technology vehicles also well beyond the regulatory test conditions and components. The emissions that were determined, included the regulated compounds

- Carbon monoxide (CO)
- unburnt Hydrocarbons (HC)
- oxides of Nitrogen (NO_X).

but in addition, also some unregulated compounds, i.e. those not (yet) having specific limit values set by the legislation, were measured. This group consisted of the following species:

- Nitrous oxide (N_2O)
- Ammonia (NH_3)
- Formaldehyde (HCHO)
- specific C_1-C_8 hydrocarbon compounds, including:
  - Methane
  - iso-Butene
  - Ethene
  - 1,3 butadiene
  - Benzene
  - Toluene
  - Xylene (m-, o-, p-Xylenes)
  - Ethyl benzene.

Although public funding and the interest of private enterprises on the subject have been rather high, this kind of research tends to be so expensive that the activities must often be accomplished concurrently or rather on top of other studies having initiatives and main targets other than just low-temperature testing. Fortunately, this has been possible in many cases providing necessary base for some additional work on this particular aspect, but to some extent it has somewhat narrowed the scope of the sub-studies.

4.3 GENERAL DESCRIPTION OF THE SUB-STUDIES

4.3.1 General remarks

The experimental work described in this report was carried out between 1990 and 1997 in five different sub-studies. Each of these studies had their own objectives and target setting to address the problem of low ambient temperatures in different viewpoints. Some of them were specifically initiated for this type of research only, but some were having other main targets. The low-temperature research aspect was only part of a larger exercise. In the following sections and in Table 10, a general description of each of these sub-studies is presented. More details, like actual test programs etc., are given later on in the chapters, where the results are discussed.

4.3.2 Basic study

The basic study was the earliest vehicle study initiated in order to supply information on the general response of cars to low ambient temperature. Excluding a few on-road measurements, all the preceding experiments had been engine-only tests. Since the new cold-test cell became available, a vehicle study was started in spring 1992. Its objective was to compare new technology, catalyst-equipped cars to traditional, non-catalyst cars.

4.3.3 Co-Nordic study

The Co-Nordic study was a joint research effort between VTT Energy and Motortestcenter, a subsidiary of the Swedish Motor Vehicle Inspection Company (AB Svensk Bilprovning). The study was initiated in 1992 by the demand of data on the emissions of current technology cars in low ambient temperature conditions when the European driving cycle was used to assess the performance. Apart from the technology evaluation, the study involved a number of functions related to the test procedures. It was reported in 1994 to GRPE for its deliberations on a European cold-temperature emissions test.

4.3.4 Technology (TM) study

The technology study has been an ongoing, joint effort with the Finnish motor magazine Tekniikan Maailma (TM). The objective has been to assess the emissions performance of new cars in more realistic ambient conditions than those prescribed by the regulations. Each year from 1993 to 1997 a fleet of some six to 17 vehicles, representing the latest model year available, has been tested. This has given a very good opportunity to evaluate the cross-section of the current technology, and track the possible evolution in the cold-start emission performance.

4.3.5 In-use study

The In-use Study was conducted parallel to a project concerning the in-use durability of catalyst cars in normal Finnish driving conditions. The main work was initiated by the Vehicle Administration Agency (Ajoneuvohallintokeskus), and comprised only testing according to the regulatory procedures, i.e. normal temperatures. However, additional low-temperature testing was performed for all the vehicles to study, if the performance of the cars at cold temperatures deteriorated, as well, like in the normal ambient conditions.

4.3.6 Catalyst study

The Catalyst study was targeted towards comparing the performance of different commercial and pre-commercial catalytic converter technologies and formulations at low ambient temperature. The client for this study was KEMIRA Metalkat Oy, a Finnish manufacturer of all-metal catalytic converters. Three different vehicles with their original converter were used for the baseline. A fresh OEM converter and three different precommercial formulations were then compared against this. Both FTP75 and EC cycles were used, and a number of unregulated emissions were measured with on-line equipment (FTIR), as well as with traditional sampling and wet chemistry methods.

Table 10 General description of the sub-studies

Sub-study name	no.of cars	main target	low amb. temps [°C]	non-regs
“Basic Study”	3	compare normal and TWC	-7, -20	n/d
“Co-Nordic Study”	10	performance, test procedure	-7, -20	n/d
“TM Study”	57	new vehicle performance	± 0	n/d
“In-Use Study”	44	in-use performance	-7	FTIR
“Catalyst Study”	3	hydrocarbon speciation	-7	GC

5 OVERVIEW OF THE TEST PROCEDURES USED IN THE EXPERIMENTAL PART

5.1 TEST VEHICLES AND FUELS

Altogether some 120 different passenger cars have been tested in connection to the various subtasks encompassed in this report. All of them were normal, OEM vehicles and most of them were petrol-fuelled and using catalytic emission aftertreatment. The only exception to this rule was one non-catalyst car measured for reference. Table 10 summarizes the overall configuration of the various sub-fleets linked to each task. It also gives an indication, which kind of fuel (commercial grade or reference fuel) was used in each of the specific studies.

Table 11 General description of test vehicles and fuel used in each of the subtasks

Sub-fleet name	no. of cars	model years	fueling
"Basic Study"	3	1990-1992	Comm
"Co-Nordic Study"	10	1993-1994	Test
"Catalyst Study"	3	1994-1995	Test
"TM Study"	57	1993-1997	Comm
"In-Use Study"	44	1990-1996	Test

Abbreviations: Comm = commercialgrade fuel
Test = test fuel complying with CEC RF-08-A-85 specification

Note: Appendix 2 gives some more detailed information of the cars and Appendix 3 of the fuels

The choice of test vehicles was rather arbitrary, and sometimes based only on vehicle availability and not particularly to the technology the car represented. In some of the cases, like with the "In-use Study", the vehicle choice was made by the client, Vehicle Administration Centre (Ajoneuvohallintokeskus), of the underlying project concerning the in-use durability of catalyst cars in normal Finnish driving conditions. However, the choice was made so that on average the cars represent rather well the cross-section of the current Finnish vehicle park. Furthermore, in the "Technology Study" vehicles tested represented always the newest model year, but the sample did not particularly well reflect the average actual sales. Therefore, the average calculated for that model year vehicles could be somewhat biased.

A more detailed description of the vehicles is given in Appendix 2, which lists all the cars included into each sub-fleet and gives some basic technical information of

them including engine displacement, model year, odometer reading, test inertia and general description of the fuel delivery system and emission control devices used in the car.

As seen in Table 11, both commercial grade and specific test fuels were used. As with the cars, the choice of fuel was also based on a rather pragmatic approach, because in most of the cases the main objective of the study was not just testing at low ambient temperatures, but something else, which dictated the fuel choice. However, the experience and some limited testing at VTT Energy suggested that the difference in emissions performance between commercial grade and specific reference fuel was minor in relation to the expected magnitude of the effect from lowering the ambient temperature. In addition, only one fuel, either commercial grade fuel or tes fuel, was used across a specific study. Therefore, results should be well comparable within the study.

Some concern was expressed over the usability of fuels complying with the specifications for normal reference petrol (CEC RF-08-A-85) at low temperatures, because its volatility was lower than the normal range of commercial fuels typical for cold climate use. However, since no particular driveability problems were encountered during testing, results should be valid even in these studies

Actual test programs for each sub-study will be presented in connection with the discussion of the results in the following chapters.

5.2 CONDUCT OF THE TESTS

5.2.1 Driving cycles

The great majority of the tests were carried out using the US FTP75 driving cycles, either in its full length or just the first sub-cycle called “cold transient” (Y_{ct}). However, some tests using the European cycle were made, as well, especially in the context of the Co-Nordic sub-study to evaluate technology and develop the European cold-test procedure. Both of these schedules are illustrated as speed vs. time plots in Figure 29 (for the FTP75) and Figure 30 (for the European Cycle). Table 12 summarizes some of the main characteristics of these cycles.

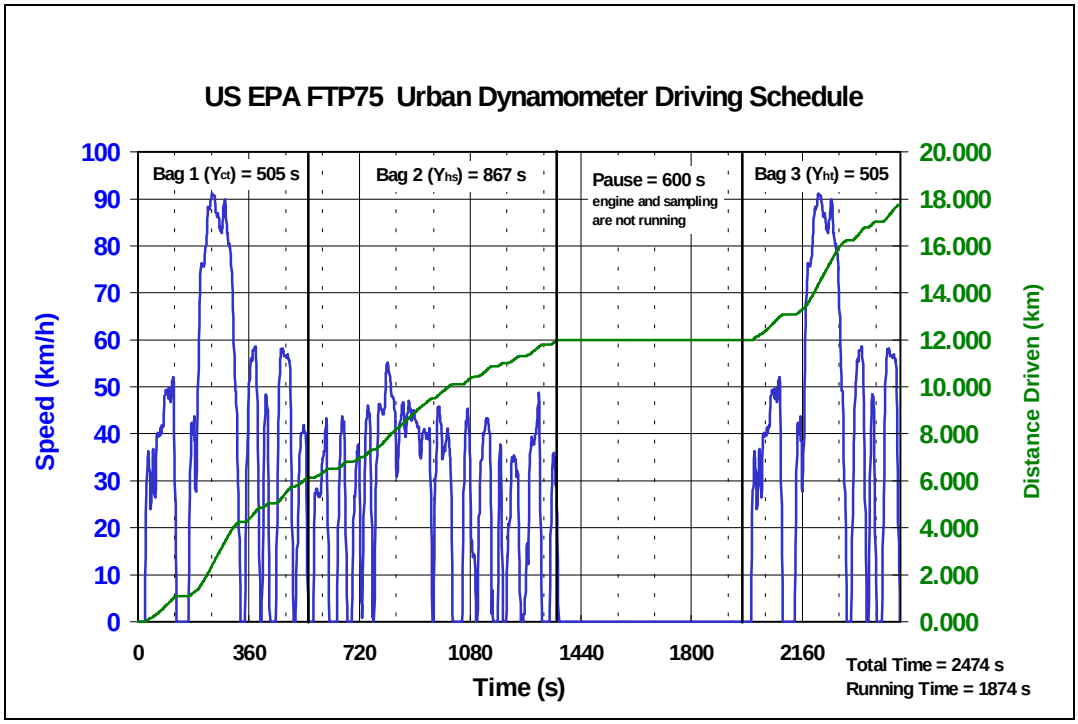

Figure 29 Speed and distance vs. Time in US EPA FTP75 driving schedule.

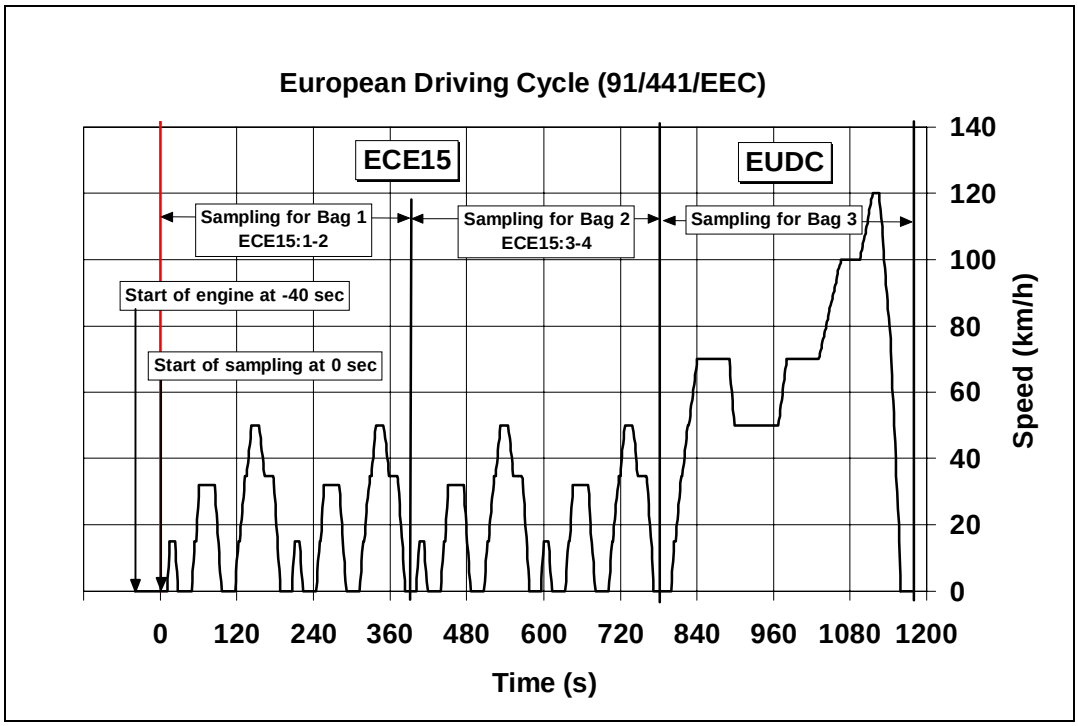

Figure 30 Speed vs. time in the current from of the European driving cycle and the modified exhaust sampling scheme employed in this work.

Table 12 Main characteristics of the european (NEDC) and US FTP75 driving schedules (see Figures 29 and 30)

parameter	Cycle	
	NEDC (ECE15+EUDC)	US EPA FTP75
max. speed (km/h)	50 / 120[1]	91.2
average speed (km/h)	19 / 62.6[1] => 33.8	34.3
total (running) time (s)	780 + 400[1] = 1180	1877 (incl. 600 s pause)
distance travelled	4.052 + 6.955[1] = 11.007	17.84
% idle of total	35.4 / no idle[1] => 23.4	17.3

[1] the first value is for the ECE15 portion and the latter for the EUDC part

5.2.2 General vehicle preparation

As a rule, tests were conducted following the procedures described in the applicable emissions regulations, i.e. the US EPA Federal test procedure[3] or the equivalent European one[4]. This means that the vehicles were normally checked, prepared and preconditioned prior to the testing by driving one full test cycle on the dynamometer. Alternatively, an equivalent road trip of some 20 km in length was made. The choice was based upon the nature of the task and in view of some practical limitations.

The vehicles were then soaked at the test temperature for at least of 12 hours but not usually more than 24 hours, because according to the legislative procedures the maximum soak time is defined to be 36 hours.

5.3 CLIMATIC TEST CHAMBER AND CHASSIS DYNO

All the work described in this report was conveyed in the climatic emissions test cell at VTT Energy in Espoo. This cell has been in operation since 1991 and it is specifically designed for light-duty vehicle emissions and fuel economy testing in low ambient temperature conditions. The cell can maintain ambient temperature in the range from +25 down to -30 °C within ± 1 °C of the set point during soak and actual testing, as well. Figure 31 illustrates the chamber and some of its equipments.

[3] Code of Federal Regulations, Title 40, Part 86, Subpart B

[4] Directive 91/441/EEC, amending Directive 70/220/EEC.

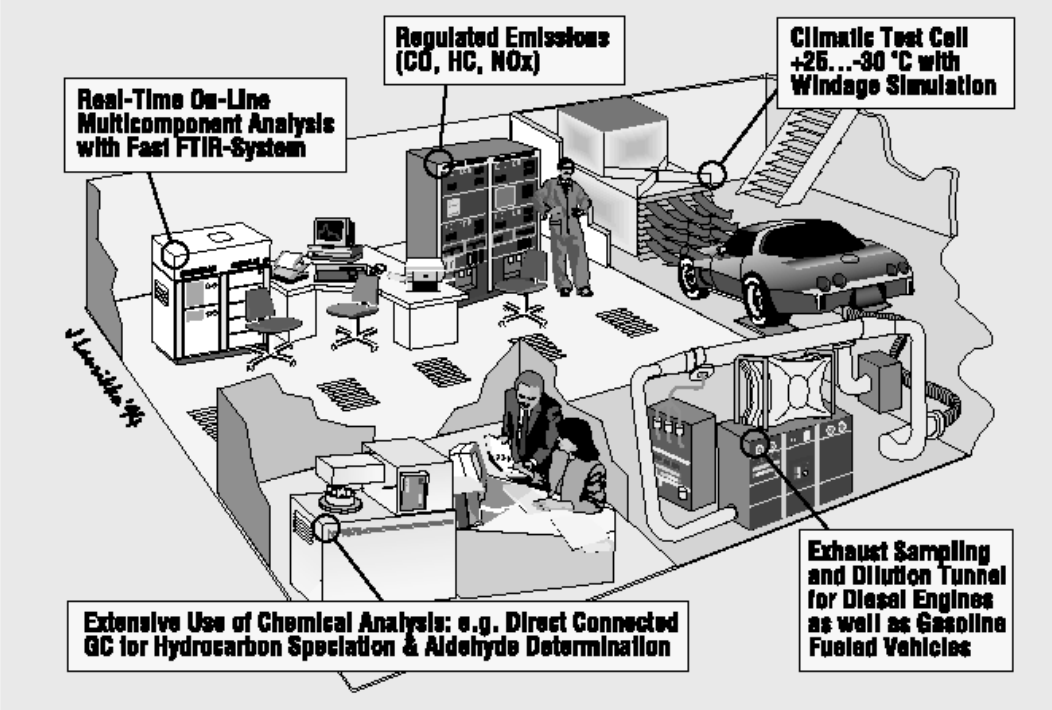

Figure 31 Climatic test facility for light-duty emissions testing at VTT Energy, Espoo.

The test cell has a variable-speed blower (nozzle size 1.2 m x 1.2 m) for windage simulation with the possibility to set the air speed relative to the roller speed up to 100 km/h. However, it was not used in these studies, but the blower was set at constant speed of 25 km/h. This choice was made in view of better comparability of the results with the figures achieved in normal regulatory testing, where only a small, fixed-speed blower is stipulated.

This choice was deemed acceptable, even if the use of a variable-speed blower would have created more real-world representable cooling effect to the engine and emission control devices, which could have had some implications to the results, e.g. to the light-off performance of the catalytic converter. This was expected, because in the most common lay-out, the converter is in an underfloor position and, therefore, susceptible to cooling by the windage caused by the vehicle movement. However, this concern was regarded somewhat speculative, as in a small sub-study involving only one vehicle the use of fixed vs. variable-speed blower was investigated with no apparent upwards or downwards trend in results.

The test facility has a single-roller DC-type chassis dynamometer for road load simulation that conforms with the requirements given in the emission regulations. It is manufactured by Froude-Consine Ltd (UK), and its roller diameter is 1.0 metres. The unit is capable of absorbing power up to 100 kW and the maximum allowable speed is 160 km/h. When the specifications of the facility were laid

down, this kind of a single-roller type of chassis dyno was chosen over the most common twin-roller type, because it allows a single-patch tyre-to-roller contact, which is more realistic and closer to the real-world driving.

This issue was felt to be particularly important, because the cell was mainly targeted to low temperature testing, where the excessive deformation imposed by the two contact patches on cold and stiff tyres would give a raise to irregular parasitic loads and losses that are also dependent on ambient conditions. Since then, single-roller type has become more and more widely used, especially in this kind of temperature-controlled testing, most probably for this kind of reasons. It is also favoured by the US EPA in the specifications for the Cold-Temperature CO testing, which is currently required as part of the certification procedure (*see 2.3.2*).

More details of the test facility with some discussion of the choice and performance of the various subsystem are included in [66].

5.4 EXHAUST SAMPLING PROCEDURES

Exhaust sampling for the determination of the emissions was performed, either continuously from raw exhaust gas directly to the analysers operating on-line, or collecting proportional samples from the air-diluted mixture into tedlar[5] bags for later analysis. The latter practice is the basic procedure in regulatory testing, as well.

To avoid condensation of water or any of the exhaust components, heated sample lines set at 190 ± 5 °C were used in the event of raw gas sampling from the sampling point all the way to the applicable analyser. In the case of bag sampling, however, the dilution with air takes the sample well above the dew point and, therefore, no heating of the sample is necessary, as condensation is not likely.

This exhaust dilution with air, sampling to tedlar bags, as well as the subsequent volume determination was performed with standard-type of CVS (Constant Volume Sampler) device. The unit was of PDP (positive displacement pump) design and had a type code WT 12.5. It was manufactured by Pierburg GmbH (FRG).

A schematic layout of the system is presented in Figure 32.

[5] Trade name for the material.

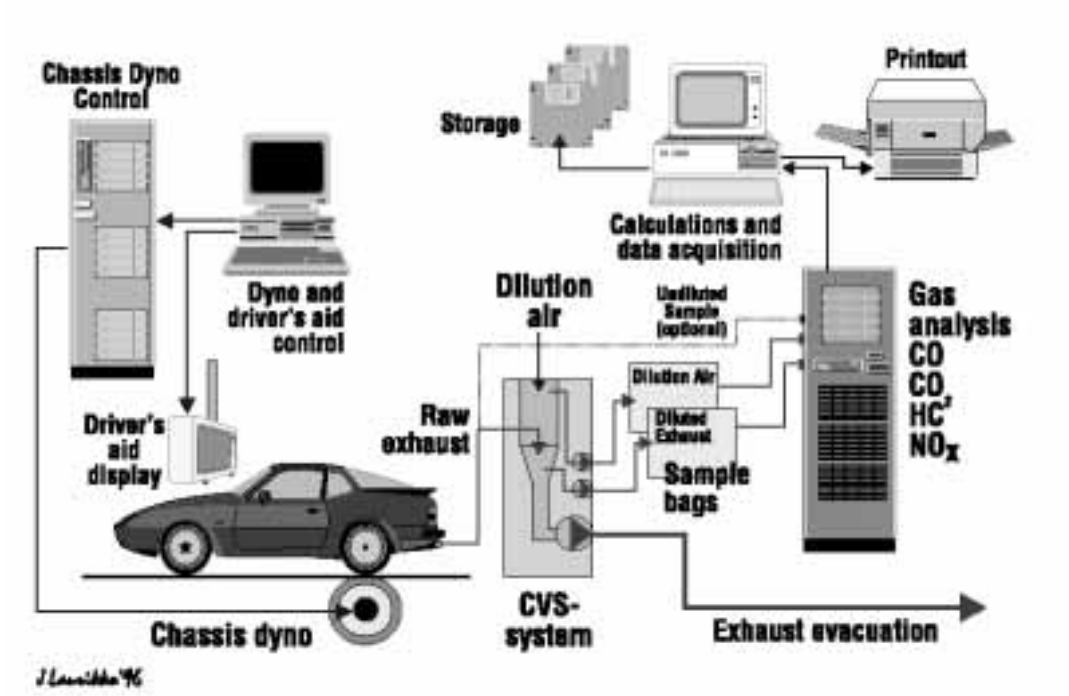

Figure 32 Schematic representation of the measurement set-up for lightduty vehicle exhaust emission determination.

Normally, three bags were collected from one full test cycle. Dividing the test cycle to different sections and corresponding bags gives the possibility to allocate the emissions more accurately to a specific phase of the driving schedule. This is particularly important in the case of low-temperature testing, where high emission rates are expected in the beginning of the test, but much lower rates are accounted later on, when the engine and all the emission control systems have reached their normal temperatures and effective operating ranges.

In the case of the US FTP75 driving cycle, the breakdown of the cycle into three phases and corresponding bags is determined in the rule itself (*see Figure 29*), and this division was used in all the test runs with an FTP75 driving schedule. However, such a definition is not included in the specifications of the European procedure, but only one sample bag is assumed for the whole test. Because of the clear advantages already discussed above, there was a need to use three bags also in connection with the European test cycle. Therefore, a self-imposed choice has to be made, and it was to use the first bag to collect a sample from the start-up to the end of the second ECE15 sub-cycle (*see Figure 30*). The second bag was then derived from the latter two of the ECE15 sub-cycles, and finally, the third one was accumulated from the remaining part of the driving schedule, the extra-urban portion (EUDC).

5.5 ANALYSIS OF REGULATED EMISSIONS

Regulated exhaust emissions are by the definition those that have specific limit values set by the emissions regulations. In case of petrol fuelled cars this means carbon monoxide (CO), unburned hydrocarbons (HC) and oxides of nitrogen (NO + NO_2 = NO_x). However, some specific extensions to this general setting exist. Those are mainly in the US and Californian regulations that determine standards additionally, e.g. for the non-methane portion of total hydrocarbons (NMHC) or for formaldehyde in case of methanol-fuelled vehicles.

Notwhitstanding, in this report the term of regulated emissions is assumed to cover just the most common three compounds, i.e. CO, total HC and NO_X. They were measured along with carbon dioxide (CO_2), which is necessary for the calculation of the mass emissions, using applicable analysers listed in the emissions regulations. Although the regulations and limit values are based on different driving cycles, the analytical side of the determination is identical in all main rules (US, Europe, Japan). Table 10 summarizes these analysers and their operating principles.

Table 13 Summary of the analysers used for determination of the regulated components.

component	analyser operating princple	make and model
carbon monoxide (CO) carbon dioxode (CO_2)	non-dispersive infra-red (NDIR)	Rosemount BINOS 1001
total hydrocarbons (HC)	flame ionization (FID)	Pierburg FID-2000
oxides of nitrogen (NO_X)	chemiluminescense (CLD); (converter to reduce NO_2 ® NO)	Pierburg CLD-2000

The same set of analysers contained in the laboratory's Pierburg AMA2000 emission analysis system, which were used to determine pollutant concentration from bag samples, were used also for the continuous, on-line analysis. This particular AMA2000 system is actually a dual-bench set, comprising two identical sets of analysers for CO, CO_2, total HC and NO_X. This design allows continuous analysis of exhaust concentrations simultaneously form two sample streams. It can be utilized, e.g. for analysing pre- and post-catalyst concentrations and determining instantaneous converter efficiencies. This feature was, indeed, employed in some of the experiments. Furthermore, an additional CO_2 analyser is included in the set for the determination of the CO_2 in the air-diluted sample, which is essential for the calculation of the instantaneous dilution ratio and subsequently, raw exhaust volume, both values needed for the calculation of mass emissions (*see 5.7 and Appendix 4*).

The analysers used in this study conformed all with the regulatory requirement in terms of accuracy, sensitivity and linearity. Furthermore, they were all frequently calibrated with certified standard gas mixtures containing applicable concentrations to the different operating ranges of the analyser. The principles of setting-up and operating the analysers according to the requirements for regulatory emissions-testing is currently laid down in the laboratory's manuals[6], and these practises were followed as a rule in most of the tests. Therefore, quite good comparability to the regulatory test values was achieved.

Because of limited resources within this study, basicly no duplicate or repeated tests has been run, which would have given basis for a direct statistical evaluation. Instead, an estimated margin of error must be used, based on similar type of work. Appendix 5 gives information about the statistical variations encountered within the measurement results at the laboratory. It is used to estimate, what would be the margin of error in the measurements of the regulated emission components in this type of tests.

Based on this analysis, a general estimate was made, that for the results achieved in a FTP75 type of test, the average margin of error for the gaseous emissions would be in the order of ± 6 % of the nominal value. Furthermore, for results in the ECE/NEDC type of tests, slightly less average margin of error could be used. However, there should be no great difference between these procedures. Therefore, a uniform figure of ± 6 % of the nominal value is used as an estimate for the margin of error, and would be used in the evaluation of all the results for regulated gaseous components in this study.

5.6 ANALYSIS OF UNREGULATED EMISSIONS

5.6.1 General definition of unregulated compounds

The exhaust gases contain plenty of chemical components beyond those regulated compounds listed in the previous chapter. These so-called unregulated or non-regulated emissions are mainly specific chemical compounds, many of which have been found responsible for environmental effects such as oxidant formation and greenhouse effects, or for human health effects such as allergies, cancer, etc. As already mentioned, for a few of these constituents, like formaldehyde, emission regulations and limit values have already been adopted in the United States (of America) and State of California, so they can be classified as "semi-regulated" or "pre-regulated".

[6] "Measurement of Regulated Emissions from Light-Duty Vehicles and Light-Duty trucks, FTP and ECE/EEC Tests", M01.01, 14.8.1996.

Some exhaust components have even been singled out also as possible carcinogens, i.e. to induce cancer by exposure over a long time at very low concentrations in ambient air. Among those components is especially benzene, but other hydrocarbon species like ethene, propene, butadiene, formaldehyde, and polycyclic aromatic compounds (PAC) are almost equally susceptible. The most common exhaust oxygenates are formaldehyde, acetaldehyde and acrolein, which also are mutagens (i.e. have genotoxic properties), and even classified as known carcinogens for humans. Furthermore, formaldehyde and acetaldehyde are both highly reactive species under certain atmospheric conditions. Therefore, they are appending considerably to the ozone forming potential of the motor vehicle exhaust emissions.

Among the US EPA's listed mobile source air toxics are: particles, including their associated organic matter, formaldehyde, benzene, 1,3-butadiene and acetaldehyde. There is a large body of data concerning emissions of these air toxics from spark-ignition petrol and heavy-duty diesel engine exhaust, but there is scarcity in measurements of these components from vehicles operating at low ambient temperatures or on alternative fuels. Therefore, the possibility of determining additional, unregulated emissions was considered one of the most valuable assets of VTT's facility having possibilities for such work.

5.6.2 Hydrocarbon speciation

Total hydrocarbon analysis made by a FID-analyser gives just an aggregate sum of all the species contained in the sample. However, according to a literature study [69], specific HC compounds tend to have very different character in terms of effects to human health or the environment. Therefore, knowing the composition of the total HC sum more in detail and the concentrations of those most harmful species[7], would give much additional relevant information in view of, e.g. comparing the performance of different technologies in various operating conditions.

Work towards a dedicated system for the speciation of exhaust hydrocarbons was initiated at VTT Energy in 1991. After an extensive evaluation phase, which involved e.g. the verification of the sampling procedure and choice of colon, the system configuration has been completed.

In its current format this system consists of a dual-channel, high-performance gas chromatograph, Hewlett-Packard HP 5890 Series II connected to a Hewlett-Packard HP 3365 Series II ChemStation computer. The sample is taken directly from the same tedlar bags in the CVS system used for the determination of the

[7] Belonging to the group designated as "Air Toxics" by US EPA

regulated gaseous emissions. With the stable current-technology colons, additional dewatering of the sample is no longer necessary.

Today, as in all measurements discussed in this report, an Al_2O_3/KCl PLOT colon is used for detection of the HC species. The system programme detects automatically 13 of the species deemed to be the most pertinent in this kind of application. Figure 33 gives an example of a test run with the peaks as a function of retention time. It also lists those 13 compounds determined.

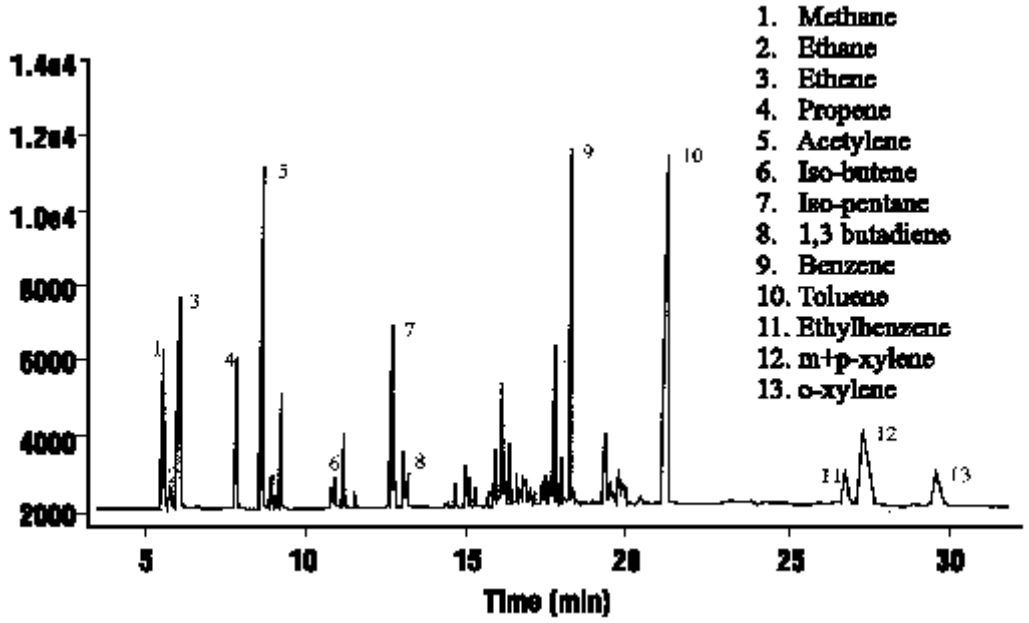

Figure 33 Example of gas chromatograph analysis of the hydrocarbon species from vehicle exhaust and the list of 13 components determined from the sample [69].

A more detailed description of the system and its evolution, including the various evaluation, verification and correlation exercises performed, is given in [69]. As an excerpt from it, Table 14 is presented describing estimates for minimum detectable levels of emissions for some of the hydrocarbon species that shall be discussed later in this work.

Table 14 An estimate for the minimum detectable levels of some selected hydrocarbon species determined at VTT Energy using GC (acc. [69]).

Species	min. detec. level [mg/km]
methane, CH_4	0.1
acetylene, C_2H_2	0.2
ethene, C_2H_4	0.2
1,3 butadiene	0.4
benzene	0.6

5.6.3 Continuous analysis of unregulated compounds with FTIR

In the measurement of unregulated components, the traditional, so called wet chemistry methods, some of which were described in the previous sections, always require separate sampling and elaborate sample handling, if conventional chemical analysis with chromatography (HPLC, GC) and spectrometry (MS) is used. Therefore, the work is both difficult and time consuming. Furthermore, the analysis of any transient phenomena has been very difficult or nearly impossible, because to collect a sample that is adequately large, sampling time is in the order of some minutes, at least. However, a cold-start and the subsequent warm up phases are very transient in their nature. Therefore, a fast real-time breakdown of the exhaust composition would greatly help the engineers in optimizing the operation of the fuel management and emission control system even for the low ambient temperature use.

Fourier transform infrared (FTIR) spectrometers equipped with flow-through gas cells are capable of measuring exhaust gas spectral information rapidly. When connected to a suitable computer, such a system can perform simultaneous multi-component determination in real-time. This technique, which is based on a principle called Michelson interferometer (*see Figure34*), is described in detail in [69] and [70].

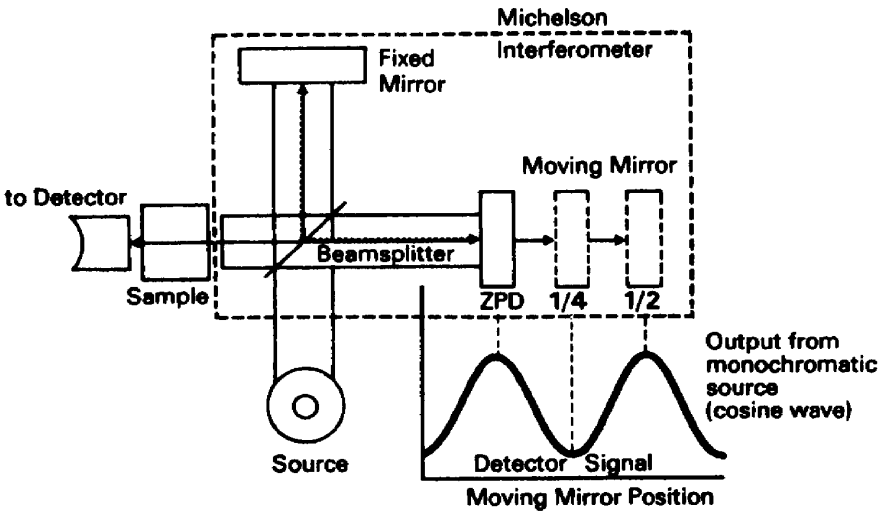

Figure 34 The Michelson interferometer, which is used in a FTIR emissions analyzer [70].

It has already been successfully implemented in steady-state emission analysis, e.g. flue gases from industrial boilers or power station stacks. However, continuous research and development efforts have recently made this technology viable even for engine exhaust analysis, where the dominating role of CO_2 and

H_2O absorption has been one of the major obstacles. In fact, one of the essential elements in making this application feasible has really been the development of the method for filtering-out this cross-interference using fuel-specific "masks".

Such a high resolution IR technique allows simultaneous quantitative measurement of several exhaust components, including those unregulated emissions that are regarded as air toxics. For some of them, like 1,3-butadiene, this kind of real-time determination is even preferable, because it is known to dissociate in bag samples, even quite rapidly.

If needed, FTIR spectrometers can simultaneously measure also the regulated components. However, it is not yet accepted to replace conventional, dedicated analysers in regulatory testing. In such an application, one of the major deficiencies is its poor detection of hydrocarbons to achieve total HC sum. In practice, specific concentrations for components heavier than C_4 cannot be accurately determined.

The system that was used for continuous analysis of unregulated components in this study was a commercially available, FTIR-based multicomponent analyser system developed jointly by three major corporations: Siemens (FRG), Volkswagen (FRG) and Nicolet (USA). The system is marketed with a brand name of SESAM (System for Exhaust Gas Sampling and Measurement).

The second-generation SESAM 2 system commissioned to VTT Energy in May 1993, allows simultaneous, quantitative and real-time (1 Hz time resolution) measurement of the currently calibrated 25 compounds. Sampling is from raw, undiluted exhaust via heated line (appr. 200 °C) to avoid condensation of water and, furthermore, through a ceramic filter to remove particles, both of which will cause errors in the measurement. More details of its technical specifications are given in [69]. The performance of this system, in terms of minimum detection limits and range of error for the 25 components currently calibrated in the system, is presented in Table 15. Furthermore, an estimate of what would be the corresponding minimum detectable emission in [g/km] is given in Table 16.

5.7 CALCULATION OF THE MASS EMISSIONS

Calculation of the mass emissions as bag values from the concentration of pollutants determined by analysers or systems discussed earlier in this chapter was performed mainly by using the applicable formulae given in the emission regulations, such as the US Federal Test Procedures and the European directives. Appendix 4 outlines this procedure.

Table 15 Components calibrated in VTT Energy's FTIR-based Siemens SESAM 2 multicomponent exhaust emission analyzer [69].

Compound	Min. detectable concentration [ppm]	typical range of error in a practical application (petrol fuel) [ppm]	max. calibrated concentration [ppm]
CO	<5	n/d	10%
CO_2	500	n/d	16%
NO	<10	5 - 13	1%
NO_2	5	2 - 6	1000
N_2O	7	5 - 14	1000
NH_3	5	2 - 3	1000
CH_4	3	1 - 4	1000
C_2H_2	6	3 - 5	3000
C_2H_4	7	2	2000
C_2H_6	6	3 - 34	1000
C_3H_6	12	5 - 9	300
C_3H_8	7	n/d	2900
C_4H_6	5 - 7	3 -7	1000
CH_2O	7	4 -7	500
CH_3CHO	25	18 - 31	1000
CH_3OH	7	2 - 3	15 000
C_2H_5OH	10	n/d	15 000
benzene	20	16 - 22	1000
AHC[1]	20	3 - 10	1000
n-C_5	8	3 - 8	8000
i-C_5	8	3 - 33	4000
n-C_8	1	n/d	100
MTBE	6 - 11	n/d	1000
SO_2	9	4 - 46	1000

[1] Estimate of the sum of aromatic hydrocarbons, calibrated with toluene
n/d = not determined

The correction of NO_X emissions according to the humidity of the air has not been applied to the results obtained at sub-zero ambient temperatures, as the formulae are not applicable to this temperature range. This policy is in line with the practise

Table 16 Minimum detectable levels of emissions for VTT Energy's FTIR based

Siemens SESAM2 multicomponent exhaust emission analyser [69].

Component	conc. [ppm] (in raw exhaust)	emission [mg/km] (over FTP75)
methane, CH_4	3	2.5
acetylene, C_2H_2	4	5.2
ethene, C_2H_4	2	2.8
propene, C_3H_6	10	20
benzene, C_6H_6	20	78
formaldehyde, HCHO	5	7.4
acetaldehyde, CH_3CHO	25	54
nitrogen monoxide, NO	2	3.0
nitrogen dioxide, NO_2	5	11.5
nitrous oxide, N_2O	5-7	10-13
ammonia, NH_3	2-3	1.7-2.6

settled in the promulgation of the US Cold-Temperature CO test procedure.

Appendix 4 gives also the applicable formulae adopted for the calculation of unregulated pollutants from bag samples. Included are even all subsequent calculations of mass emissions from the continuous, time-resolved measurements of both regulated and unregulated components.

All calculations have been performed using a personal computer with applicable software (Microsoft® Excel® version 7). The procedures have been verified with examples taken from the emission regulations.

The graphs and other presentations of the results were also produced by this software package using directly the output files generated by the calculation.

6 EMISSIONS PERFORMANCE OF MODERN TWC CARS AT LOW AMBIENT TEMPERATURES

6.1 BASIC COMPARATIVE STUDY: NON-CAT vs. TWC

6.1.1 General description of the study

The pioneering work described in Chapter 2.4 strongly suggested that cars using catalytic converters for exhaust emission control would be especially susceptible to the effects of low ambient temperature. Therefore, the first-hand basic studies performed at VTT Energy included a comparative study on a regular, non-catalyst car versus three-way catalyst-equipped cars.

This study, initiated in 1992, involved one carburetted car and two current-technology TWC-equipped cars. The low ambient temperatures in these tests were -7 and -20 °C, whereas baseline emissions were determined at +20 °C. Table 17 lists the cars and comprises the test program. Further details of the cars are presented in Appendix 3. In this work, the US FTP75 driving schedule was used to retain compatibility with the existing emissions regulations implemented in Finland at that time. Normal, commercial grade unleaded petrol (RON95) was used for fuel.

Table 17 Test program for the basic, comparative study.

Vehicle Code	Displ. (dm^3)	Fuel delivery system; emission control devices	Tests at ambient temperatures [°C]		
			+20	-7	-20
BS92A	1.4	Carburettor	x	x	x
BS92B	2.1	Multi-Point Fuel Injection; TWC	x	x	x
BS92C	1.3	Multi-Point Fuel Injection; TWC	x	x	x

6.1.2 Results from the comparative study

The results from this comparative study on the impact of the ambient temperature on exhaust emissions of non-cat (BS92A) vs. three-way catalyst cars (BS92B and BS92C) are illustrated as composite FTP75 values in Figures 35 to 40. Figures 35 and 36 present CO emissions, first in absolute scale [g/km] and then relative, in [%], to the baseline level measured at +20°C. Figures 37 and 38 graph results from HC emission measurements in the same way. Finally, Figures 39 and 40 portray the figures for NO_X output according to the same pattern.

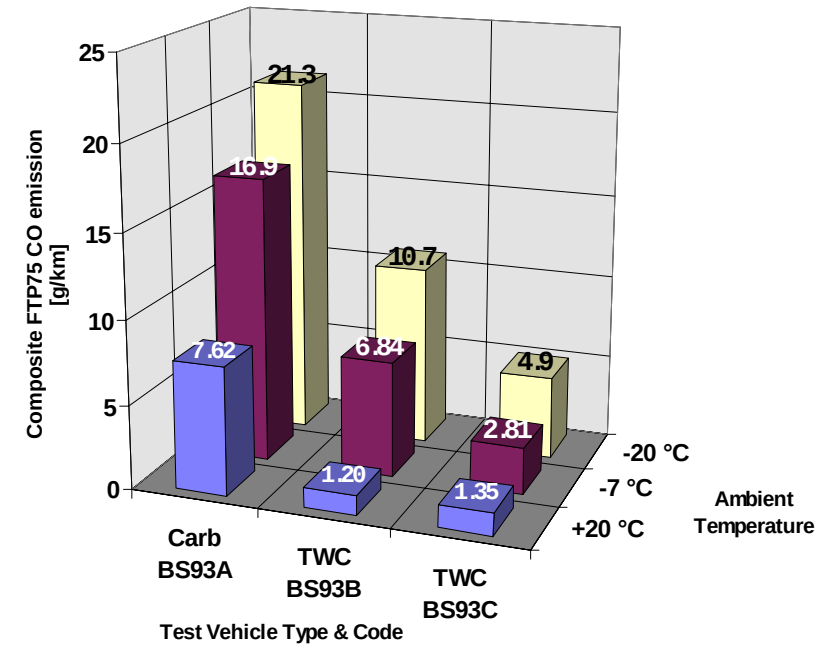

Figure 35 Composite FTP CO emissions for the one non-catalyst (Carb) and two three-way catalyst-equipped cars (TWC) at ambient temperatures of +20, -7 and -20 °C.

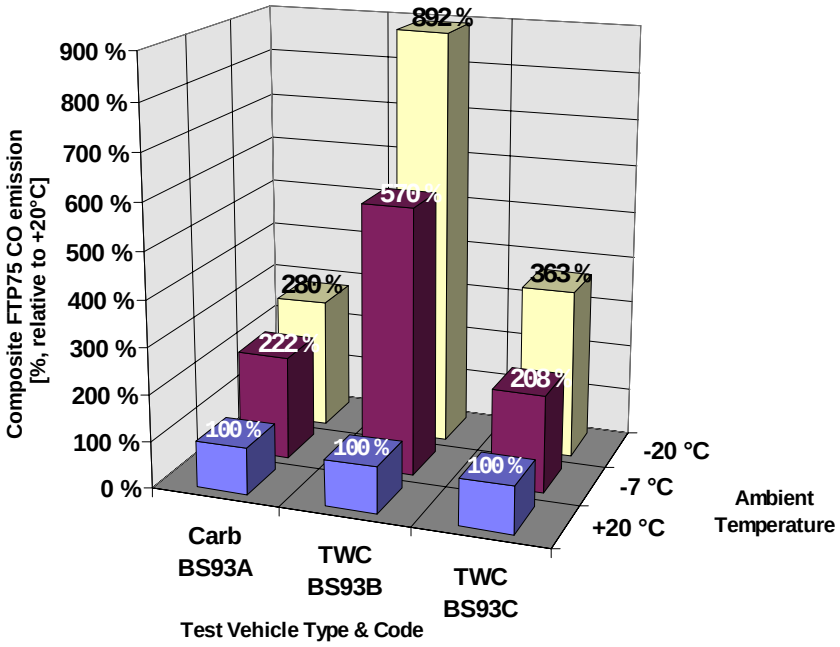

Figure 36 Composite FTP75 Emissions relative to baseline level (at +20 °C) for one non-catalyst (Carb) and two three-way catalyst-equipped cars (TWC) at ambient temperatures of -7 and -20 °C.

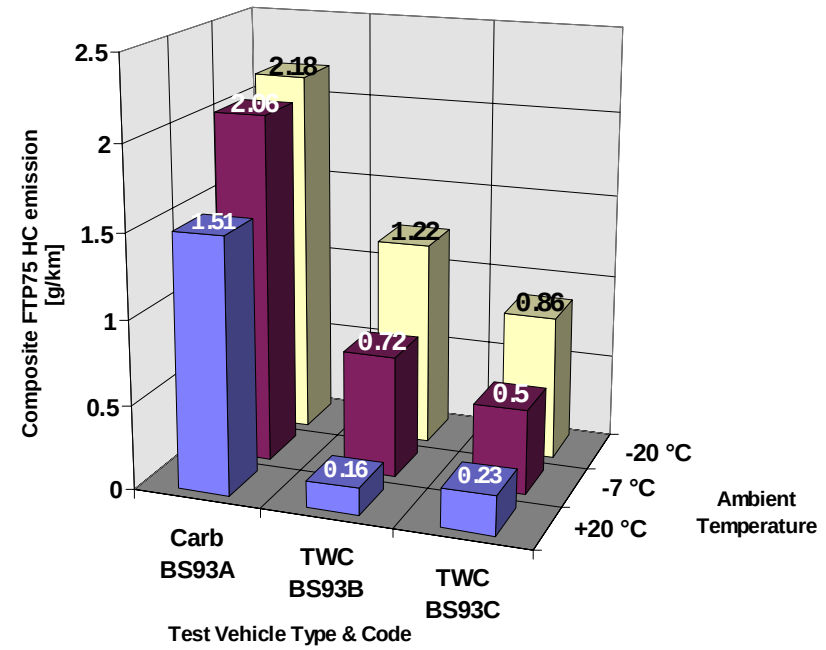

Figure 37 Composite FTP HC emissions for one non-catalyst (Carb) and two three-way catalyst-equipped cars (TWC) at ambient temperatures of +20, -7 and -20 °C.

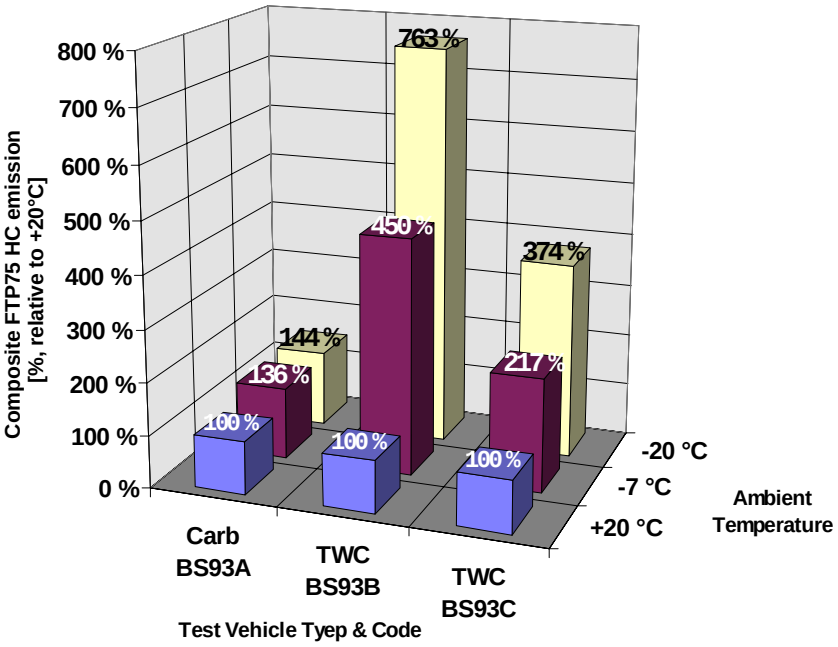

Figure 38 Composite FTP HC emissions relative to baseline level (at +20 °C) for one non-catalyst (Carb) and two three-way catalyst-equipped cars (TWC) at ambient temperatures of -7 and -20 °C

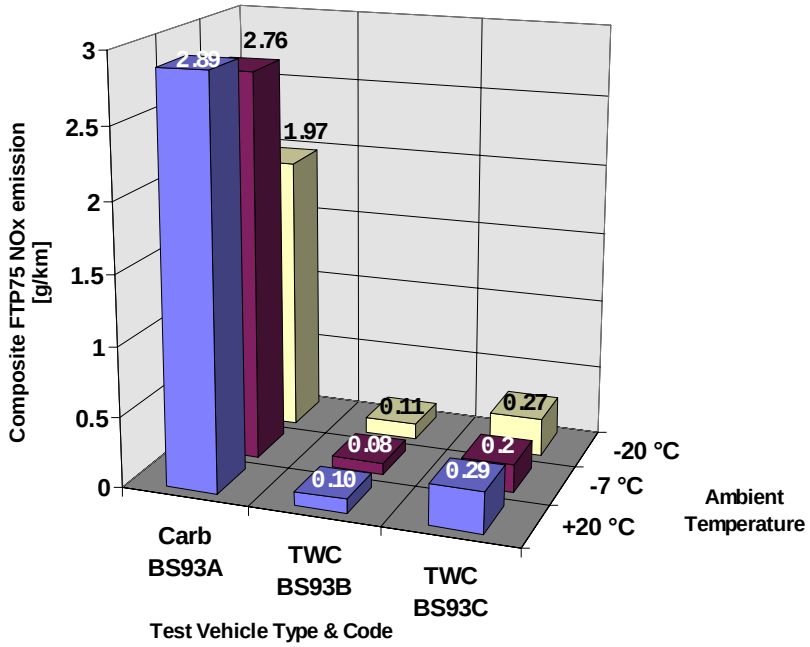

Figure 39 Composite FTP75 No_x emissions for one non-catalyst (Carb) and two three-way catalyst-equipped cars (TWC) at ambient temperatures of +20, -7 and -20 °C.

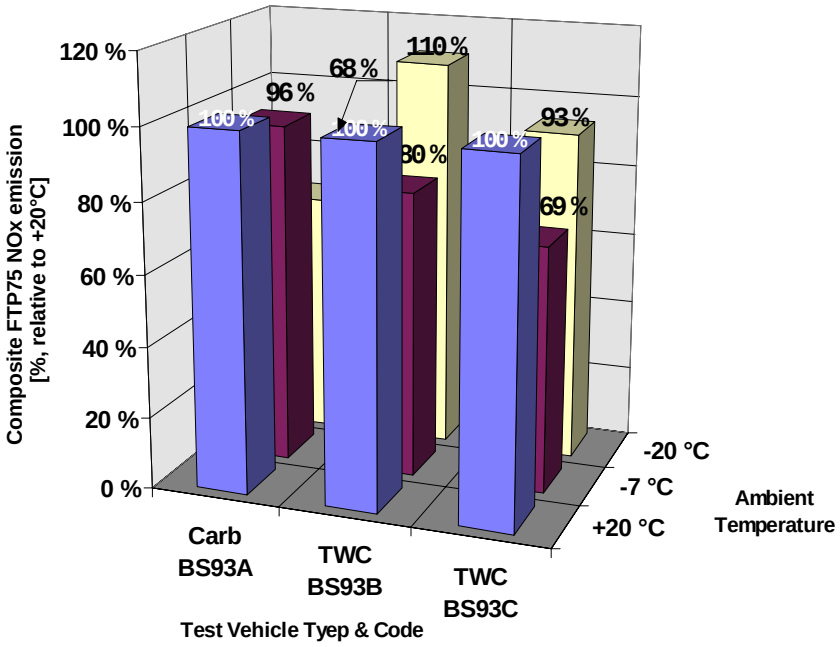

Figure 40 Composite FTP75 NO_x emissions relative to baseline (at +20 °C) for one non-catalyst (Carb) and two three-way catalyst-equipped cars (TWC) at ambient temperatures of -7 and -20 °C.

As can be seen from the figures, both CO and HC emissions increased quite dramatically, when the test temperature was lowered. Although not illustrated separately, it can be commented that especially the levels in bag 1 were distinctly elevated. According to the anticipation, the non-catalyst carburetted car had higher base emission levels compared with the two catalyst-equipped vehicles. At baseline temperature (+20 °C), both of the TWC cars emitted CO and HC components at levels only about 10 to 20 % of the values for the non-catalyst car. In case of NO_X emissions, this effect was even stronger, as the levels of NO_X emissions from both of the TWC cars were at all temperatures on average only some 10 % of the output of the car without external aftertreatment.

In relative scale, however, the lowering of the ambient temperature did cause more additional emissions in the case of the TWC cars. This, which was also highly expected, can be seen in Figures 36 (CO) and 38 (HC). The reason to this was considered to be the fact that after a cold start at low temperatures, not only the engine produces higher emissions, but also the light-off of the catalyst is delayed. Thus the rate of emissions from the TWC cars rose to levels that were about 25 to 50 % of the respective output from the carburetted, non-catalyst car. Nevertheless, in all but one case, even the elevated emissions levels were below the level set by the non-catalyst car at baseline temperature. Only the heavier and also more temperature-sensitive of the two TWC cars produced CO emissions at -20 °C in amounts that exceeded the output of the non-catalyst car at +20 °C.

When NO_X emissions are considered, it was interesting to note from Figure 39 that in case of the carburetted, non-catalyst car the emissions were lowered with falling ambient temperature. At -20 °C ambient, the level of emissions was more than 30 % lower than the baseline figure. Contrary to this, both of the three-way catalyst cars seemed to be quite insensitive to the test temperature, and attained very low absolute levels of emission in all tested conditions. Aside, slight relative variations, seen in Figure 40, were encountered that inclined in the same way in both of the cases. First, when the test ambient was lowered to -7 °C, the emissions of NO_X declined compared with the baseline. However, as the temperature was lowered further down to -20 °C, somewhat higher NO_X values than those at -7 °C were measured for TWC cars.

6.2 QUANTIFICATION OF THE EFFECT OF LOW AMBIENT TEMPERATURE: THE CO-NORDIC STUDY

6.2.1 General description of the study

The effect of low ambient temperature on the level of the regulated exhaust emissions was further studied at VTT Energy in cooperation with the Swedish

authorities (Swedish EPA and Motortestcenter) during 1993-1994. The purpose of this study, referred as the Co-Nordic study throughout this report, was to quantify the effect of low ambient temperature on the regulated emissions for the deliberations in both of the bodies[8] responsible for developing a European low-temperature test procedure and related emissions standards. This was deemed necessary, because all the previous work was made using the US Federal Test Procedure. Therefore, emissions levels attained were not comparable to the European situation because of the differences in test cycle.

The results of this study have previously been reported as an internal, non-public report to the WP.29/GRPE working group, as well as in a couple of conference papers [68] and [71].

6.2.2 Test programme

In this study the work was divided between VTT Energy and Motortestcenter so that each laboratory tested five cars and two vehicles were tested at both of the facilities for cross-reference. Test vehicles were picked quite randomly, pursuing some kind of cross-section of the average European car fleet. However, this was not all successful, because at that time Finland and Sweden were, among the other EFTA countries Austria, Norway and Switzerland, implementing emission regulations that closely followed the US regulations for model year 1987, which made the cars somewhat different from the model marketed in other European countries following either the directives of the European Community or the ECE regulations. Details of the cars used in this study are given in Appendix 2.

Throughout the study, the European test cycle was used, but in a modified form known as "OICA alt.C", which was then (and still is) supposed to be the upcoming definition in the EC regulations for the year 2000 and beyond. This modification, illustrated in Figure 41, meant that the 40 second idle period prior to the start of sampling currently contained in the cycle (as defined in 91/442/EEC) was omitted, and both the engine, as well as the exhaust sampling were started simultaneously leaving only 11 seconds idle before actual driving started. Thus the test cycle would embody more actual driving and the results would be much better representation of the real-world performance of the car and its associated emission control systems.

Baseline testing was performed at an ambient temperature of 22 °C. The low ambient temperature was chosen to be -7 °C, because at that time, a preliminary agreement upon choosing it as the European cold-test temperature was already reached in the MVEG, thus harmonizing the procedure with the existing US EPA specifications. However, a small subset of cars was tested at

[8] WP.29/GRPE and EC/MVEG working groups.

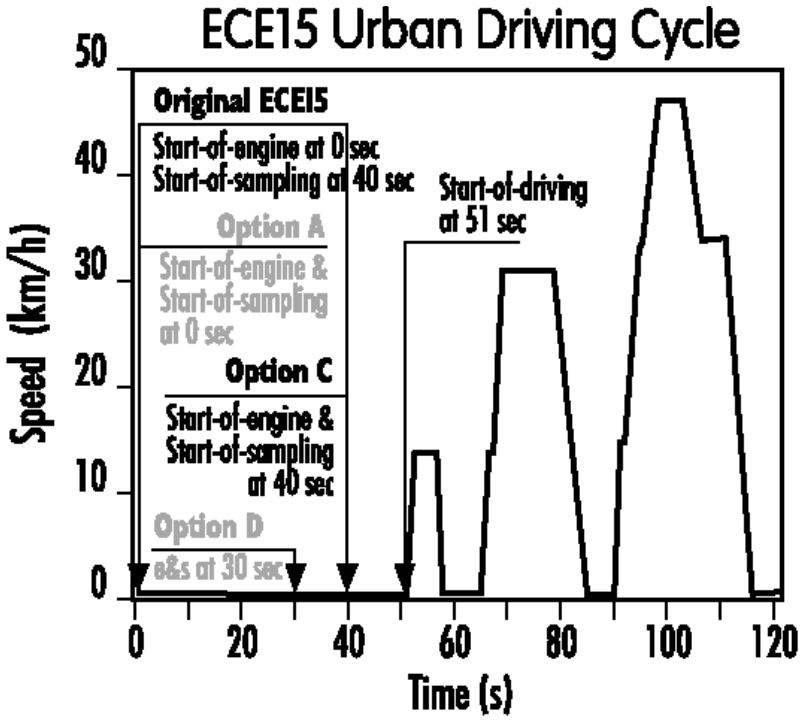

Figure 41 Various alternatives suggested by OICA for start-of-engine and start-of-sampling in the ECE15 Urban Driving Schedule. Option C was used in this study.

VTT Energy even at -20 °C, which more closely reflected Scandinavian winter ambients.

Because the work was mainly targeted towards setting emission standards, all testing was made using test fuel complying with the specifications of reference petrol (CEC RF-08-A-85) currently specified in the legislation. This was a conscious choice, although the volatility of this fuel (Reid vapour pressure max. 64 kPa) does not fully match the RVP range of commercial fuels typical for a cold climate (around 90 kPa). However, no particular driveability problems were encountered and, therefore, results should present a valid response of the tested cars to the lowering of the ambient temperature. Apart from that, some additional work was performed using commercial unleaded petrol, as well. This can be seen in Table 10, which comprises the complete test programme.

6.2.3 Average emissions levels at -7°C

All preliminary work suggested that the ambient temperature effect would primarily be seen in the first stage of the driving cycle. This was also the case with this study, as the contribution of the later stages of the ECE15 cycle or even the extra-urban portion (EUDC) was almost negligible, apart from NO_X emissions. Therefore, the test results for the regulated emissions are presented here only for bag 1, sampled from the two initial sub-cycles of the ECE15 driving schedule (marked as ECE15:1-2 in Fig 26). Additionally, the results are presented as relative values, in order to make it easier to quantify the effect of ambient temperature.

Table 18 Test programme for the Co-Nordic study.

Vehicle Code	Displ. (dm^3)	Fuel delivery system; emission control devices	Test temperatures and fuels used TF=test fuel (CEC spec), CF=commercial petrol n/a = not applicable (no test)		
			+22 °C	-7 °C	-20 °C
Vehicles tested at VTT Energy; # Vehicle tested at both of the laboratories for cross-reference					
CN93A	1.1	SPFI; TWC	TF	TF	n/a
CN93B	1.79	MPFI; TWC	TF,CF	TF,CF	CF
# CN93C	1.8	MPFI; TWC	TF	TF	TF
CN93D	1.38	MPFI; TWC	TF,CF	TF,CF	CF
CN93E	1.59	MPFI; TWC (lean-burn)	TF,CF	TF,CF	CF
Vehicles tested at Motortestcenter / AB Svensk Bilprovning, Sweden					
CN93F	2.5	MPFI; TWC	TF	TF	n/a
CN93G	2.0	SPFI, TWC; EGR	TF	TF	n/a
CN93H	3.0	MPFI; TWC (metal)	TF	TF	n/a
CN93I*	2.0	MPFI; TWC; EGR	TF	TF	n/a
CN93J*	1.5	MPFI; TWC; EGR	TF	TF	n/a
* Vehicles certified to Swedish Environmental Class 1 (EC1), which equals to CARB TLEV standards					

Figures 42 to 43 represent CO emissions, Figures 44 to 45 represent HC emissions and Figures 46 to 47 NO_X emissions, respectively. In all of these figures, the cars are in the same rank-order based on their CO emissio4ns results for bag 1 at +22 °C. The order is starting from the left, first for the regular cars, from the least emitting one to the highest emitting one, and then came the two low-emission (Swedish Environmental Class 1[9]) cars. Apart from the values of each individual test car, averages for three vehicle groups (all, non-EC1, EC1) are also presented.

If the CO emissions are first considered, Figure 42 shows that already at the base temperature (+22°C) the cars were performing rather differently, although all were certified against the same numerical CO standard (2.11 g/km in an FTP75 test). Among the regular cars, which were certified according to the US'87 standards applicable to all of the EFTA countries at that time (1993), CO emission levels ranged from a low of 4.6 g/km (car CN93D) to a high of nearly 15 g/km (car CN93H), the average being 10.4 g/km. Thus, the best-to-worst ratio was around 1:3.

However, those two cars certified according to the requirements of the Swedish Environmental Class 1, which are equal to the Californian TLEV standards, were much cleaner, although their CO limit value was the same as

[9] see Chapter 3.1.3. for more details on the Swedish Environmental classification for passenger cars.

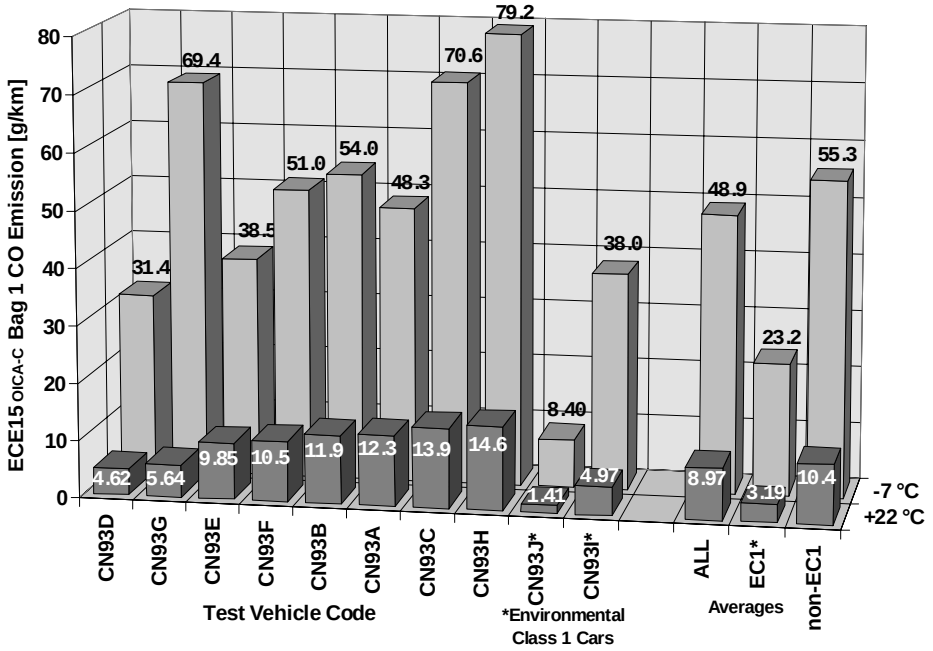

Figure 42 Average CO emissions for Bag 1 at ambient temperatures of +22 and -7 °C for the petrol-fuelled cars tested in the Co-Nordic study.

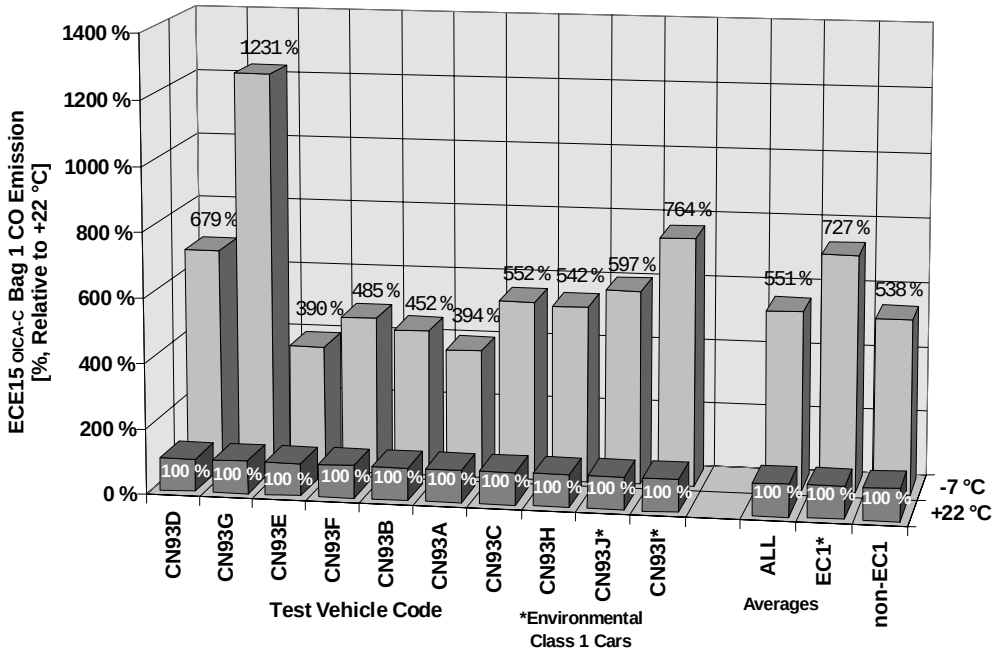

Figure 43 Relative CO emissions for Bag 1 at ambient temperatures of +22 and -7 °C for the petrol-fuelled cars tested in the Co-Nordic study.

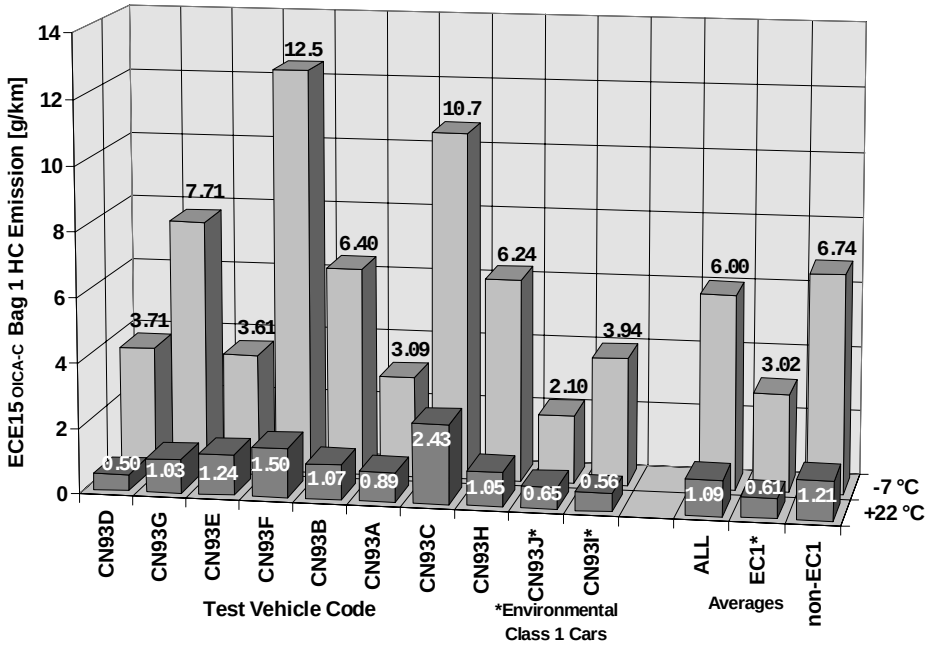

Figure 44 Emissions of total HC for Bag 1 at ambient temperatures of +22 and -7 °C for the petrol-fuelled cars tested in the Co-Nordic study.

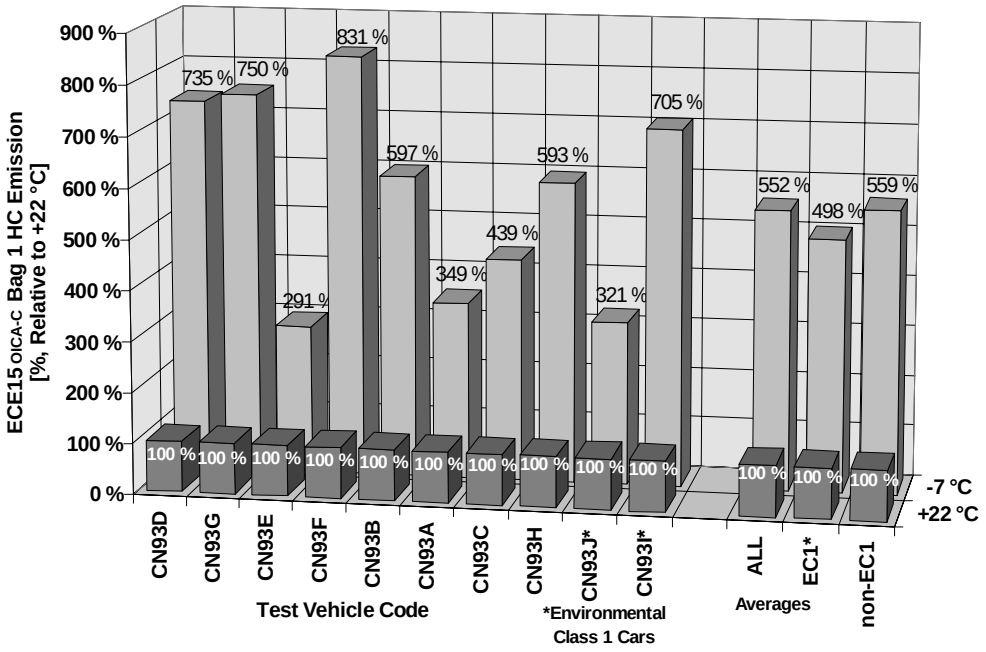

Figure 45 Relative emissions of total HC for Bag 1 at ambient temperatures of +22 and -7 °C for the petrol-fuelled cars tested in the Co-Nordic study.

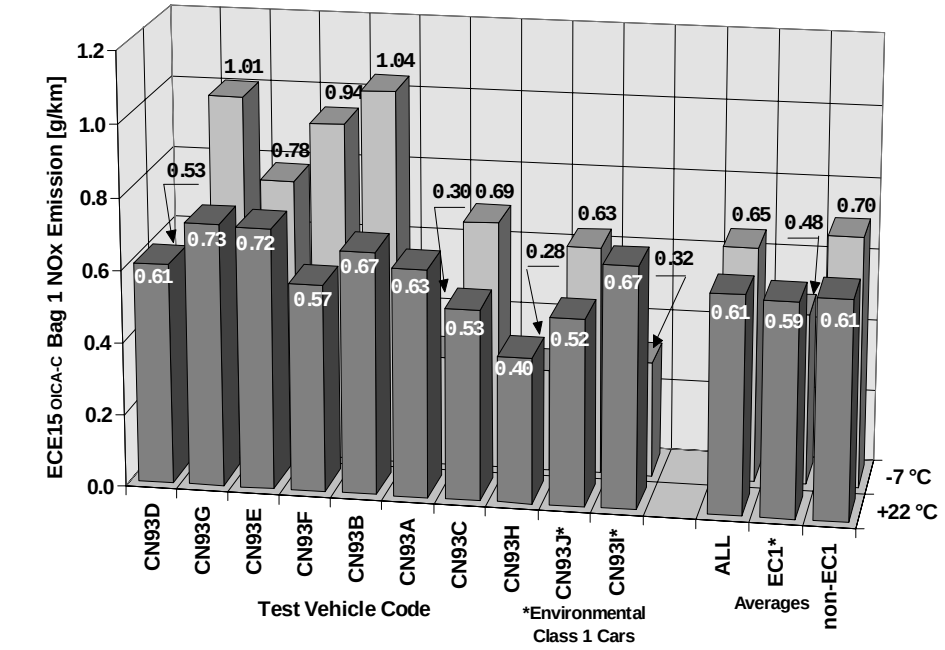

Figure 46 Emissions of NO_x for Bag 1 at ambient temperatures of +22 and -7 °C for the petrol-fuelled cars tested in the Co-Nordic study.

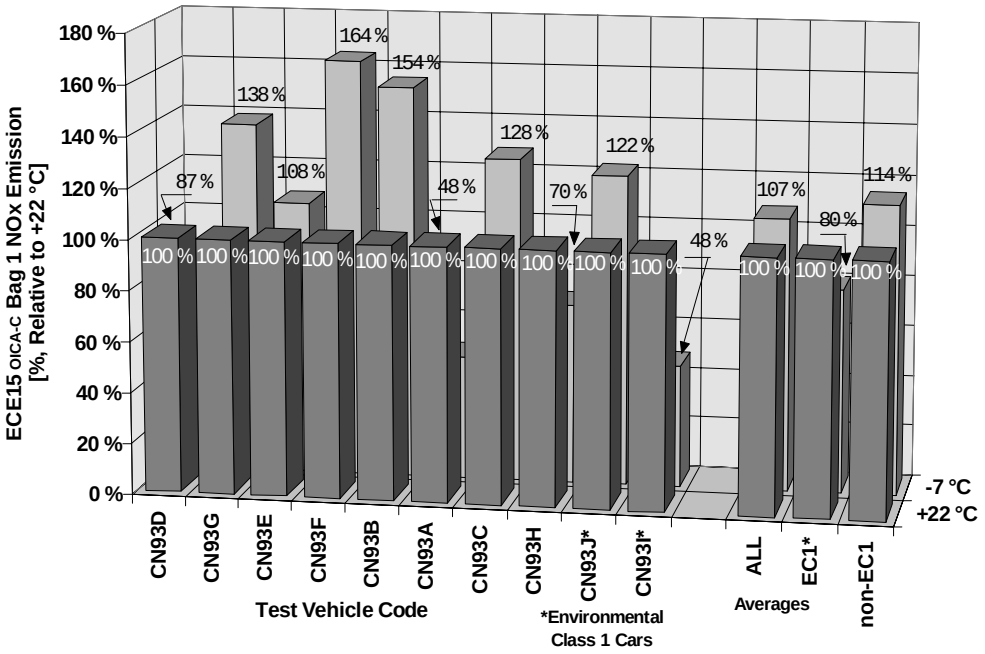

Figure 47 Relative emissions of NO_x for Bag 1 at ambient temperatures of +22 and -7 °C for the petrol-fuelled cars tested in the Co-Nordic study.

with the other cars. On average, they gave only some 3 g/km emissions, as the least emitting car (CN93J) had an output of only 1.4 g/km, although the other (CN93I) was on the same level with the best of the regular cars, about 5 g/km.

Considering then the emissions measured at -7 °C ambient, Figure 42 shows that the average emission level rose quite substantially, to a value of 55.3 g/km. However, the scatter from one car to another, described as the best-to-worst ratio, was now slightly lower, some 1:2.5, as the least-emitting one (CN93D) gave a CO output of 31.4 g/km and the highest value (CN93H) was somewhat below 80 g/km. The cleaner of the two EC1 cars was superior even at a low temperature, because its CO output at -7 °C was only 8.4 g/km. The other EC1 car with a bigger engine, however, was again on the same level (38 g/km) as the best two of the regular ones.

The effect of low ambient temperature on the CO emissions is best discussed using Figure 43 as the reference. It represents the emissions measured at -7°C ambient relative to the base-level emissions measured at +22 °C ambient. Considering the regular cars, the CO emissions were on average more than fivefold at -7°C compared with the average emissions at +22°C. Those two EC1 certified cars were even more sensitive to the low temperature than the regular ones, as the average for EC1 cars was more than seven times higher at -7°C compared with the average for the emissions at +22°C ambient.

Figure 43 shows also, how the sensitivity of individual cars varied quite substantially. At the lowest, the increase in emissions was only about fourfold, but the most temperature-sensitive car (CN93G) showed more than 12 times higher CO emissions at -7°C compared with its baseline results at +22°C. The variations in the low-temperature sensitivity clearly distract the rank-order based on the CO emission level measured at +22°C ambient temperature. Therefore, one cannot necessarily assume that if the vehicle has low CO emissions at normal temperature, it will retain its performance even at low ambient temperatures. This is a clear indication towards the need of setting a separate low-temperature test procedure and an applicable standard.

When going further on to discuss HC emissions Figure 44 shows that on average, the non-EC1 cars emitted about 1.2 g/km of total hydrocarbons in baseline testing at +22°C. Here it can be clearly seen the better hydrocarbon emission control associated with the stricter HC standard in the certification of the EC1 cars. On average, their HC emissions were only some 0.6 g/km, which is about 50% lower than the average for the regular cars. Nevertheless, the lowest emissions in baseline testing at +22°C were recorded for vehicle CN93D, which belongs to the group of regular cars.

Furthermore, this HC emission control seemed not to perform consistently at low ambient temperature, albeit the fact that the average sensitivity of the two EC1 cars to low temperature was somewhat lower than that of the regular, non-EC1 cars. According to the Figure 45 that shows HC emissions in relative scale, the better-performing one of the EC1 vehicles (CN93J) had a sensitivity figure of 3.2 (or 321 %), expressed as emissions relative to the baseline, but the other one (CN93I), was with its sensitivity factor of seven (705 %) in the same league with the worst of the regular ones, where the sensitivity to low temperature ranged from about six to over eight (593 % to 831 %). Vehicle CN93E was least sensitive to the lowering of the test temperature, as its HC emissions rose only to an about threefold level (291 %), when the test temperature was lowered from +22°C to -7°C.

Whereas both CO and HC emissions followed more or less the same pattern when the test temperature was lowered, the picture was strikingly different for the NO_X emissions. This can clearly be seen, when studying Figure 46. On average, the regular non-EC1 cars emitted NO_X at a level of 0.61 g/km, when tested at the baseline temperature (+22 °C). Although the EC1 cars should reflect their stricter NO_X certification standard (0.248 g/km as opposed to the 0.62 g/km for the non-EC1 cars) in their emissions output even in this European test, this seemed not to be the case. Both emitted NO_X at levels very much comparable to those non-EC1 vehicles, as the average for the two EC1 cars was 0.59 g/km.

Furthermore, when the test temperature was lowered to -7°C, the layout became even more complicated. Of the regular, non-EC1 cars five were emitting NO_X at higher rates than at high ambient. The same was true for one of the EC1 vehicles (CN93J). However, the other half of the test fleet performed exactly the opposite way: lower NO_X results were achieved in tests at -7°C. For the complete test fleet (combining both regular and the EC1 cars) the outcome was nearly equal emission levels at both of the test temperatures. This was almost the case for the regular cars, as well, because according to the Figure 47 they showed only 14 % increase relative to the emissions at baseline temperature. However, the relatively strong decrease (52 %) in NO_X output measured at the low ambient for the other of the EC1 cars (CN93I) pushed the average for EC1 cars at -7°C down to 80 % of the baseline level attained at +22°C.

6.2.4 Emissions at -20°C ambient temperature

As already indicated in Table 18, a sub-study was initiated parallel to the work described in previous section to expand the test temperature range beyond the would-be standard (-7 °C) and to quantify the emissions at temperatures that are typical in the Nordic climate. Four cars of the aforementioned test fleet were tested at ambient temperatures of +22, -7 and -20°C. Because the primary target was now to address “real world” emissions performance and not specifically seek any base for setting a standard, commercial unleaded petrol was used as fuel in this part of the work, except with one vehicle (CN93C), which was using test fuel in compliance with CEC RF-08-A-85 specification even in this part of the study. All

other arrangements were similar to the tests previously described.

From the results of these tests, Figures 48 and 49 illustrate CO emissions and Figures 50 to 51 show the results for HC measurements. Furthermore, Figures 52 and 53 graph the respective values for NO_X. In each of these sets the first figure gives the emissions (in g/km) for bag 1 of the ECE15 cycle (ECE15:1-2 with the start-up modified as OICA alt.C) and the latter figure presents the same data as relative to the baseline emissions, i.e. results in +22°C ambient. Again, as with the previous figures, cars are rank ordered from left to right based on their CO emission output at +22°C. Additional to the values for individual cars, an average for this sub-fleet is also presented.

Looking first CO emissions, presented in Figure 48, one would see how more or less linear growth of emissions was measured with lowering of the test temperature except for car CN93D, in which the emissions seemed to increase almost progressively, when the test ambient went from -7 to -20°C reaching similar levels attained with cars CN93B and CN93C, having much higher CO output at higher ambient temperatures. This relatively high sensitivity to low temperature is strikingly well expressed in Figure 49 presenting the CO results scaled to the baseline measured at +22°C. Whereas the other three cars demonstrated about four to five fold emissions at -7°C and a sensitivity factor around 6.5 to 7.5 (636 % to 748 %) at -20°C, car CN93D had much higher sensitivity figures: almost eight (774 %) at -7°C and nearly as high as 18 (1755 %) at the lowest ambient of -20°C. Again, this kind of performance underlines the factor that if a car has very low emissions in normal ambient conditions, like car CN93D had, it may not necessarily retain this low-emission capability at real-world operating conditions, as well, This is especially true, if Nordic winter temperatures are included.

On average, this four-car sub-fleet presented some 50 g/km CO emissions levels at -7°C and a slightly over 80 g/km figure for emissions at -20 °C, respectively. Compared to the average level of 10 g/km attained at baseline level (+22°C), this is quite a strong increase and further emphasis needs to be set on developing standards or guidelines for the performance at low ambients.

Very much similar conditions to the CO emissions performance just discussed was encountered with HC emissions, as well. As seen in Figure 50, this sub-fleet emitted hydrocarbons at 1.3 g/km level, on average, at the baseline (+22 °C), but fourfold emissions (5.8 g/km) were confronted at -7 °C. A further rise to the level of 15 g/km was measured for the -20 °C ambient. In relative scale presented in Figure 51, this increase in HC emissions was more than fourfold at -7 °C and nearly 12 times at -20 °C, compared with the baseline level set at +22 °C. This means that each kilometre driven in these kind of conditions, which are quite typical for the Nordic countries, produces roughly

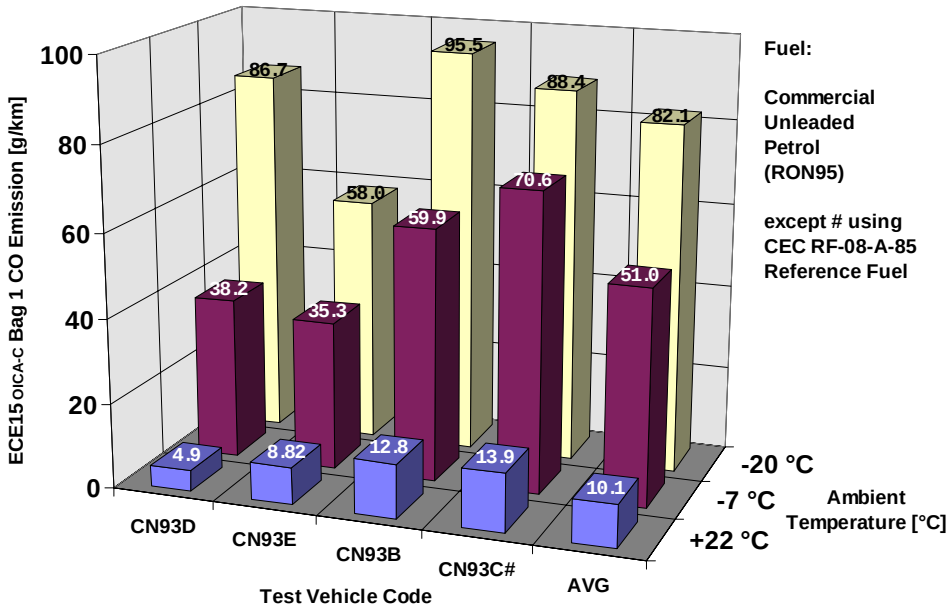

Figure 48 CO emissions for Bag 1 (ECE15:1-2, start-up modified, no 40 s idle) at ambient temperatures of +22, - 7 and -20 °C for a four car sub-fleet in the Co-Nordic study.

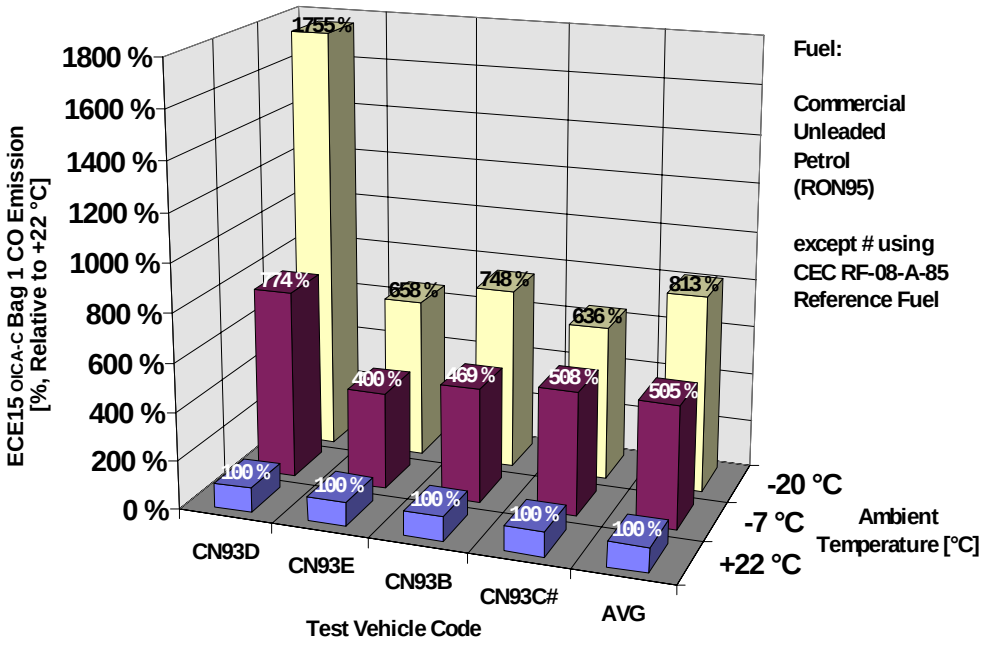

Figure 49 Relative CO emissions for Bag 1 (ECE15:1-2, start-up modified, no 40 s idle) at ambient temperatures of +22, - 7 and -20 °C for a four car sub-fleet in the Co-Nordic study.

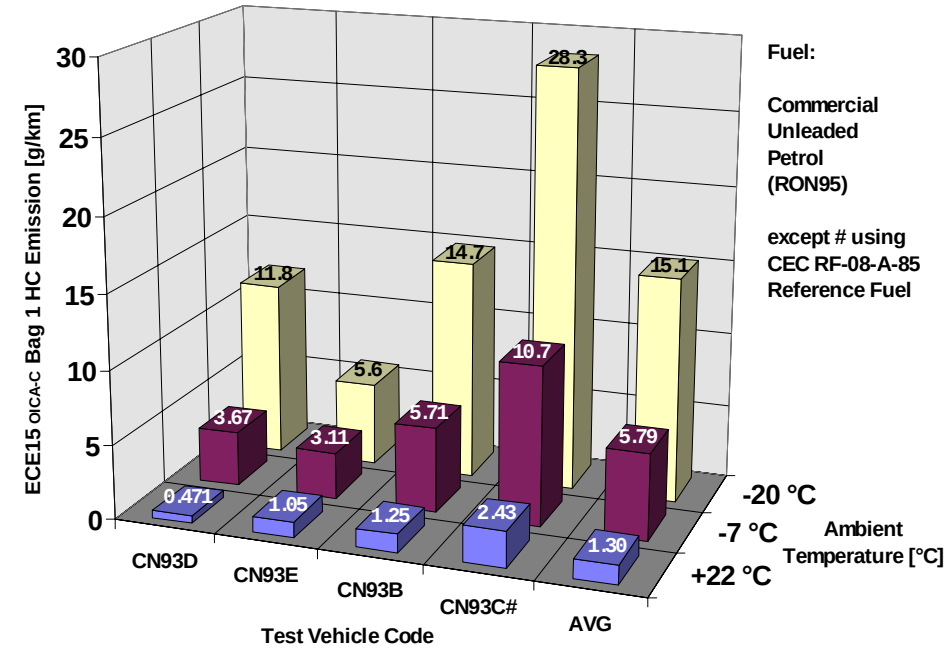

Figure 50 Total HC emissions for Bag 1 (ECE15:1-2, start-up modified, no 40 s idle) at ambient temperatures of +22, - 7 and -20 °C for a four car sub-fleet in the Co-Nordic study.

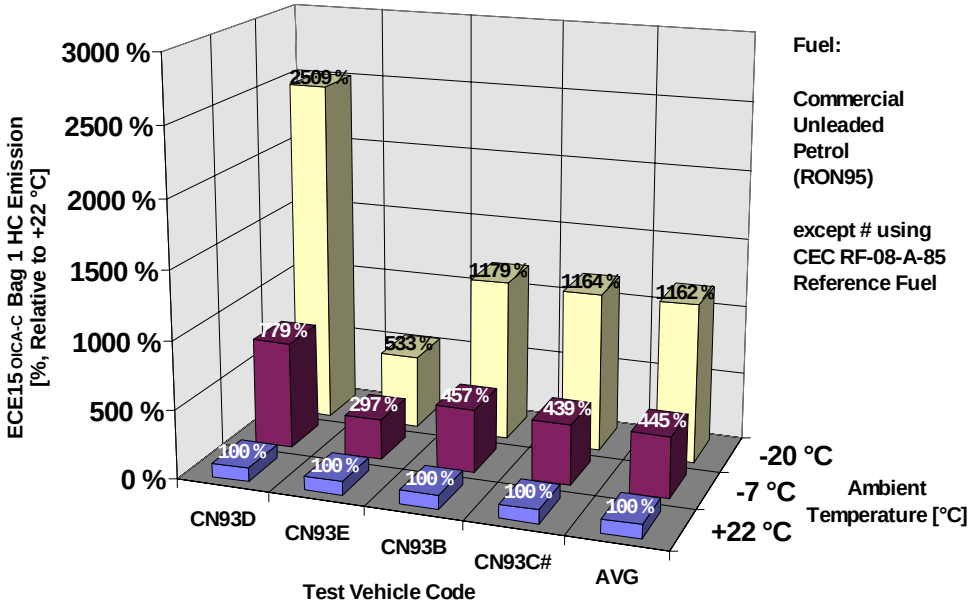

Figure 51 Relative total HC emissions for Bag 1 (ECE15:1-2, start-up modified, no 40 s idle) at ambient temperatures of +22, - 7 and -20 °C for a four car sub-fleet in the Co-Nordic study.

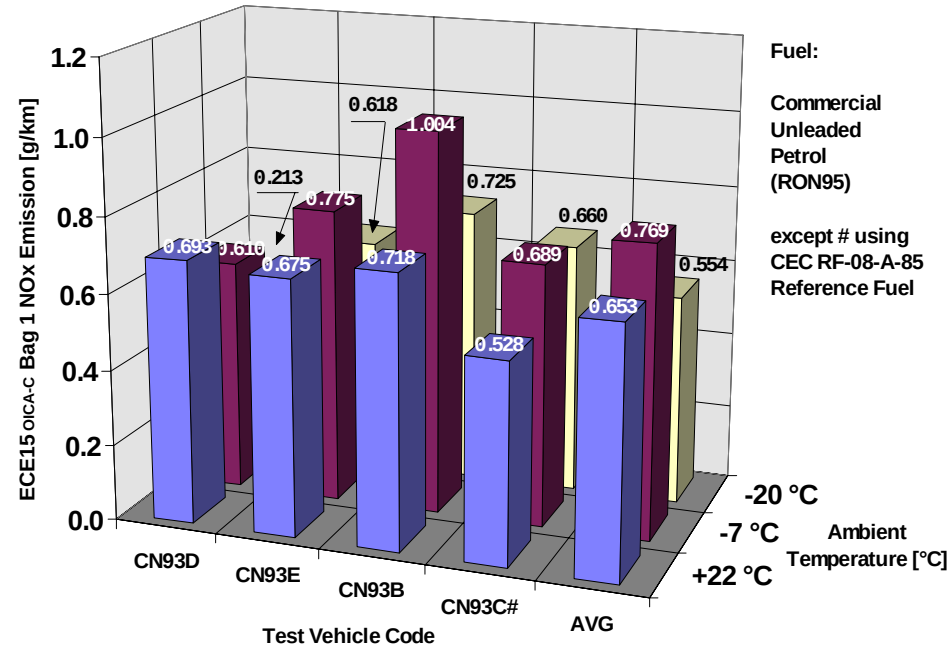

Figure 52 Emissions NO_x emissions for Bag 1 (ECE15:1-2, start-up modified, no 40 s idle) at ambient temperatures of +22, - 7 and -20 °C for a four car sub-fleet in the Co-Nordic study.

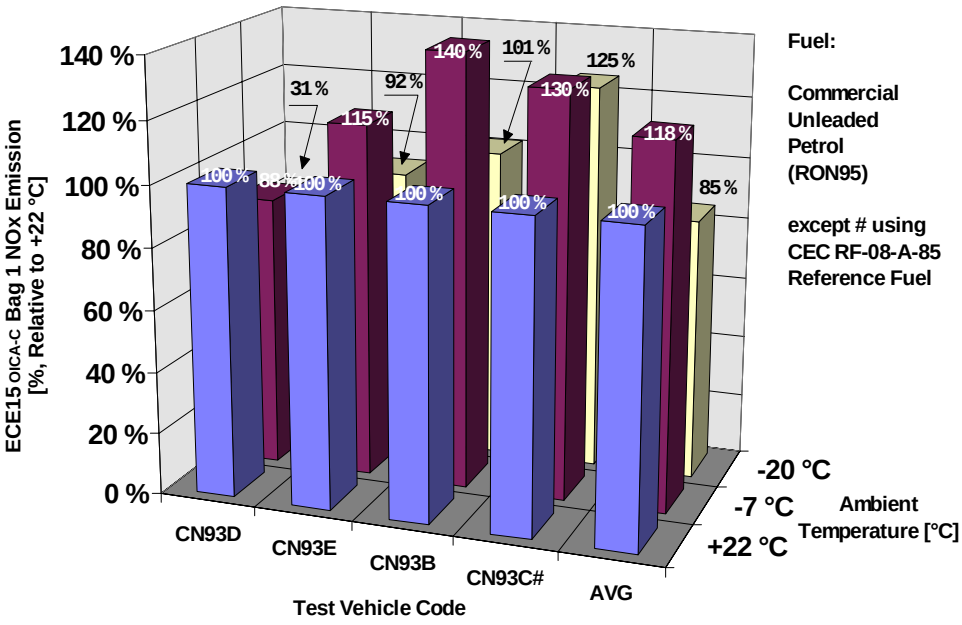

Figure 53 Relative emissions NO_x emissions for Bag 1 (ECE15:1-2, start-up modified, no 40 s idle) at ambient temperatures of +22, - 7 and -20 °C for a four car sub-fleet in the Co-Nordic study.

ten times more emissions than expected, if the emissions performance is evaluated using only currently standardized procedures, where the ambient temperature range is set to be from +20 °C minimum to +30 °C maximum.

Regarding both CO and HC emissions, the cleanest one (CN93D) of the test cars in this sub-fleet (and of the whole fleet, as well) was even more sensitive than the rest of the sub-fleet. It presented already a nearly eightfold (779 %) figure for HC emissions at -7 °C, and an extremely high value, about 25 times the baseline (2509 %) at -20 °C. In spite of this very high sensitivity to low temperatures, the actual HC emissions level, however, remained at a rather acceptable level, because according to Figure 50, this car produced well-below-average emissions at -7 °C and even at -20 °C, being second only to car CN93E, which was the best-performing one at low ambient temperatures. The best-to-worst ratio within this sub-fleet at -20 °C was around 1:5 for HC emissions, whereas for CO, it was only less than 1:2 (58 g/km lowest, 95.5 g/km highest).

A set of very mixed results were obtained for NO_X emissions, as seen in Figure 52. All but one car (CN93D) in this sub-fleet produced slightly higher emissions of NO_X at -7 °C ambient compared with the baseline values measured at +22 °C. On average, this computed to a nearly 0.8 g/km output at -7 °C, which was only a slight increase to the 0.65 g/km baseline figure. However, at -20 °C ambient, the sub-fleet average went down to 0.55 g/km, mainly because car CN93D presented an extremely low result, only 0.21 g/km. The rest of the sub-fleet agreed again much better with each other producing NO_X emissions in a 0.62 to 0.73 g/km bracket.

In relative scale, presented in Figure 53, average NO_X emissions were about 20 % higher at -7 °C but some 15 % lower at -20 °C, compared with the baseline set at +22 °C ambient. This kind of performance, i.e. falling NO_X figures when lowering the ambient temperature beyond -7 °C, was attained even if emissions over the total NEDC driving cycle, consisting of ECE15 and EUDC cycles, were considered. Figure 54 shows this comparison. As presented there, the emissions rose with falling ambient temperature, and much stronger increase than for bag 1 values was accounted at -7 °C, because the average level was nearly 60 % higher than the baseline. However, when proceeding to the lowest test temperature, contrary to the situation in bag 1 values, each of the tested cars produced total NO_X values that were lower than those measured at -7°C, but higher than the baseline. The sub-fleet average at -20°C was nearly 40 % higher than the average at +22°C.

It is somewhat interesting to note that this kind of dependence on ambient temperature for NO_X emissions just described is in direct contrast to what was encountered in the basic study (*see 6.1.2, Fig. 40*), where two three-way catalyst cars were similarly tested, but using the US FTP75 driving cycle instead of the

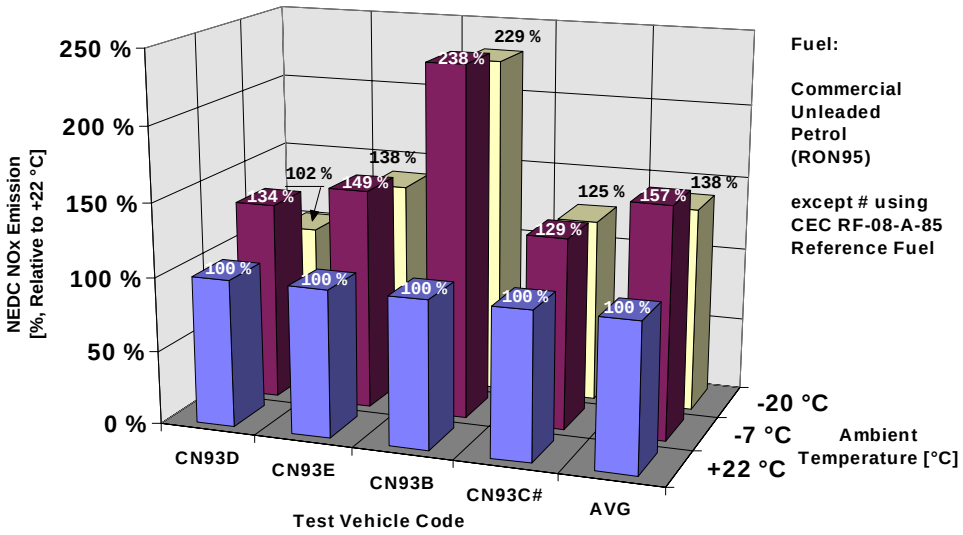

Figure 54 NO_x emissions for the NED (ECE15+EUDC) driving cycle (start-up modified, no 40 s idle) relative to baseline (+22 °C) at ambient temperatures of -7 and -20 °C for four of the test cars in the Co-Nordic study.

European cycle used in this study. However, as the test vehicle sample was very limited in both of the cases, conclusions of this difference should be avoided.

6.3 TIME-RESOLVED ANALYSIS OF THE COLD-START EMISSIONS

6.3.1 Accumulation of the emissions over distance travelled

In the context of the Co-Nordic study, emissions were determined from the cars measured at VTT Energy not only as bag values just commented, but on a continuous basis, as well. This kind of time-resolved “dynamic” analysis enabled the allocation of the emissions accumulation over the driving cycle and gave information on which part of the driving was the most critical in terms of high emission rates.

Traditionally, this kind of distribution has been presented over the cycle per running time. However, linking the accumulation of the emissions to the distance travelled instead, gave a new view to the analysis. This way it is also more closely connected to a real-world situation, where distance rather than time spent is the usual unit for measuring the outcome of driving. Figures 55 and 56 present CO emission accumulation in this manner, i.e. as a function of distance travelled.

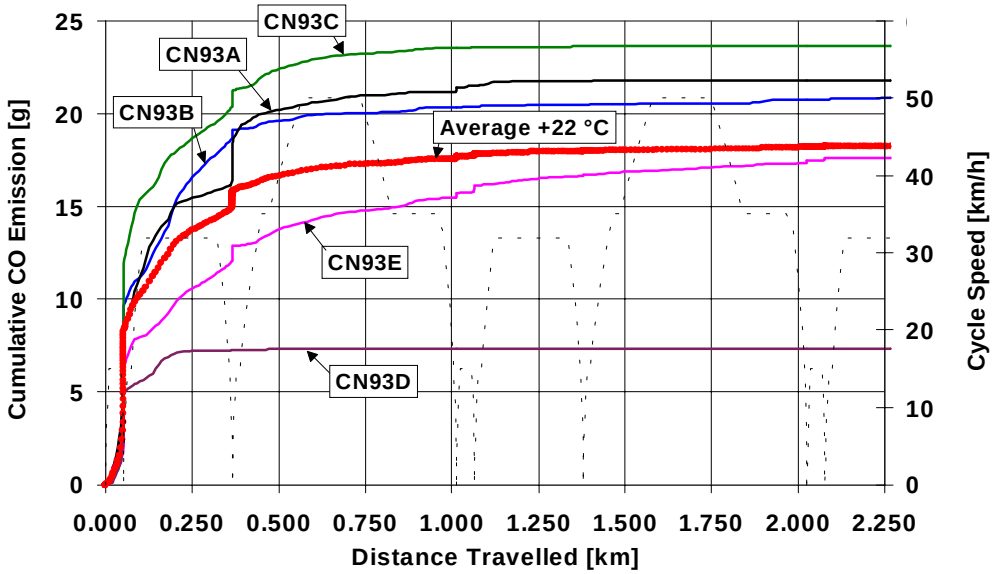

Figure 55 Accumulation of CO emission as a function of distance travelled in the first two sub-sycle of ECE15 driving cycle (start-up modified, no 40 s idle) at +22 °C ambient temperature for five of the cars tested in the Co-Nordic study.

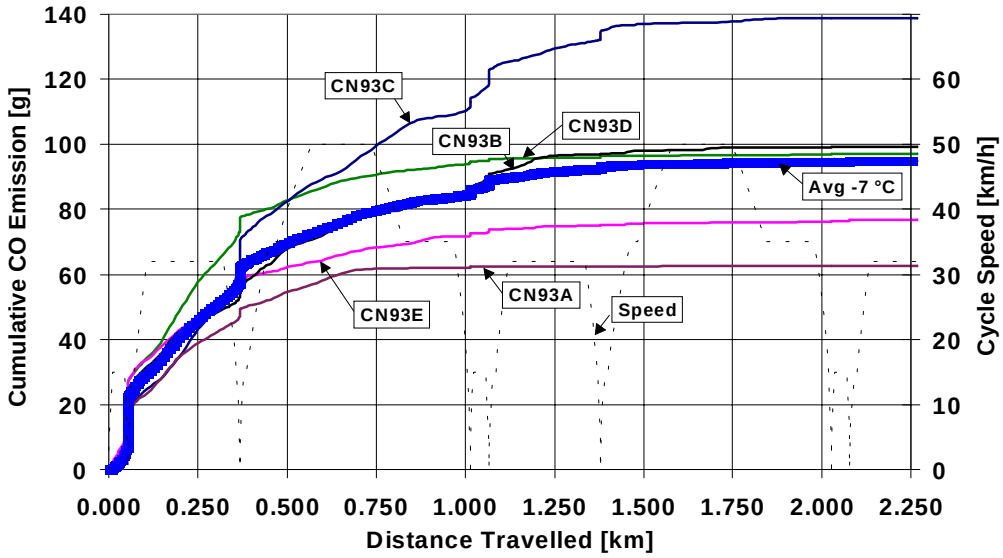

Figure 56 Accumulation of CO emissions as a function of distance travelled in the first two sub-cycles of ECE15 driving cycle (start-up modified, no 40 s idle) at -7 °C ambient temperature for five of the cars tested in the Co-Nordic study.

Comparing these two figures, one can see that not only the scale, required by the much higher CO emission measured at -7 °C compared with the baseline results in +22 °C, is different from one to another, but also the shape. At +22 °C ambient 90

% of the total accumulated emission over the ECE15 cycle has been released already during the first 0.5 km of driving, on average. This is true for most of the cars, although car CN93E presented somewhat slower accumulation. However, in tests at -7 °C ambient the accumulated emissions were much higher and the accumulation tapers off much more slowly than in baseline tests. On average, 1 km of driving was needed to reach 90 % level of the total accumulated emissions in the ECE15 cycle, which is theoretically 4.052 km in length.

The differences in the accumulation profiles for each of the tested cars can more clearly be seen in Figures 57 and 58, which present the accumulation in relative scale as a share of the total accumulated mass in the ECE15 cycle. Figure 57 is for +22 °C ambient and Figure 58 for -7 °C, respectively.

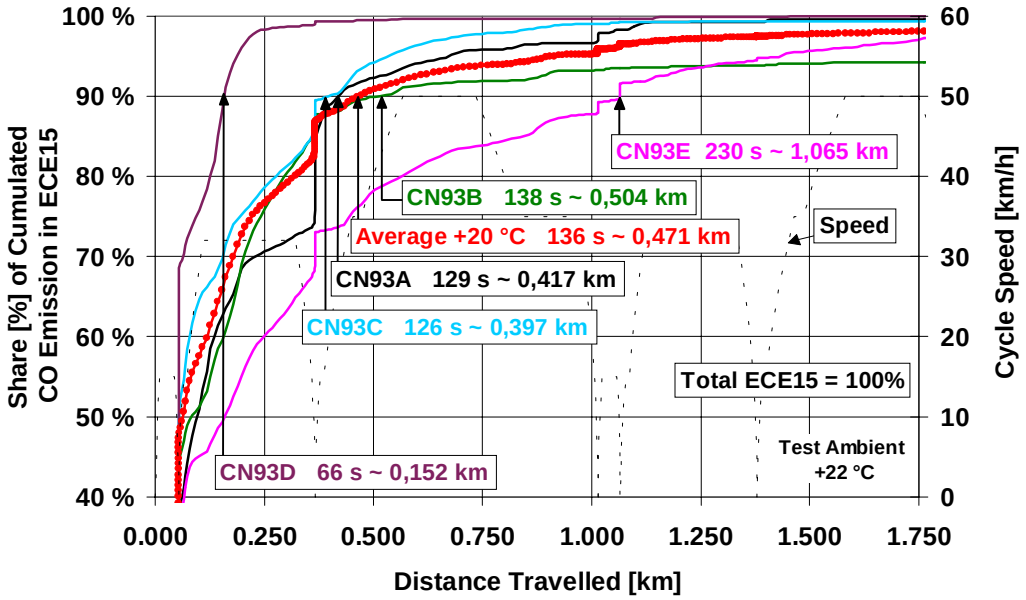

Figure 57 Share of total accumulated CO emissions over the front part of ECE15 driving cycle (start-up modified, no 40 s idle) as a function of distance travelled for five of the cars tested in the Co-Nordic study at +22 °C ambient temperature.

As the average plotted in Figure 57 shows, slightly less than 500 m driving was needed to reach the 90 % level of accumulated emissions over the complete ECE15 driving cycle in tests at +22 °C ambient temperature. However, as the average in Figure 58 points out, driving for about twice the distance (954 m) was necessary for the same result at -7°C ambient temperature.

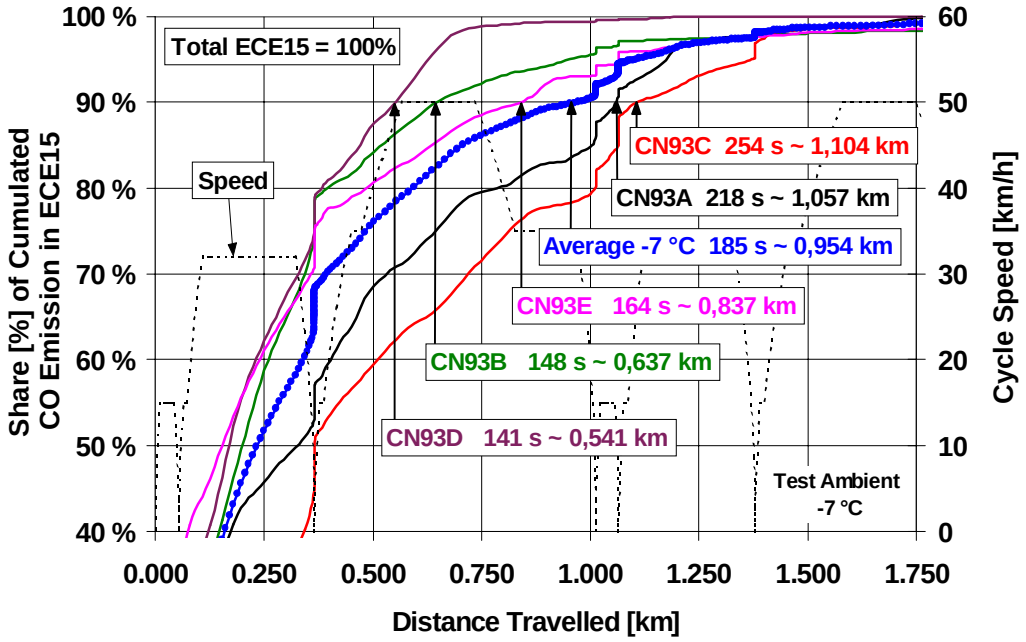

Figure 58 Share of total accumulated CO emissions over the front part of ECE15 driving cycle (start-up modified, no 40 s idle) as function of distance travelled for five of the cars tested in the Co-Nordic study at -7 °C ambient temperature.

Comparison on a vehicle-to-vehicle basis reveals rather strong variations in the performance of their emission control systems. At baseline temperature (+22 °C) vehicle CN93D, which was the one with the lowest overall CO emissions, produced 90 % of the total output over the ECE15 driving cycle already at about 150 m driving. Furthermore, in a test at -7 °C ambient the same car needed only some 500 m to reach 90 % level of total ECE15 cycle output. This was nearly 50 % below the average distance.

On the other hand, vehicle CN93E needed more than 1 km driving at +22 °C test temperature to come up to the 90 % mark. However, in a test at -7 °C, the same car behaved rather differently, as 90 % level was attained already after some 840 m of driving. In spite of this relative sluggishness, this car had overall emissions second only to the best one, which was car CN93D just discussed. It was only this profile of emission accumulation that was different.

Figures 59 and 60 represent the results for accumulated HC emissions and Figures 61 to 62 their relative profiles in the same manner as results for CO emissions were previously plotted.

Regarding the accumulation of the hydrocarbon (HC) emissions, the pattern was almost similar to the one just described for the emissions of carbon monoxide (CO). As seen in Figures 59 and 60, quite large variations between different cars in their total emissions output were encountered at both test temperatures. Furthermore, this analogy was maintained based on the profile of the emissions output plotted on a relative scale in Figures 61 and 62.

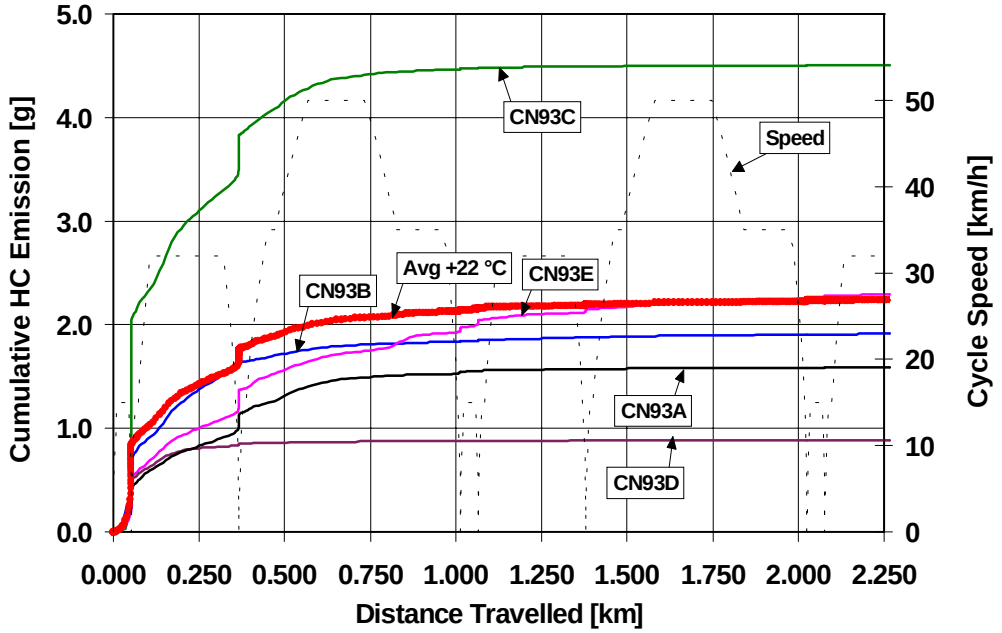

Figure 59 Accumulated emission of HC over the front part of the ECE15 driving cycle (start-up modified, no 40 s idle) as a function of distance travelled for the five of the cars tested in the Co-Nordic study at +22 °C ambient temperature.

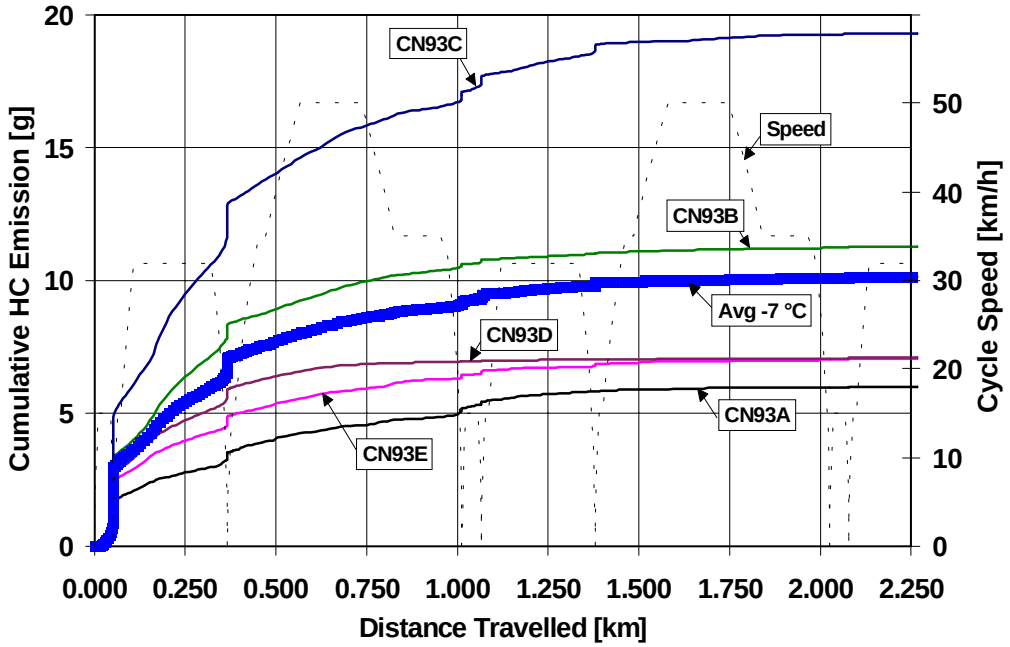

Figure 60 Accumulated emission of HC over the front part of the ECE15 driving cycle (start-up modified, no 40 s idle) as a function of distance travelled for the five of the cars tested in the Co-Nordic study at -7 °C ambient temperature.

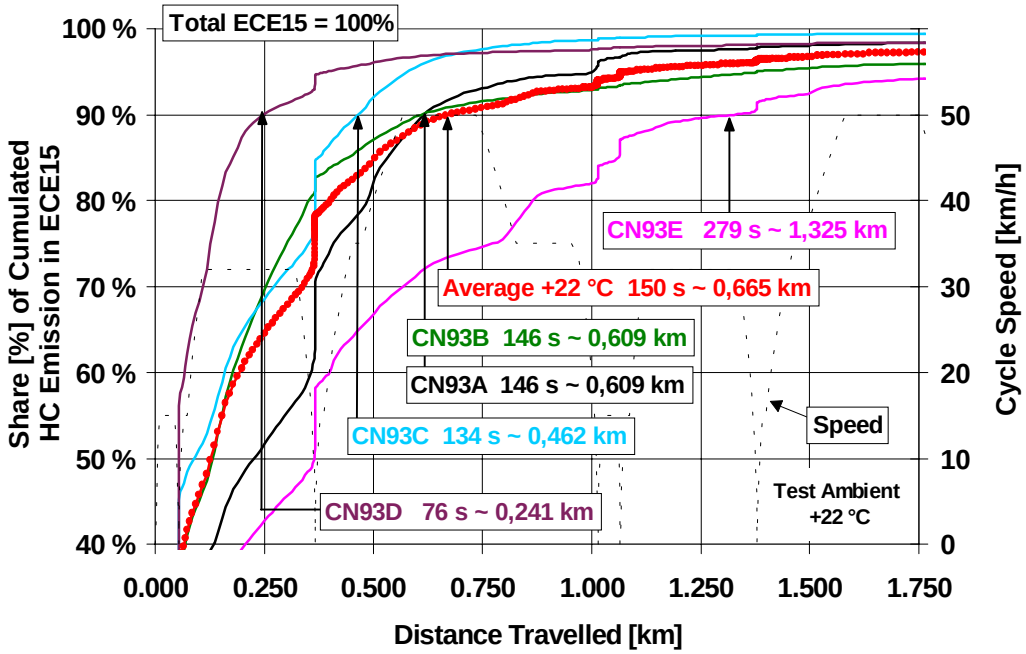

Figure 61 Share of total HC emission over ECE15 driving cycle (start-up modified, no 40 s idle) as a function of distance travelled for the five of the cars tested in the Co-Nordic study at +22 °C ambient temperature.

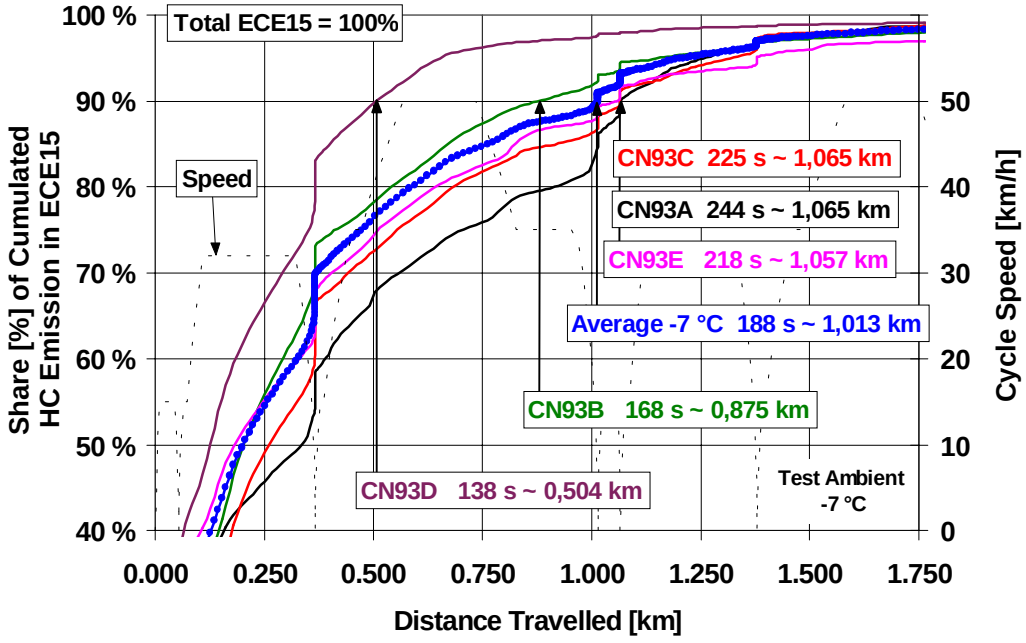

Figure 62 Share of total HC emission over ECE15 driving cycle (start-up modified, no 40 s idle) as a function of distance travelled for the five of the cars tested in the Co-Nordic study at -7 °C ambient temperature.

Regardless of the ambient temperature during the test, the profiles for the car CN93D were quite sharp-rising both for CO and HC, as well. Only some 500 m of driving was needed to reach stabilized operating conditions even at the low ambient temperature of -7 °C, which was about the same distance as in case of CO emissions, as well. Moreover, car CN93E had a rather slow-reacting emission control system even for hydrocarbon control, as well more than 1 km was travelled before the emissions output levelled. Quite in line with the performance of this car in terms of CO emissions, relatively low level of total HC emissions was retained, though.

The profiles of emission accumulation for both of these pollutants discussed so far were more widely spread at +22 °C ambient than in the case of -7 °C ambient temperature, which can be seen when comparing Figure 57 to Figure 58, and Figure 61 to Figure 62.

Figures 63 and 64 present the results for NO_X accumulation over the driving cycle as a function of distance travelled in the NEDC driving cycle. Rather than limiting the display just to the foremost 2 km of the driving, as was done with CO and HC emissions, figures contain full length of the cycle. This is logical, because one can immediately see when looking at these figures how the emissions of NO_X are more widely spread over the entire length of the trip, rather than emitted at the very first kilometre, like those other pollutants just discussed.

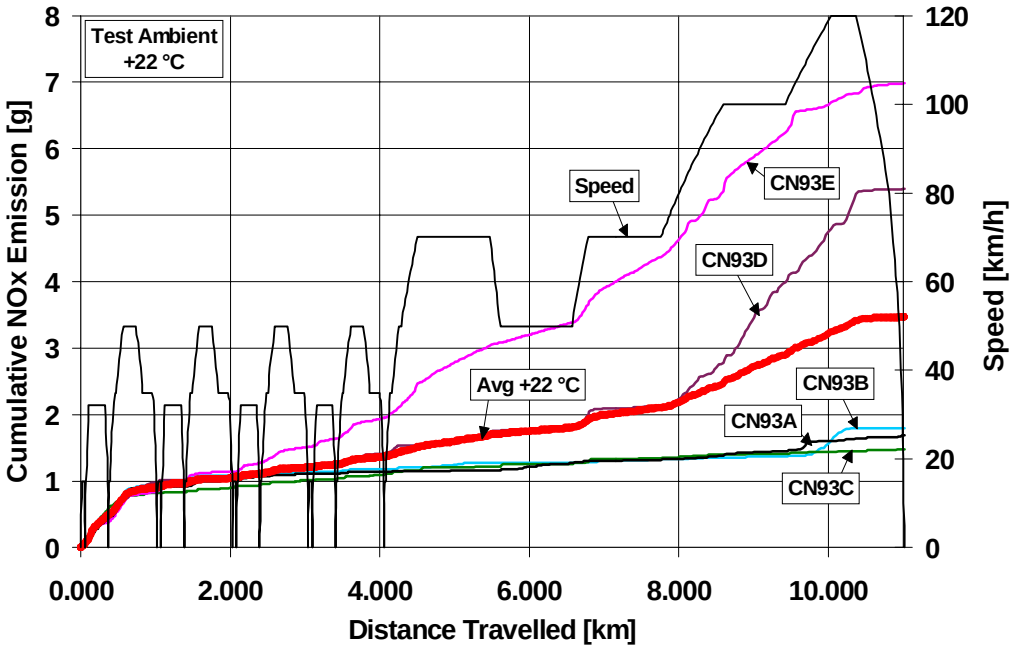

Figure 63 Accumulated emission of NO_x as a function of distance travelled in NEDC driving cycle (start-up modified, no 40 s idle) at the ambient temperature of +22 °C for five of the cars tested in the Co-Nordic study.

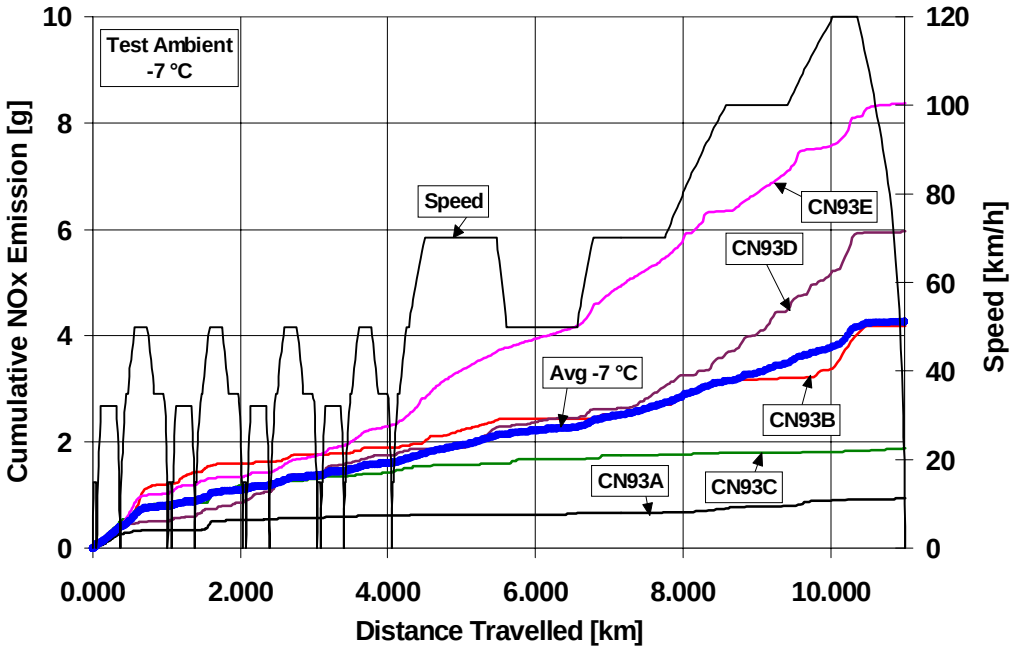

Figure 64 Accumulated emission of NO_x as a function of distance travelled in NEDC driving cycle (start-up modified, no 40 s idle) at the ambient temperature of -7 °C for five of the cars tested in the Co-Nordic study.

Furthermore, Figures 65 and 66 present the accumulation of NO_X more specifically in the front part of the driving cycle, in analogy with the corresponding figures for CO and HC emissions.

In addition, the accumulation is presented in relative scale in Figures 67 and 68. Unlike with CO and HC, where the basis was cumulated emission in the ECE15 cycle, this time the emissions are scaled to the total output in the full driving cycle, i.e. ECE15+EUDC=NEDC. Therefore, the figures are not directly comparable to the aforementioned presentation for CO and HC emissions, but as the output of CO and HC occured nearly 100 % over this urban portion of the NEDC cycle, they are closely parallel. This kind of choice was made since some of the vehicles tested produced rather irregularly excess emissions of CO and HC during the high-speed mode in the EUDC cycle. Therefore, choosing total NEDC output for the basis of a relative scale would have lead to misleading conclusions of the importance of the first part of the driving.

When the total accumulated sum of NO_X and its spread over the driving cycle is considered, it can be immediately seen how very little effect the low ambient temperature has on NO_X. This was quite a contrast to CO and HC emissions, where falling ambient temperature had much more stronger effect. On average, these five cars emitted some 3.5 g of NO_X at +22 °C ambient and only slightly more, about 4.2 g at -7 °C ambient temperature.

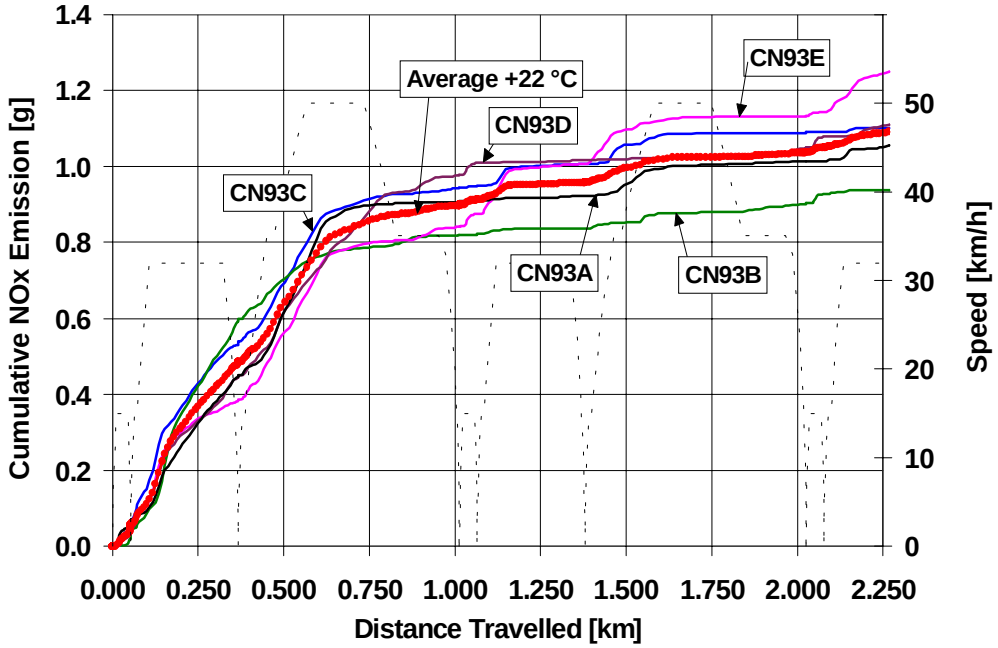

Figure 65 Accumulated emission of NO_x as a function of distance travelled in ECE15 driving cycle (start-up modified, no 40 s idle) at the ambient temperature of +22 °C for five of the cars tested in the Co-Nordic study.

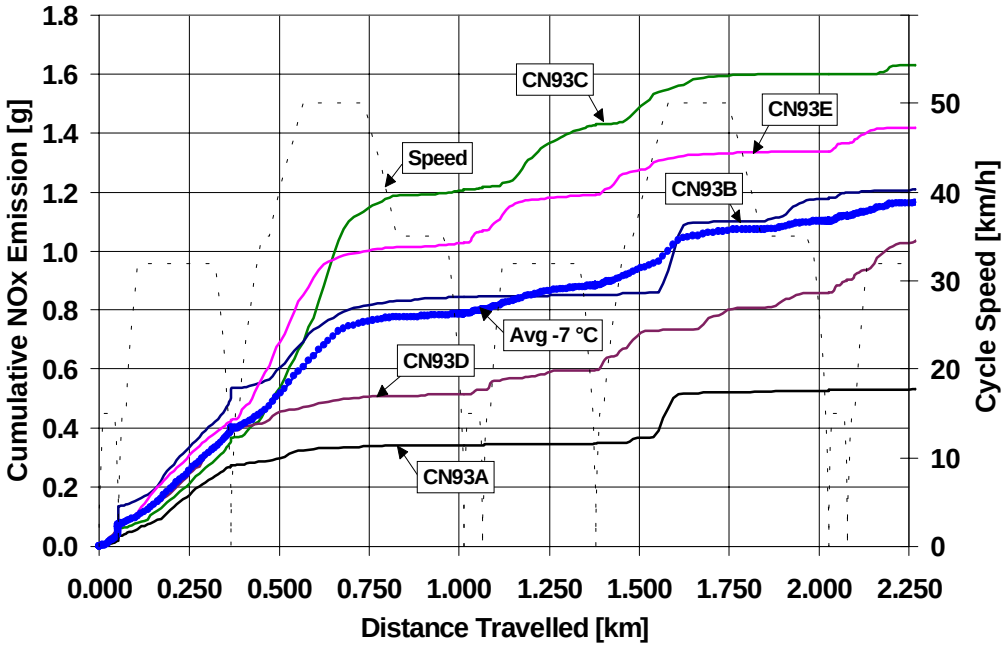

Figure 66 Accumulated emission of NO_x as a function of distance travelled in ECE15 driving cycle (start-up modified, no 40 s idle) at the ambient temperature of -7 °C for five of the cars tested in the Co-Nordic study.

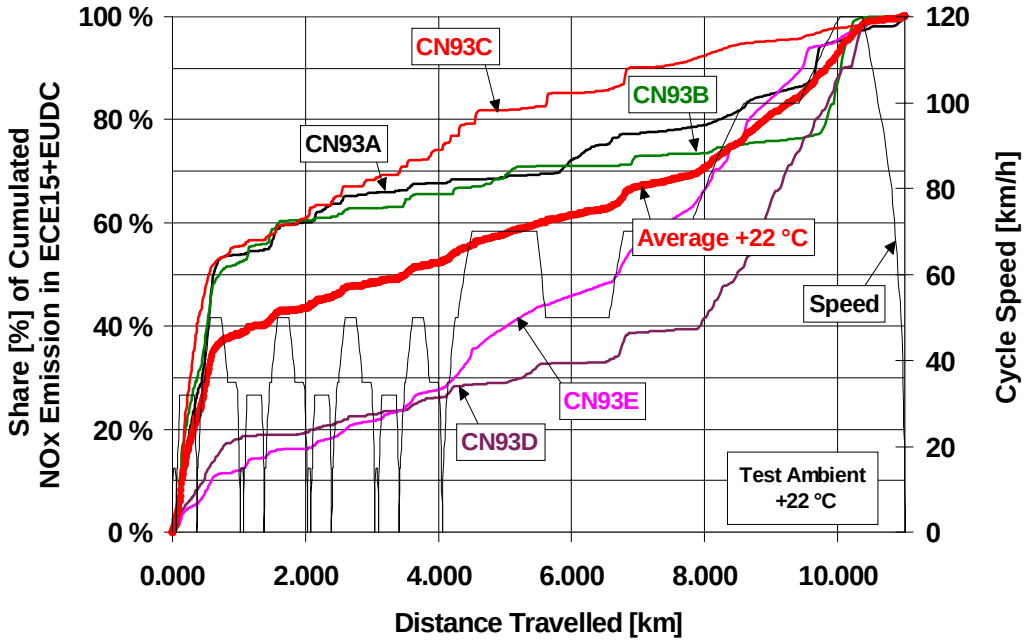

Figure 67 Share of cumulated NO_x emission as a function of distance travelled in NEDC driving cycle (start-up modified, no 40 s idle) at the ambient temperature of +22 °C for five of the cars tested in the Co-Nordic study.

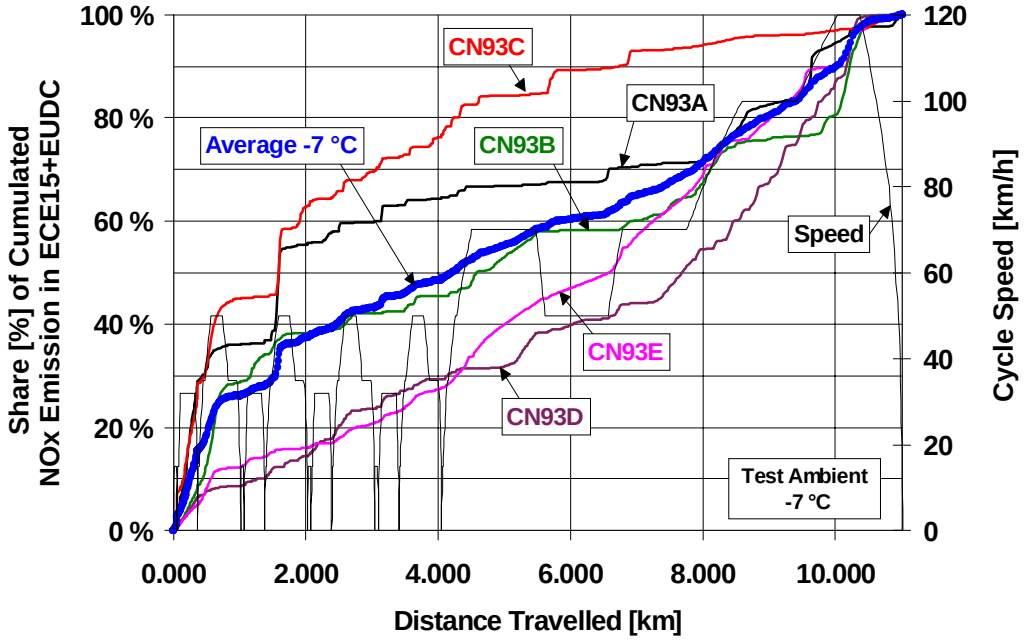

Figure 68 Share of cumulated NO_x emission as a function of distance travelled in NEDC driving cycle (start-up modified, no 40 s idle) at the ambient temperature of -7 °C for five of the cars tested in the Co-Nordic study.

In the weighing of individual cars, one could notice how cars CN93A, CN93B and CN93C had very similar performance in output of NO_X at +22 °C ambient laying some 50 % below average (Figure 63). However, at -7 °C ambient some differences were accounted. The almost identical performance of all tested cars during the first two kilometres of driving according to the initial cycles of ECE15 at +22 °C shown in Figure 65 was altered at -7 °C. Figure 66 shows how vehicle CN93A retained its good emission control even at this low ambient temperature, but cars CN93B and CN93C took a different route. Of these two, especially car CN93B had very much higher output of NO_X during the initial cold-start phase at -7 °C. In spite of this, it did not produce the highest overall figures over the complete NEDC cycle, as vehicles CN93D and CN93E recorded much higher rates during the EUDC phase like they did at +22 °C, as well.

This difference in the functioning of the cars is very well displayed in Figures 65 and 66, which show how cars CN93D and CN93E retained almost similar profiles for the output regardless of the ambient temperature, and were producing NO_X in much higher total amounts compared with those other three in this five-car sub-fleet. After the initial cold-start phase, where all cars were emitting at very similar rates, NO_X was produced in vehicle CN93D especially during the high-speed mode (over 80 km/h) of the NEDC driving cycle. Moreover, car CN93E emitted NO_X at high rates during all modes of operation after the initial cold-start phase. This was in accordance with all expectations, as this vehicle was using an engine with lean air-fuel ratio strategy at part-throttle operation thus being more susceptible of losses in NO_X conversion efficiency.

Turning now over to Figures 67 and 68, which show the emissions of NO_X in a relative scale, where total NEDC output is 100 %, it can be seen, how the ambient temperature had only a minor effect on the average values, because in both of the cases 50 % level is accomplished at about the end of the ECE15 cycle. Individual vehicles had different behaviour, though. At baseline temperature (+22 °C), cars CN93A, CN93B and CN93C were balancing their emissions very heavily on the cold-start and warmup phase, putting out 50 % of the total sum already well before passing the 1 km mark. Furthermore, even at -7 °C ambient, cars A and C were strongly affected by the first 2 km of the driving, reaching some 60 % of their total output at the end of the second initial ECE15 sub-cycle. Car CN93B, however, was less offset, producing then closer to the average buildup of emissions and balancing the output almost equally between the ECE15 cycle, which is some 4 km in length, and the extra-urban EUDC portion, responsible of the remaining distance of the full 11.07 km comprised in the NEDC driving schedule.

The totally different distribution of the emissions of NO_X with the remaining two cars is apparent and well-displayed also in these figures with relative scaling. Even their relatively low sensitivity to the ambient temperature level is well-dis

played, as the traces of relative accumulation as a function of distance travelled in the test are nearly identical at both of the test temperatures. Both of these cars, vehicles CN93D and CN93E, needed 7 to 8 km to reach the 50 % level, because of their strong output in the high-speed EUDC cycle.

6.3.2 Instantaneous concentrations and emission rates

A further "dynamic" analysis of the effect of ambient temperature conditions on the instantaneous emission output was done based on the data collected from a four-car sub-fleet run parallel to the main Co-Nordic study already discussed in 6.2.4. In this series commercial, oxygenated petrol was used for fuel, except with car CN93C, which used test fuel complying with the specifications for reference petrol (CEC RF-08-A-85) without any oxygenates. This detail in fuelling was regarded not to have any major effect on the air-fuel mixture strength or profiles of enrichment during cold-start and warmup running, hence the fuel feed is, in this mostly open-loop phase subsequent to the cold-start, mainly driven by the engine coolant temperature and not adjusted by the oxygen sensor, which would possibly react to the oxygenates in the fuel. Therefore, the data obtained from vehicle CN93C was used with the others to form four car sub-fleet averages.

Because previous studies had quite solidly manifested that ambient temperature affects mainly CO and HC emissions, this examination was limited to these pollutants only. The analysis is presented in detail in Appendix 6, because it entails so many illustrations, and placing all of them among the main text was considered inappropriate. In this Appendix a general pattern is followed, where one figure displaying concentration and another one illustrating instantaneous emission output are given separately for both of the pollutants (CO and HC) and each of the three test temperatures (+22, -7 and -20 °C). As a rule these figures give traces individually for each of the four tested cars in this sub-fleet, as well as an average calculated as an unweighted sum from the instantaneous values of each individual car. The traces for individual cars were here merely representing the disperse of the performance. Therefore, the choice was made not to mark individual cars into the figures in an attempt to emphasize the average nature of the value and generalize this approach rather than pointing out the behaviour of any type of car in particular.

The outcome of the analysis is presented in four figures combining the average values from each of the temperatures. In these figures, 2^{nd} order polynomials are fitted to the data to form a kind of simple mathemathical model of the situation. Figures 69 and 70 portray values for CO, whereas Figures 71 and 72 illustrate the outcome of the analysis for the HC emissions.

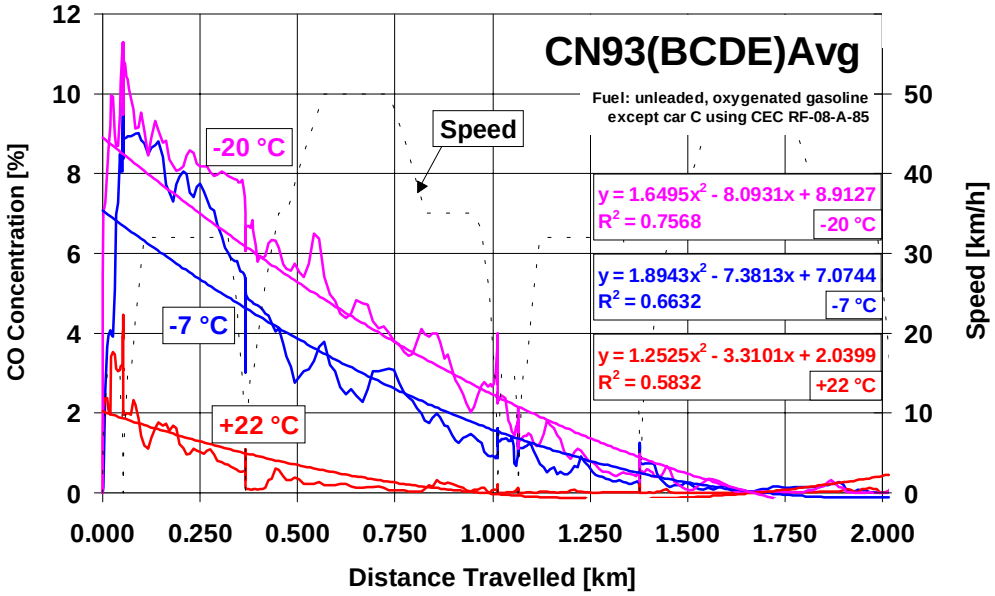

Figure 69 Concentration of CO as a function of distance travelled in ECE15 driving cycle (start up modified, no 40 s idle) at +22, -7 and -20 °C ambient temperatures as an average for this four car sub-fleet in the Co-Nordic study and 2nd order polynomials fitted to the data.

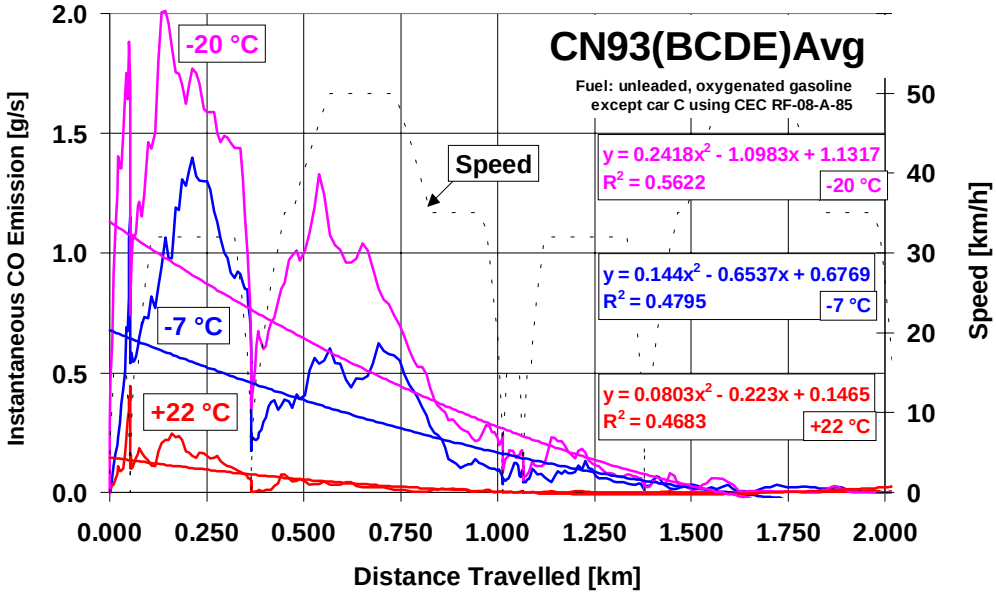

Figure 70 Instantaneous CO emission rate as a function of distance travelled in ECE15 driving cycle (start up modified, no 40 s idle) at +22, -7 and -20 °C ambient temperatures as an average for this four car sub-fleet in the Co-Nordic study and 2nd order polynomials fitted to the data.

As one would see, when comparing the average CO concentration traces in Figure 69, the concentrations are highly elevated right after a cold-start even at the mild sub-zero temperature (-7 °C), and even more at the lowest temperature included in this study (-20 °C). Equally distinct was the increase in CO output rate, portrayed

in Figure 70. This instantaneous emission rate is perhaps even more indicative of the low-temperature emissions performance than the concentration alone, because it links concentration values to the exhaust flow, which in an SI engine is modulated by the throttle according to the driving cycle. The outcome is a pollutant mass flow rate indicating how much CO is produced during each portion of the cycle. This "modulation" can be seen when comparing concentration traces with the mass flow rate traces: concentration tends to even out gradually as the engine warms-up, but the mass flow oscillates more clearly according to the speed-demand of the driving cycle, and the driver actuates the accelerator accordingly. This is most distinctive in the acceleration modes of the cycle.

If one would consider the differences between individual cars, which is possible by viewing the detailed figures in Appendix 6, one would see that they were rather sizeable even among this small four-car sub-fleet. The best car was superior, i.e. emitting less CO, even at -20 °C than the poor-performing ones at -7 °C. The probable cause for such a heavy enrichment seen in some of the cars was that the manufacturers had presumably chosen such a fuelling strategy in view of ensuring the driveability and avoid hesitation during warmup running. Yet, no reports of any problems with driveability were recorded for any of the vehicles, not even for those having very mild enrichment. This suggests that at least for some designs and manifold configurations it was possible to tune the engine to run with less enrichment than currently employed in most of the cases.

The polynomial functions fitted to the averaged data suggested that the engine warmup time (or distance) was not necessarily a function of ambient temperature in sub-zero conditions. This hypothesis was set on the basis of denoting, at both of the sub-zero temperatures considered, almost identical distances driven from the start to the point, where the excess emission rate (or the elevated concentration) caused by the cold-start and cold engine running seemed to "phase out", i.e. approach asymptotically a zero-value. Even if the concentration and subsequent emission rate were markedly higher at -20 °C than at -7 °C, the traces representing the average functioning met at about 1.6 to 1.7 km of driving. At +22 °C, however, this happens already well before the 1 km milemarker, which is illustrated in Figures 7 and 8 in Appendix 6.

Furthermore, very similar performance was attained in terms of HC emissions. As seen in Figure 71, high concentration peaks, averaging over 4000 ppm, were observed already at normal ambient temperature. However, they were quite short in duration. At lower ambients these elevated concentrations were attained for quite some time. At -7 °C, the average concentration level was above 2500 ppm for the first 500 m of driving in all tested cars. At -20 °C, this level rose to about 5000 ppm. Subsequently, the instantaneous rate of HC emission, portrayed in Figure 72, was more than three times the rate at normal ambient for the first 1 km of driving

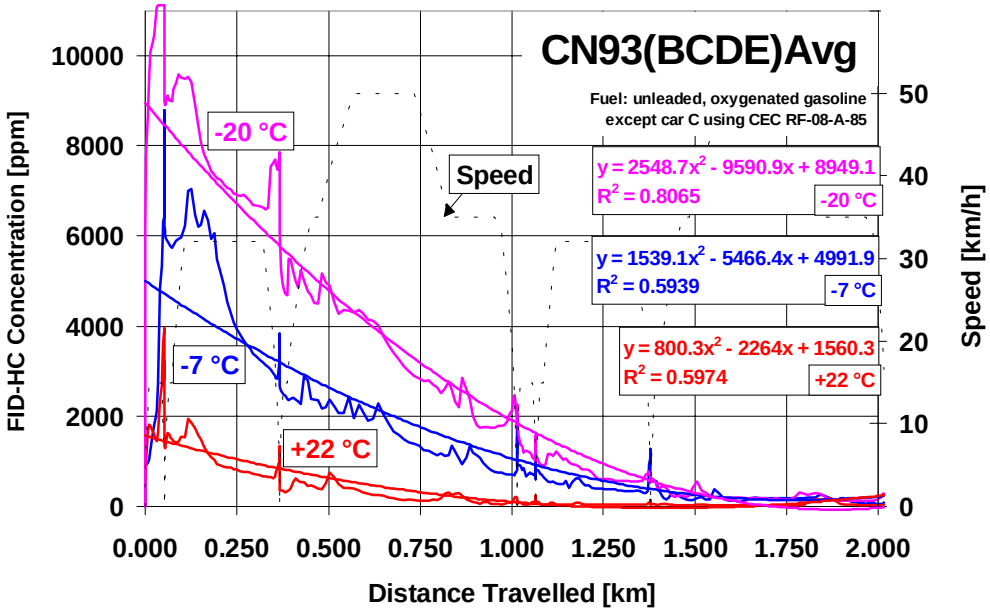

Figure 71 Concentration of HC (FID) as a function of distance travelled in ECE15 driving cycle (start up modified, no 40 s idle) at +22, -7 and -20 °C ambient temperature as an average for this four car sub-fleet in the Co-Nordic study and 2nd order polynomials fitted to the data.

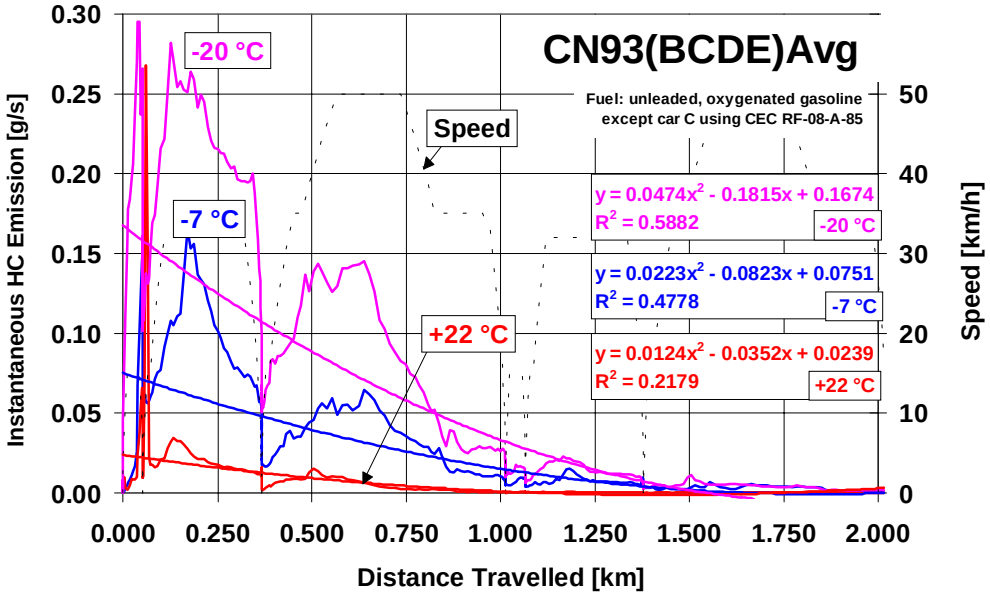

Figure 72 Instantaneous HC emission rate as a function of distance travelled in ECE15 driving cycle (start up modified, no 40 s idle) at +22, -7 and -20 °C ambient temperature as an average for this four car sub-fleet in the Co-Nordic study and 2nd order polynomials fitted to the data.

at -7 °C, and nearly sevenfold at -20 °C, compared with the performance recorded at normal ambient temperature. This is quite in line with the observed increases in average emissions for bag 1, as well, which have been discussed earlier in this chapter.

6.4 PROFILE OF THE LOW-TEMPERATURE EMISSIONS PERFORMANCE OF NEW CARS: THE TM STUDY

6.4.1 General description of the study

The emissions performance of new cars at low ambient temperature has been studied at VTT Energy in cooperation with a Finnish consumer technology-oriented magazine "Tekniikan Maailma" during 1993-1997. The purpose of this study, referred as the TM study in this report, was to give the public a better perception of the real-world emissions performance of new passenger cars. The differences among new cars are moderate on type approval level, where the emissions are measured at normal ambient temperature. However, the effectiveness of the emission control systems was expected to vary much more in low-temperature conditions, that are more close to the actual operating conditions of cars in service. Therefore, a test series to evaluate low-temperature emissions performance was initiated as a part of the annual winter testing program contained in the magazine's new car test series, which evaluates new motor vehicles for the purpose of providing additional information for the new car buyers and motorists in general.

Some of the results of this study has previously been reported in the articles published in the magazine "Tekniikan Maailma".

6.4.2 Test vehicles

The test series was initiated in 1993, and was repeated annually until 1997. The test vehicles for each of the annual fleets were picked by the editorial staff of the magazine. In most of the cases this was made quite randomly, either forming groups that are comparable in some way, usually vehicle size and engine displacement, but some fleets were just representing typical vehicle types of that particular year. As a whole, however, the total fleet of tested cars, altogether 57 different types, pursues some kind of cross-section of the average Finnish new car fleet, i.e. those registered in 1993 and onwards.

In view of the emissions certification the test fleet breaks into two categories. From 1990 until 1996 all new cars of that era were certified according to the requirements derived from the US Federal standards for model year 1987. This practise was shared with other EFTA countries (Sweden, Austria, Norway and Switzerland), which made the cars somewhat different from the model marketed in other European countries following either the directives of the European Community or the ECE regulations. From 1995 onward a parallel recognition of EC type approved vehicles has been possible, and some of the new types of model year 1996 were certified according to the directive 94/16/EEC. Since 1997 it has been the only option.

Excluding a few small cars, the basic technology used in these vehicles has mostly been what could be considered typical for present-day mid-sized cars for the European market: a single underfloor three-way catalyst in connection with closed-loop air-fuel ratio control using a single exhaust gas oxygen sensor and multi-point fuel injection equipments. Even some of the most novel additional features, like air pumps, has been used in some cars. Some main characteristics of the cars used in this study are given in Appendix 1. It also identifies car types with their respective ID# used later on in the figures.

6.4.3 Features of the test program

In view of limiting the expenditure involved, this test series was limited to one cold-test only for each car with no parallel test at normal ambient temperature. Therefore, the accuracy and statistical value of the results are only moderate, and it has not been possible to determine the sensitivity of the cars to low ambient temperature like was done in the previous, Co-Nordic study.

The test temperature was set at ±0 °C. Although it can be considered as a typical low ambient for Europe in wintertime, this choice was made mainly for practical reasons. Because of the large number of vehicles to be soaked simultaneously, the test cell space normally used for conditioning of the vehicles prior to the testing was not large enough anymore. Instead, cars were parked in an outdoor space for an overnight soak. Expected ambient conditions at the time of testing in mid-January were quite close to ±0 °C, and this concluded the decision. Fortunately the weather conditions have been quite consistent and this temperature level has been predominant each year, giving sufficient comparability for the results across the whole series.

Throughout the study, the US EPA FTP75 test cycle was used. However, in order to shorten the time involved, only the first phase of the driving schedule was used. This portion, referred also as “Cold Transient” (Y_{ct}), comprises the first 505 seconds of the cycle, and gives, according to the experience at VTT, a very good assessment of the low-ambient emissions, as usually more than 95 % of the CO and HC emissions and some 80 % of the NO_X is contained in the bag collected during this period of the test. In later years (1996, 1997) the full FTP75 schedule has been employed, but the 10 minute pause between Y_{hs} and Y_{ht} phases (bags 2 and 3) was shortened to 1 minute only, thus giving a better estimate of warmed-up emissions performance, as well.

The choice of the driving cycle was at first based on the initial certification of the cars. However, it was retained later on, even if the type approval was now carried over according to the European standards, because it was felt that the US test cycle would embody more actual driving and the results would be much better re-presentation of the real-world performance of the car and its associated emission control systems.

As this study was supposed to produce real-world emissions data, commercial unleaded RON95 fuel was used in all tests. During the first two years (1993, 1994) the main market fuel in Finland was of an oxygenated quality introduced in 1991, with some 11 % of MTBE added giving 2 % typical oxygen content for the fuel. Furthermore, since spring of 1994 the most common market fuel quality has been of the reformulated type, with very low sulfur level (< 0.01 %) and less than 1 % benzene. As oxygenates (MTBE or TAME) are still added into the fuel to give a typical 2 to 2.7 % oxygen contents, results fairly comparable to those obtained in earlier years should be attained. Product information data sheets of some of the commercial fuel grades available in Finland during 1993-1997 are included in Appendix 2.

As the tests were all performed in January, winter quality fuel (REID vapour pressure < 90 kPa) was automatically used, which was good for the cold-start performance and driveability of the cars.

6.4.4 Main results

Only the regulated exhaust constituents (CO, HC, NO_X) were measured in this study. However, in addition to the normal bag sampling, continuous method allowing the determination of the instantaneous concentrations and emission rates was employed. This allowed also resolving of the starting point for effective emission control system operation. This was made based on the converter-out (or rather tailpipe) concentration of CO. When the concentration value fell below 0.5 % (vol.), the cycle time was recorded as "light-off point" and referred as $T_{light\text{-}off}$. However, this is not the same as T_{50}, which determines 50 % conversion rate, and is usually the base for light-off performance evaluation.

The main results of this study are presented in five figures. Figures 73 to 75 give the specific emissions of CO, HC and NO_X, respectively. Additionally, emission control system performance is presented in Figure 76 as $T_{light\text{-}off}$ time, determined as just discussed. Furthermore, Figure 77 gives the same comparison, but this time as distance travelled during the $T_{light\text{-}off}$ time, because it was felt that this would provide a more realistic assessment of the system performance than the time-based evaluation alone.

In these figures, values are presented not only for individual cars, but also as averages for each of the annual test fleets. It is assumed that these averages would represent typical performance of cars of a given model year, although the compilation of the annual fleets was somewhat arbitrary, as discussed before in 6.4.2. Furthermore, a value for standard deviation is also presented for each of these fleets. In each of the figures, cars are presented in the same rank order. It is based on the CO emission results so that in each of the annual sub-fleets, the one with the highest value in the group is the topmost, and the rest are counted downwards in their respective order.

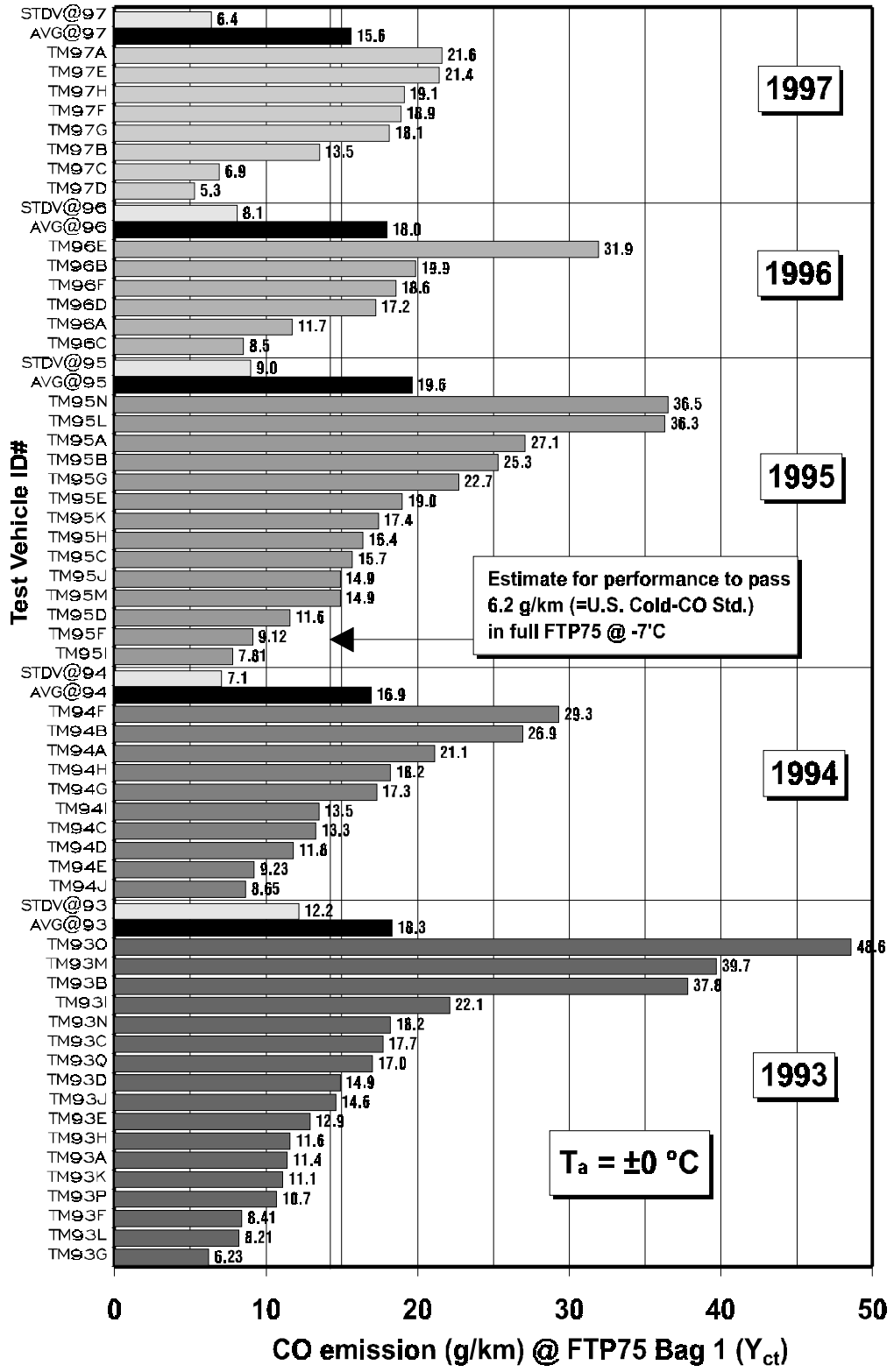

Figure 73 Emissions of CCO in Bag 1 of FTP75 test at ± 0 °C ambient temperature as values for individual cars with averages and standard deviations for the subsequent annual fleets in th TM study.

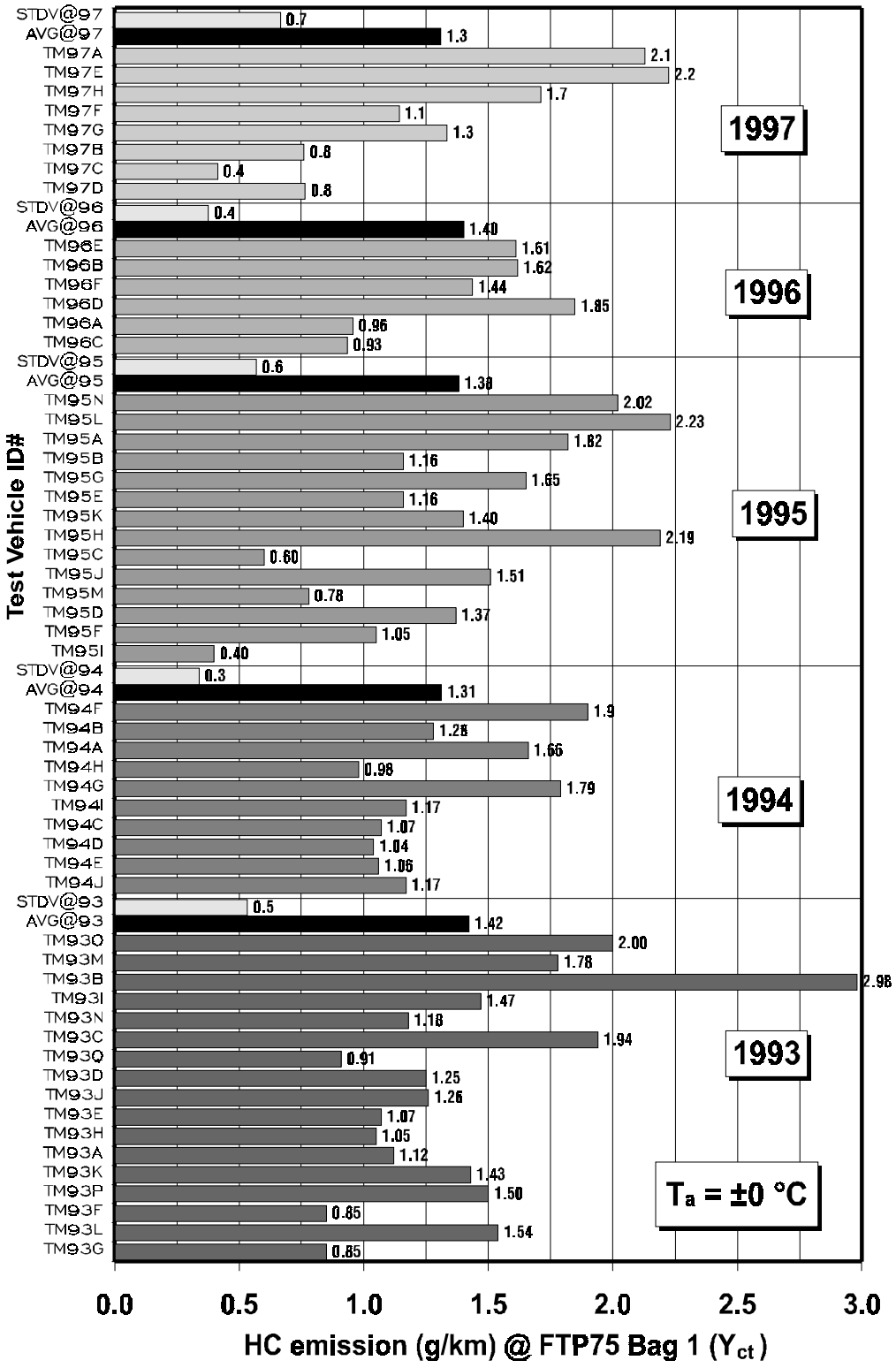

Figure 74 Emissions of HC in Bag 1 of FTP75 test at ± 0 °C ambient temperature as values for individual cars with averages and standard deviations for the subsequent annual fleets in th TM study.

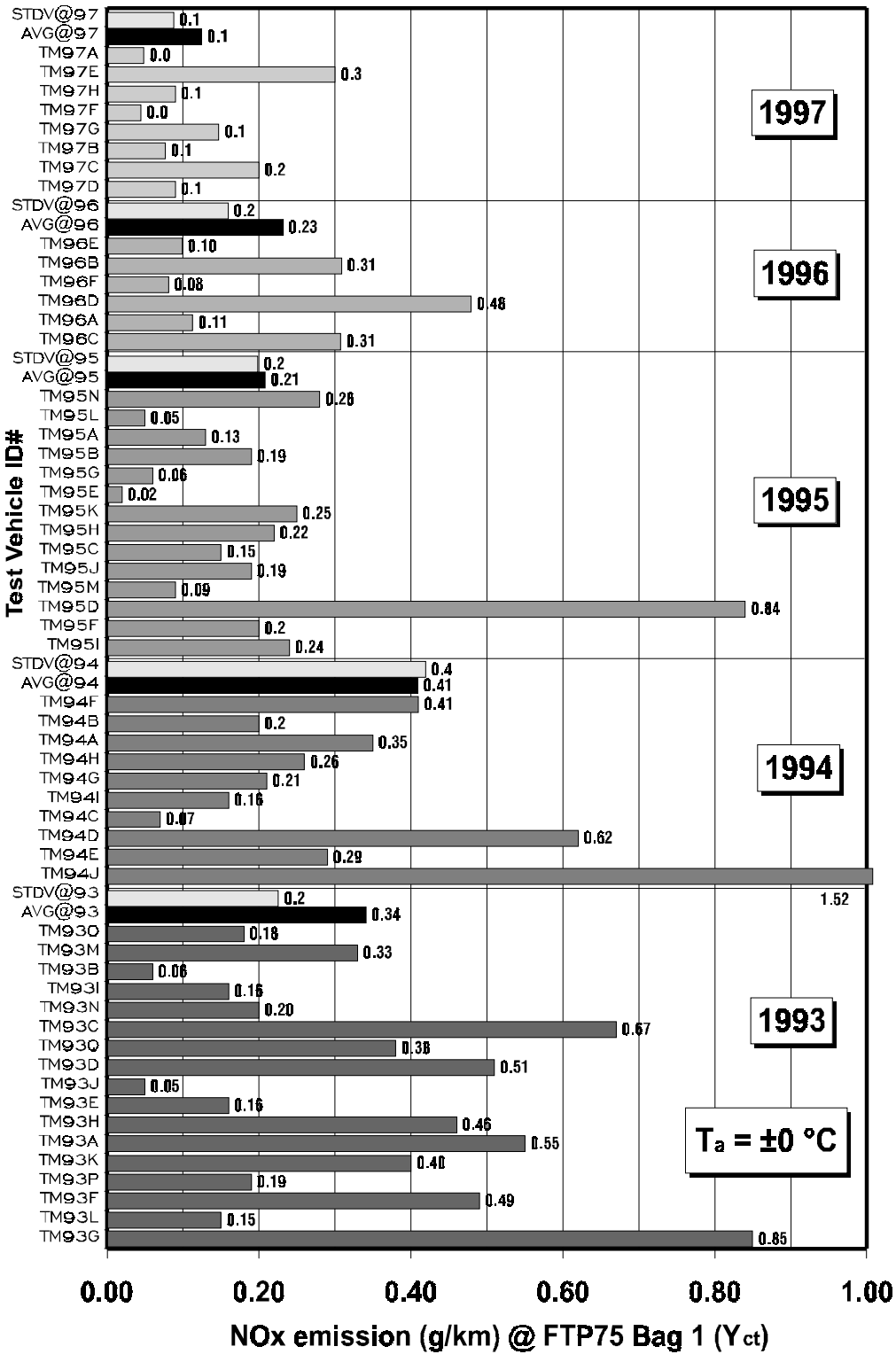

Figure 75 Emissions of NO_x in Bag 1 of FTP75 test at ± 0 °C ambient temperature as values for individual cars with averages and standard deviations for the subsequent annual fleets in th TM study.

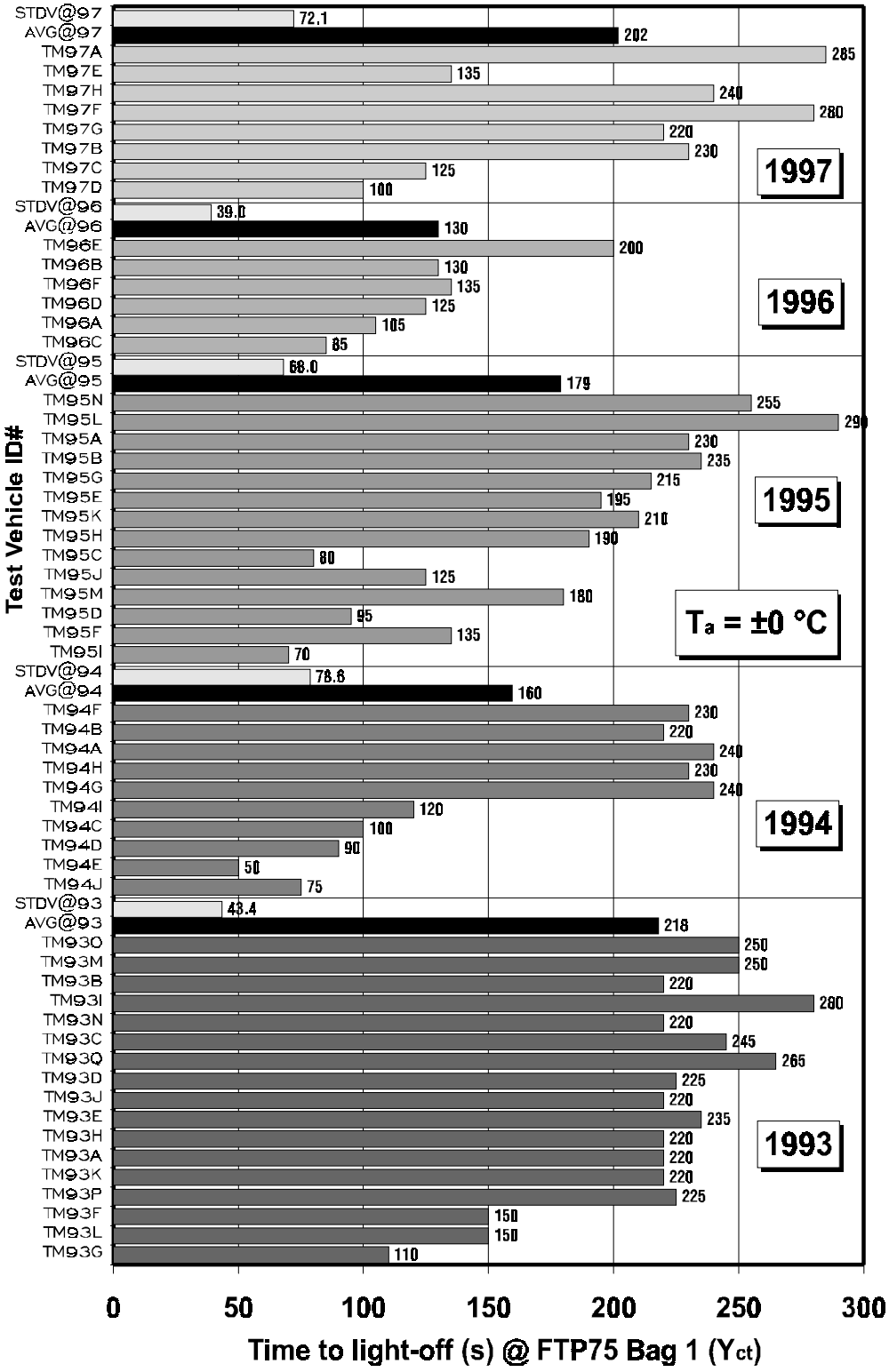

Figure 76 Time to reach light-off in FTP75 test at ± 0 °C ambient temperature as values for individual cars with averages and standard deviations for the subsequent annual fleets in th TM study.

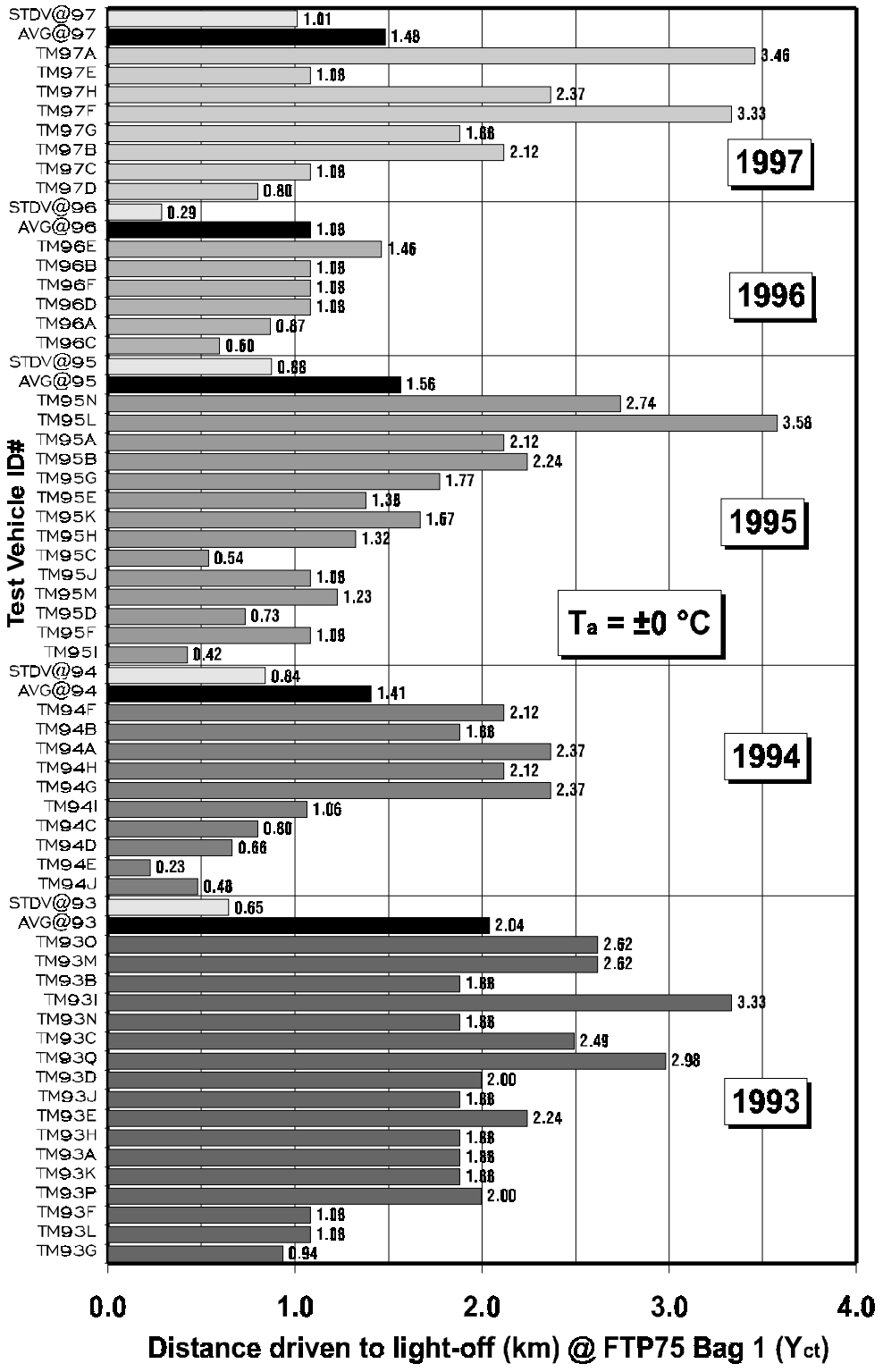

Figure 77 Distance driven to reach light-off in FTP75 test at ± 0 °C ambient temperature as values for individual cars with averages and standard deviations for the subsequent annual fleets in th TM study.

Considering first CO emissions, Figure 73 clearly shows how cars that shared the same basic technology and were certified against the same set of standards (EFTA/US'87) were performing very differently even at a very moderate low ambient temperature. The best of all tested vehicles (TM97D) emitted only 5.3 g/km during the cold transient portion of the FTP75 driving schedule. At the other end of the scale, the car (TM93O) with the highest CO output of all cars in these fleets showed almost a tenfold emission rate at 48.6 g/km.

Actually, this was not as surprising as it may, because none of the tested cars had been optimized or type approved against any low-temperature standard. Thus, other factors, such as cold driveability, have most likely been predominant in, e.g. calibrating the fuel delivery for cold-start and warmup drive. It was however, quite interesting to note that none of the cars, not even those having very low CO emissions, presented any specific driveability problem.

Even if there was no cold-temperature standard applicable for these cars, a kind of measure for their cold-temperature emissions performance could be postulated by calculating an estimate, what kind of performance would be needed in this type of test to pass the US Cold-Temperature CO Standard, set at 20 °F (-7 °C) for a full FTP75 cycle. This estimate was based on the following two hypotheses:

- linear growth of emissions with falling ambient temperature, so that if emissions at -7 °C are five times the emissions at +22 °C, emissions at ±0 °C are four times as high

- of the total emissions in FTP75, 95 % are contained in bag 1.

These assumptions led to the calculation of the estimate as follows:

(1) 6.2 g/km x 17.76 km = 110 g CO (for full FTP75)

(2) 110 g (at -7 °C) x 4/5 = 88 g (at ±0 °C)

(3) 0.95 x 88 g = 84 g (for Bag 1)

(4) 84 g / 5.779 km = **14.5 g/km**

Thus, a conservative estimate for emissions in this type of test (Y_{ct} at ±0 °C) was considered to be about 14 g/km for a car that would pass the current US Cold-Temperature CO Standard at 20 °F (-7 °C) for a full FTP75 cycle.

Taking this as a guideline to rate the performance, an estimated 22 cars out of the total of 55 cars would comply with the prescribed standard. This is 40 % of the total tested fleet. However, none of the yearly averages met this arbitrary guideline, even if the latest fleet (model year 1997) came close with the 15.6 g/km

average result. Furthermore, there seemed to be no apparent trend in the annual fleet average value, like it would decrease with later model years. The scatter, however, expressed in the form of standard deviation seemed to decrease slightly with the newer fleets. Nevertheless, this should not be taken as conclusive evidence, because the composition of each model year's test fleet was rather inconsistent, and would not represent any true average or cross section of the cars for a given model year.

Going further to the HC emissions presented in Figure 74, one would immediately see, that quite like with the CO performance just discussed, same kind of spread in the behaviour of the cars in respect of this exhaust constituent was encountered. A somewhat lower best-to-worst ratio, however, was recorded, as the cars with the lowest HC emission rates (TM95I and TM97C) were producing only 0.4 g/km of total HC, whereas the worst of the whole compilation of all the sub-fleets (TM 93B) presented a value of slightly below 3 g/km, which is less than eightfold compared to the best result.

Because the rank order of individual cars based on CO performance was retained in this Figure also, one would see that low CO emissions did not necessarily meant low HC value, as well. There were even a few rather contrasting examples with a low CO value, but with a quite high HC result. This discrepancy was quite easy to accept, if one thinks of the mechanisms of the combustion process and emissions formation in a cold-started engine. According to the well-accepted theories, CO is mainly derived as a product of incomplete combustion of fuel-rich mixture, whereas a high HC output is not only caused as remains of incomplete combustion, but also as a derivate of the condensation and subsequent evaporation of unburned fuel on the cold surfaces and crevices in the combustion chamber, a phenomen often called "wall wetting".

In order to further portray this non-dependency, Figure 78 gives a plot of Bag 1 HC vs. Bag 1 CO, where a trendline for the correlation is also plotted. The measure for this inconsistency can be seen in the R^2 value, which expresses in a numerical value how well the data fitted to the trendline. When $R^2=1$ would represent a "perfect fit" and true correlation of these two emissions, a value below 0.5, as in this case 0.47, could be considered as a rather poor evidence of correlation. The incurred meaning of this low level of correlation is that separate standards for both of these constituents are advisable, if a low-temperature test becomes a part of the type approval and certification process. Limiting CO alone, would not necessarily lead to lower HC emissions, too.

Furthermore, an almost reverse correlation could be found in terms of NO_X emissions, presented in Figure 75. At least in the three oldest annual fleets (1993, 1994 and 1995), cars having a low CO output, registered high NO_X values, and vice versa. However, many notable exemptions to this rule existed, especially in the mid-field of each fleet, thus combining a moderate CO result with the lowest-of-the-fleet NO_X output.

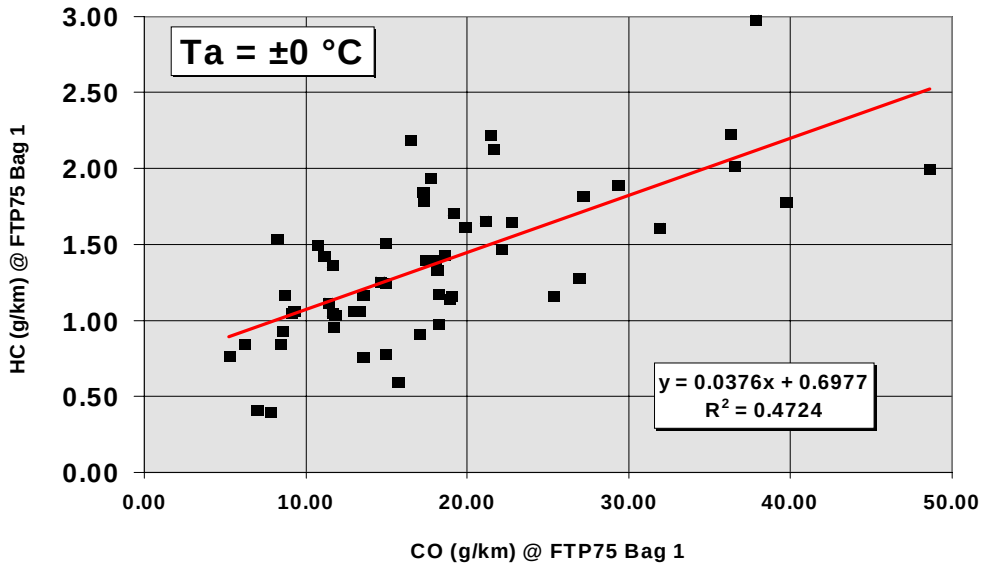

Figure 78 HC emissions (in Bag 1) as a function of CO emission (in Bag 1) for all of the tested cars in the TM study.

Among individual cars, the spread of results for NO_X was extremely wide. The highest value of all tested cars was 1.52 g/km (TM94J), but the lowest one (TM95E) was as low as 0.02 g/km. The best-to-worst ratio would then be more than 1:70, which is an extremely high value. This rather heavy disperse can also be seen in the values of standard deviation, which in most of the cases was close to the average value.

Whereas the average values of CO and HC calculated for each of the annual test fleets showed almost no change from one model year to another, there seemed, however, to be a slight downward trend with NO_X, as the later model years were showing lower average values than the earlier. Aside, one must again remember the random and non-statistical nature of the vehicle selection to these test fleets. Therefore, this finding of a lowering trend in NO_X must not be regarded as highly conclusive, especially when the deviations from one vehicle to another are so strong.

Going further over to the light-off time and distance travelled during the warmup, displayed in Figures 76 and 77, respectively, one would see that a low CO output, placing the vehicle in the figure in a low rank order within its group, as well, would also denote a short light-off time and short distance, which is actually only another scale for the same dimension, but more practical. It shows, how long one

has to travel on his or hers daily commute, before the emission control system starts to operate efficiently.

Of all the annual sub-fleets, the best ones and the worst ones have been picked up to draw Figure 79, which combines these values on a distance scale together with the driving speed of the FTP75 cycle.

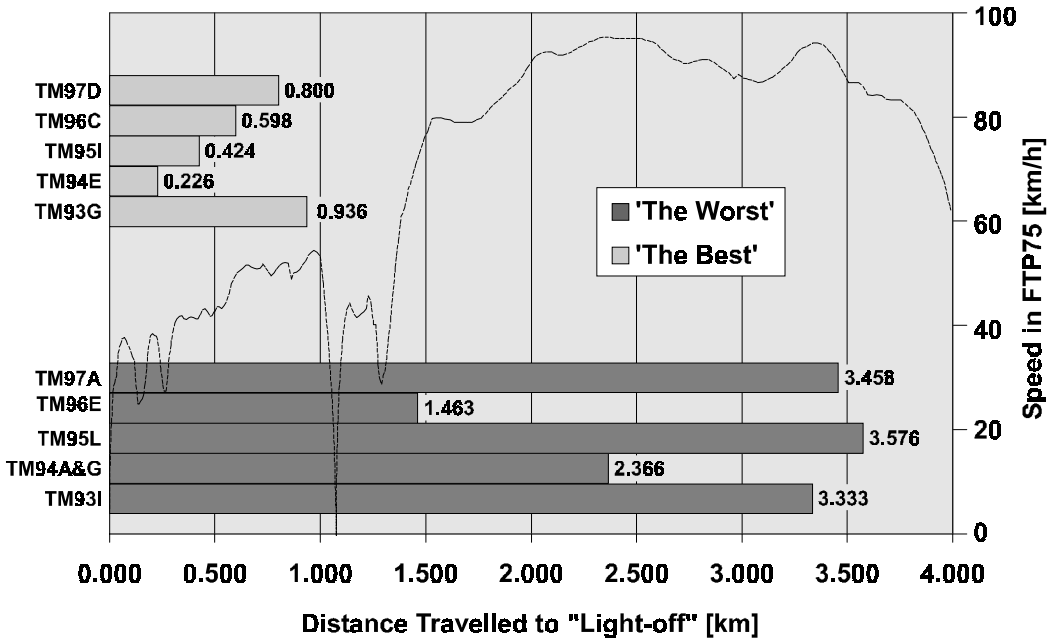

Figure 79 Distance travelled to the "light-off point", i.e. starting of efficient operation of the emission control system. The best and the worst cars from each of the annual test fleet. Tests at ± 0 °C ambient temperature.

It illustrates rather well how the start of operation in the fastest reacting cars coincides with the first “uphill” of the FTP75 driving schedule, i.e. the exceedence of 45 km/h speed, which occurs at about 600 m after the start. However, those cars that are activating their emission control system much more slowly, need as long as over 3 km of driving distance and a long period of high speed in the over 80 km/h range, which in FTP75 cycle starts at about 1.5 km mark.

6.5 CONCLUSIONS FOR THE EVALUATION OF THE PERFORMANCE OF MODERN TWC CARS

6.5.1. The effect of low ambient temperature

Based on the studies (Basic and Co-Nordic), the following conclusions upon the performance of modern-technology TWC cars at low ambient temperatures could be made:

Low ambient temperature caused elevated emission levels for carbon monoxide (CO) and unburned hydrocarbons (HC). The emissions of nitrogen oxides (NO_X), however, were largely unaffected. Furthermore, cars with a TWC system were, on average, more sensitive to the adverse effects of low temperatures than conventional cars without exhaust aftertreatment. However, the emission levels measured for TWC cars at low temperatures did not exceed those recorded for their non-catalyst counterparts.

It also appeared that vehicles with more sophisticated emissions control technology, represented in this study as cars certified as Emission Class 1 (*Miljöklass 1*), had, in spite of their very low emissions level at normal ambient temperature, and additional requirement of passing the US Cold-Temperature CO Standard included in the Swedish regulation for such vehicles, comparably or even stronger sensitivity to the lowering of the test temperature. Even if the number of such vehicles in this test fleet was only two, this result must be taken, if not conclusive, at least indicative of their peformance.

The four-car sub-fleet, which was subjected to further testing at extremely low ambient temperatures (-20 °C), showed that in such conditions further growth of CO and HC emissions was encountered. Especially the HC output increased strongly. Again, inconclusive NO_X performance was recorded.

6.5.2. Time-resolved analysis of the emissions output

The time-resolved, continous analysis of the emissions output revealed that in most of the cases, especially at the very low ambient temperatures, more than 90 % of the excess emissions generated over a given driving cycle were released during the first 1 km of driving. Furthermore, it clearly appeared that the emission control system works efficiently despite ambient temperature conditions once the engine and emission control system has reached their normal operating temperatures.

It was found, when analysing the instantaneous emission rates, that the enrichment was on average proportional to the ambient temperature, but was phased out almost at the same distance, about 1.6 km, after cold-start at both of the sub-zero temperatures (-7 and -20 °C) studied.

6.5.3. Evaluation of the latest technology

Although quite randomluy selected, the tested 55 different cars, representing each year's new models between 1993 and 1997, presented rather good cross section of modern-technology TWC vehicles. About 40 % of the total tested fleet were passing the arbitrary target level for expected compliance with the US Cold-Temperature CO Standard set at 10 g/mile in full FTP75 test at 20 °F ambient or with the similar 6.2 g/km at -7 °C limit value prescribed in the Swedish Environmental Class 1 specifications.

The total fleet-average low-temperature emissions performance for CO and HC did not appear to have markedly improved over the studied period. However, the scatter and "best-to-worst ratio" within the annual sub-fleets seemed to have been lessening somewhat over the years. Furthermore, for the NO_X emissions, slightly lower average emission levels were registered for the later model year sub-fleets compared to the averages for the earlier model years.

On average, some 1.5 km of driving seemed to be needed before the emissions control start working efficiently, if driving has been initiated with a cold-start at ±0 °C ambient temperature. Furthermore, the best-performing vehicles had their systems reaching sufficient control already at about 500 meters. The "worst cases", however, needed nearly 3 kilometers before their emission output leveled to normal operation.

7 THE EFFECT OF VEHICLE MILEAGE ON LOW-TEMPERATURE EMISSIONS

7.1 GENERAL DESCRIPTION OF THE IN-USE STUDY

7.1.1 Main objective of the study

The Finnish Vehicle Administration Centre (Ajoneuvohallintokeskus) has been contracting VTT Energy for investigations of the compliance of in-service catalyst-equipped vehicles with their respective certification standards, which apply today up to 80,000 km (or five years) of use. These tests, which were first conducted in 1994 and have been repeated in 1995 and 1996, provided an excellent opportunity to study also the effect of vehicle mileage on the low-temperature emissions performance. There was a definite need for this kind of assessment, as most of the prior work has been done on new cars having normally less than 20,000 km on their odometer. Yet, normal vehicles usually travel in service today at least 200,000 to 300,000 km, sometimes even much more, before they are written off. Therefore, estimating their true, in-use performance in regard of low ambient temperatures was highly desirable.

7.1.2 Test fleet composition

The choice of cars in this study was made by the Vehicle Administration Centre. The target was to cover most of the high-volume cars in the current Finnish vehicle park. Altogether 15 different types (i.e. make and model) of cars were tested. In all but one case, each type was represented by three vehicles. Due to a mismatch in the selection process, one type was of such an uncommon type, that the car importer, which was responsible for the delivery of the vehicles, could not supply more than two representative cars.

In the first sub-fleet (1994), the target was set on rather high-mileage vehicles. Therefore, most of the odometer readings in these cars, which were between model years 1990-1993, were in the range from 40,000 to 80,000 km. The second fleet (1995), however, contained fairly new vehicles between model years 1993-1995. Thus, their mileages were lower, mostly in the 10,000 to 30,000 km range. Some exemptions to this rule were counted, however, as a few of the cars had more than 60,000 km on their odometer. The third fleet (1996) consisted again of vehicles with fairly high mileage readings representing a broad range of model years between 1991 and 1996. The majority of these cars laid within 65,000 to 75,000 km range, with some notable exceptions even up to 90,000 km’s.

Emission control technology in most of these cars was based on a single three-way catalytic converter in an underfloor position and a multi-point fuel injection system with closed-loop control by an oxygen sensor. However, this was not the only option, as two types were equipped with electronically controlled carburetor and one type was using a single-point injection system. Appendix 2 lists all the vehicles used in this study and gives some more details of their technology.

7.1.3 Test programme

The basic test program consisted of three FTP75 tests for each car at normal ambient (+22 °C), with one additional test per car at a low ambient temperature, which was now -7 °C. This choice of low temperature provided comparability with the existing US Cold-Temperature CO Standard, although none of the vehicles had included such a procedure in their initial certification. However, it was deemed interesting to see how typical present-day European and Japanese cars were measuring against such a scale.

One vehicle of each type was subjected to a more in-depth emissions analysis. Apart from the normal, regulated pollutants measured with the standard-type CVS and bag-sampling procedure, on-line measurement with continuous recording of the concentrations was performed. In addition, a continuously operating fast FTIR system was employed to provide analysis of a number of unregulated pollutants. More detailed descriptions of these procedures are presented in Chapter 5.

Vehicle preparation and preconditioning were carried out according to the definitions in the US Federal Test Procedure. Prior to the low-temperature test, cars were soaked in the test cell for at least 12 hours, but not more than 24 hours, although the certification procedure allows cold-soak up to 36 hours. Dynamometer settings were based on the data provided by the vehicle manufacturer. The same settings were used at low ambient temperatures, as well, without any low-temperature compensation.

As this was a certification-type of exercise, test fuel according to standard reference fuel (CEC RF-08-A-85) was used throughout the study. An example of specifications for the fuel used are given in Appendix 3.

What was said of the use of normal reference fuel at low-temperature testing in Chapter 6.2.2 applies also here. Using different fuel for the cold-temperature test alone was considered impractical in this context.

7.2 EMISSIONS OF IN-SERVICE CARS AT LOW AMBIENT TEMPERATURES

7.2.1 Emission levels attained at -7 °C

The overall level of regulated emissions at low ambient temperature as well as the sensitivity to lowering of the temperature of the tested cars in this study are presented in the following figures. First, the regulated pollutants at the designated low ambient temperature (-7 °C) are presented in Figures 80 (for CO), 81 (for HC) and 82 (for NO_X). The vehicles of the same type are grouped together, but results are given separately for each individual car. The order, in which the groups are laid out in all of these figures, is quite random, and based only on the chronological order of the testing itself.

Starting from the CO emissions, which are presented in Figure 80, one can see once again how large differences were encountered between different types of cars. This phenomenon has already been discussed in previous chapters. The differences among similar cars, however, were rather small, even if in some of the cases cars representing the same type had very disparate mileages. The strongest variation among any types was recorded for type ANH95G, where car ANH95Gb emitted CO about twice as much as its parallel representatives. No apparent reason for this could be found, although this car presented the highest CO values among the types at normal ambient temperature, too. However, it was of the oldest model year (1993), the others being 1994 or 1995 models. Despite this fact the mileage on this car was comparable to ANH95Gc, which incidently had the highest mileage among these three cars. Therefore, this could not necessarily be the reason for nearly 50 % higher emissions, unless different fuel delivery calibration and enrichment strategy was employed in this model year. This assumption, however, has not been corroborated from the vehicle manufacturer or its representative.

Although none of the tested types were specifically designed to meet any low-temperature limit values, all but two of the tested types and most (80 %) of the individual cars passed the US Cold-Temperature Standard set at 6.2 g/km at -7 °C ambient. Three of the types presented even emission levels that were below 50 % of that limit value.

Considering the HC emissions, illustrated in Figure 81, a pattern quite similar to the one displayed for CO emissions was repeated here. However, differences in emission levels from type to type were somewhat smaller than with CO.

Furthermore, the disperse among individual cars of the same type were about the same as in case of CO emissions. One clear exemption to this rule, though, was again type ANH95G, among which the ANH95Gb showed an HC value

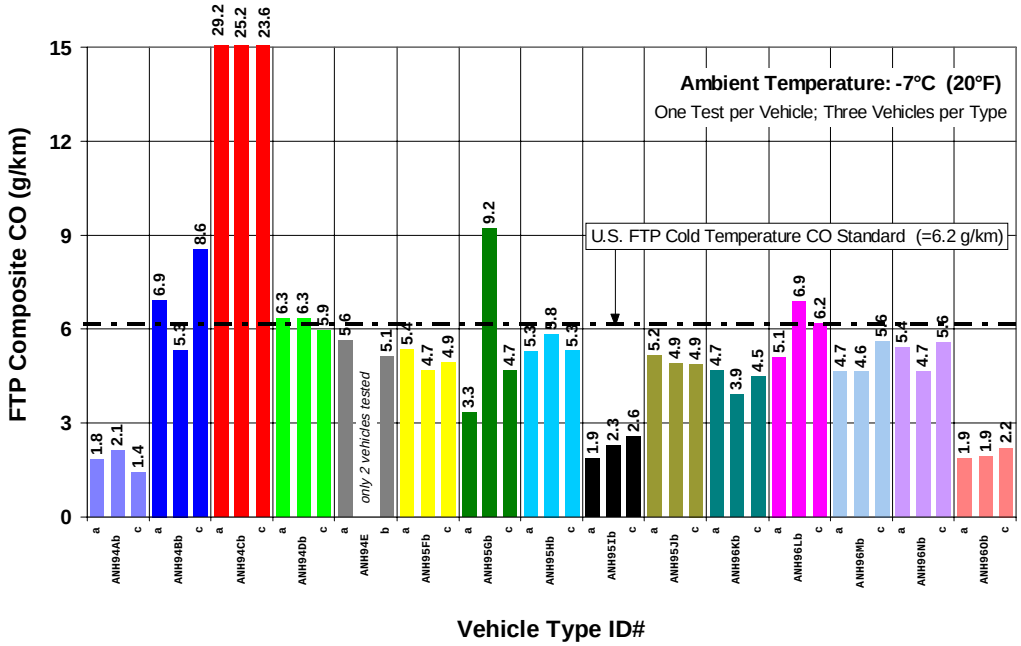

Figure 80 CO emissions in a FTP75 test at -7 °C ambient temperature for normal, in-service vehicles with variable mileages that have been in private ownership use in Finnish driving conditions.

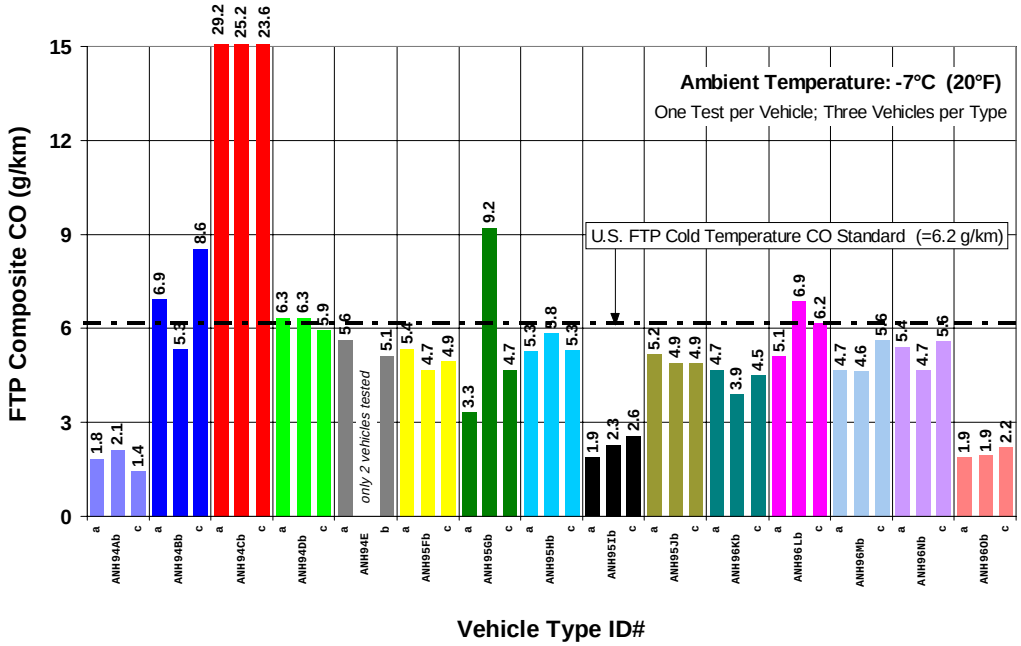

Figure 81 HC emissions in a FTP75 test at -7 °C ambient temperature for normal, in-service vehicles with variable mileages that have been in private ownership use in Finnish driving conditions.

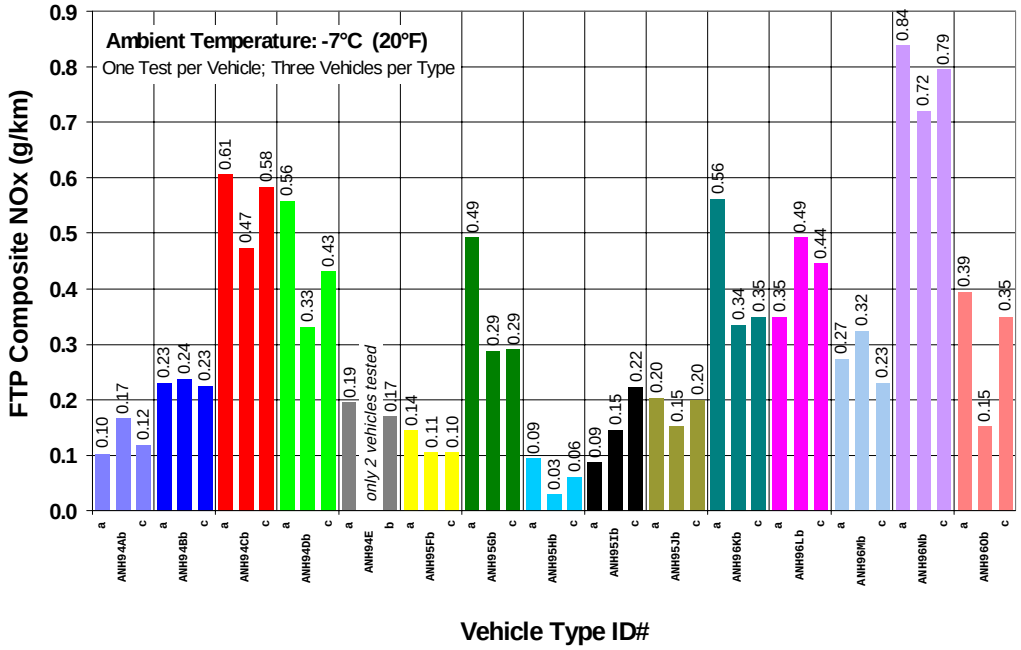

Figure 82 NO_x emissions in a FTP75 test at -7 °C ambient temperature for normal, in-service vehicles with variable mileages that have been in private ownership use in Finnish driving conditions.

twice as high as what was recorded to its two siblings. On the other hand, also within the type ANH96K, one representative (ANH96Kb) gave an HC result, which was only about 60 % of the other two. It was the best of this group even at normal temperature, but not by a margin this high.

As there is no specific standard or limit value for HC emission at low ambient, not even in the US Cold-Temperature program, a comparison of the emissions level attained to any kind of guideline could not be made. Some of the best results, however, were nearly comparable with the standard of 0.25 g/km set at normal ambient temperature. For instance, all tested three cars among the types ANH94A and ANH95I demonstrated HC values on average in the 0.25 to 0.30 g/km range. This must be regarded as quite excellent performance.

Lastly, regarding NO_X emissions, that are portrayed in Figure 82, the rank order between the high and low-emitting cars seems to be somewhat different from the order set by CO and HC emissions performance, which tend to correlate with one another. Again, like with the other regulated compounds, the spread of results between the individual representatives of the given type were quite small, on average. Like with CO and HC, some exemptions, however, were noted. For instance among types ANH95G and ANH96K, one car showed results that were

almost twofold to what was recorded to the other two ones. Vice versa, for type ANH96O, one car had an NO_X result, which was less than half the level emitted by the remaining two. Here, and with cars G and K, the same behaviour applied even to emissions at normal ambient temperature (not illustrated here).

As with HC, there is no standard or other guideline for low-temperature NO_X to compare the average level of emissions. However, in all but one case, type ANH96N, the results were all below the value of 0.62 g/km, being the limit value set for normal ambient conditions. Even the one exemption was on average at the level of 0.8 g/km. This was hardly any surprise, because all previous experience suggests that ambient temperature has only a marginal effect on NO_X, and in many cases the emissions at cold ambient temperatures are even lower than the baseline.

7.2.2 Low-temperature sensitivity of different types

The relative sensitivity to low temperature of the types of cars involved in this study was then evaluated using Figure 83 for CO, Figure 84 for HC, and Figure 85 for NO_X. In these figures, a parameter called "sensitivity" is presented. It was derived from the ratio between emissions at -7 °C compared with baseline emissions measured at +22 °C. In the case of NO_X , however, excess emissions rather than sensitivity was used. It was obtained by subtracting the emissions at -7 °C from the baseline value at +22 °C.

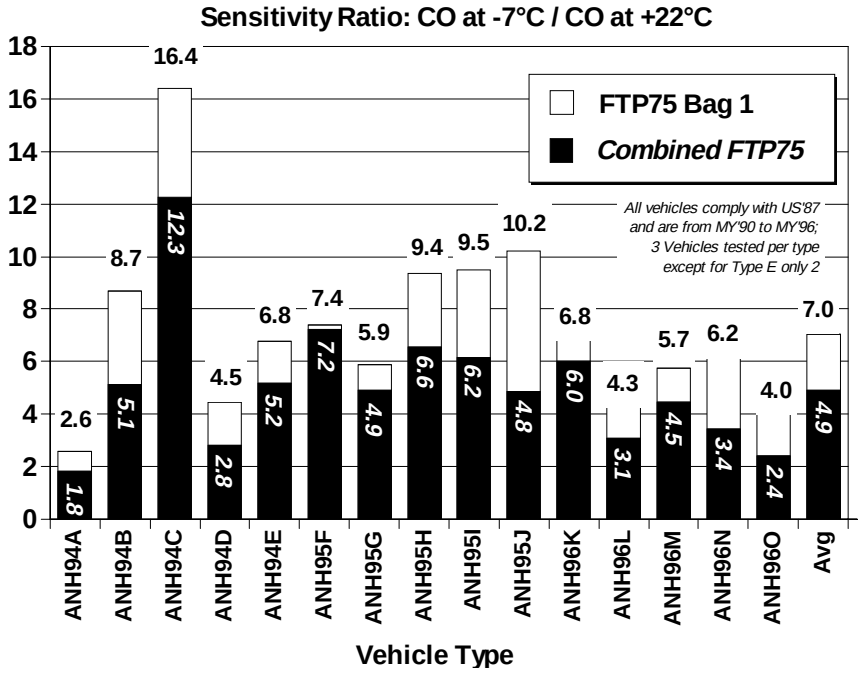

Figure 83 Sensitivity of different car types in the In-use study to low ambient temperature; i.e. ratio of CO emissions at -7 °C ambient compared to baseline emissions at +22 °C ambient temperature.

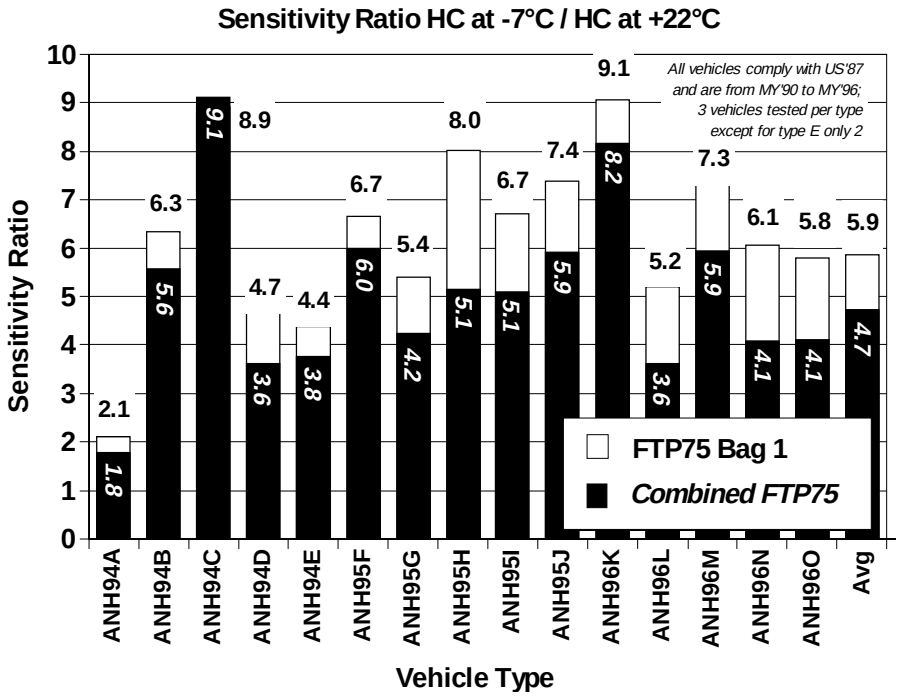

Figure 84 Sensitivity of different car types in the In-use study to low ambient temperature; i.e. ratio of HC emissions at -7 °C ambient compared to baseline emissions at +22 °C ambient temperature.

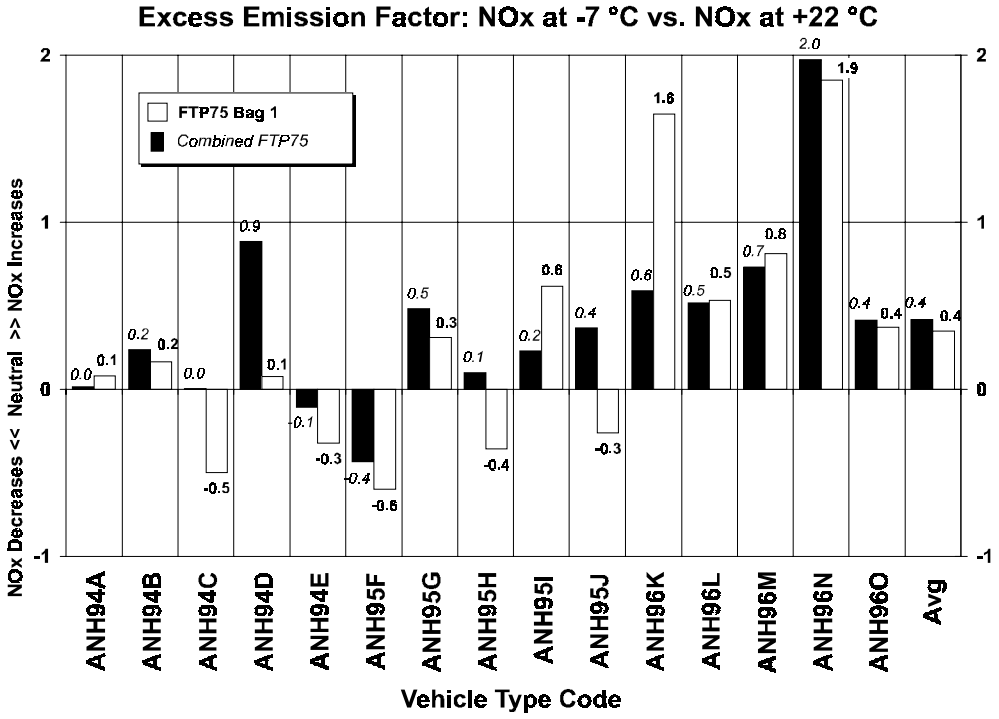

Figure 85 Sensitivity of different car types in the In-use study to low ambient temperature; i.e. ratio of NOx emissions at -7 °C ambient over to baseline measured at +22 °C ambient temperature.

This procedure was chosen, because with NO_X, the emissions at low ambient were in some of cases lower and in other cases higher than the baseline. This kind of behaviour was easier to demonstrate by using emission differential rather than relative emissions. The baseline value for each type is a fleet average consisting of three tests per individual car, total of nine tests. The value for emissions at -7 °C, however, is an average of only one test per car, total of three tests.

As can be seen by just comparing the scales in the corresponding figures, CO emissions presented by far the greatest sensitivity values. Even the differences in this sensitivity ratio from one car to another were largest in terms of CO emissions, although the average sensitivity for all of the 15 types tested was about the same for CO and HC, if total combined FTP75 results are dealt with. The high CO emission values at cold start for Bag 1 recorded for some car types, however, raised the average sensitivity figures. Overall, the Bag 1 sensitivity values were then greater for CO than they were for HC emissions.

Like the previous figures well demonstrated, the lowering of the ambient temperature affected emission rates of the tested cars quite differently from one type to another. Cars that presented low CO and HC emission rates at normal ambient temperature did not necessarily retain this performance at low ambient, as well. The sensitivity seemed to be also different for CO and for HC emissions, which was quite in line with the previous findings, how these two emissions are not essentially interlinked (see Chapter 6.4.4).

On average, CO emissions increased by a factor of five, if the total, composite FTP75 values are discussed. However, the strong influence of the cold-start at low temperatures raised the sensitivity to an average of seven on Bag 1 values. The corresponding figures for HC emissions were five and six, so the cold start seemed to have slightly less effect about HC compared with CO. The sensitivity among the tested car types varied from two to 16 for CO, but for HC, the range was somewhat narrower, from only two to nine.

In all of tested types emissions of CO and HC increased because of lowering the ambient temperature. Regarding NO_X, however, the outcome was not quite as conclusive. In five of the tested car types (codes ANH94C, ANH94E, ANH95F, ANH95H and ANH95J), the emissions of NO_X were some 30 to 60 % lower than the baseline at low temperature. However, this was mostly applicable just for Bag 1 results, because only for types ANH94E and ANH95F also the total, combined FTP75 emissions were lower, when test temperature was lowered from +22 °C to -7 °C. Otherwise, NO_X was neutral or elevated, in the extreme case (ANH96N) by a factor up to two, meaning that NO_X emissions at low temperature were 300 % of the baseline level.

Overall, cars of type ANH94A seemed to be least affected by the low temperature, because NO_x remained almost neutral, and the other sensitivity factors were on

average the lowest (from about two for HC and to 2.6 for CO). On the contrary, the strongest temperature sensitivity, especially in terms of CO emission, was recorded for cars of type ANH94C. This, however, was not surprising, as this car type employed electronically controlled carburettor for fuel-air mixture preparation, and that kind of design is known to be more sensitive to ambient conditions (temperature, pressure) than current fuel injection equipments, where the control is more sophisticated and the fuel delivery is easier to adapt to changes in operating conditions. Even the manufacturer of this vehicle has recognized this deficiency and started to use multi-point fuel injection in the later model years of the same type.

7.3 THE EFFECT OF TOTAL VEHICLE MILEAGE

7.3.1 Main purpose of the sub-study

Vehicle mileage was expected to affect cold-start emissions, because it is a well-known fact that the light-off temperature in a catalytic converter tends to elevate due to chemical poisoning and thermal deactivation of the catalyst. The proving of this presumption and its demonstration was one of main objectives for this study on in-use vehicles. The outcome of the investigation, however, was to some extent in direct contrast to these expectations.

7.3.2 The effect of vehicle mileage on baseline emissions

At first, the emissions at normal ambient temperature (+22 °C) were plotted as a function of the distance driven with the test vehicle. Figure 86 shows this plot for CO emissions, Figure 87 does it for HC emissions and Figure 88 illustrates the out-come of this modelling for the NO_X. Apart from the actual data points, a trendline representing a linear function was fitted to the data and plotted in the figures. This procedure was executed using computer software (Microsoft® Excel® 7.0) employing the least-square method. Apart from this function, R^2 values representing different function fits are also given.

In addition to this trendline, another (broken) line represents the certification standard adjusted with the so called assigned deterioration factor (DF). The current certification is based on 80,000 km useful life, which means that the limit values set for each of the exhaust components actually applies to the car up to the point it has collected 80,000 km's or is older than five years.

The progression of emissions during this period is usually forecasted by multiplying the results of emissions measurement at a lower mileage with a deterioration factor (DF), which reflects the decline of performance in the emission control system and the subsequent increase in emissions. This factor can either be

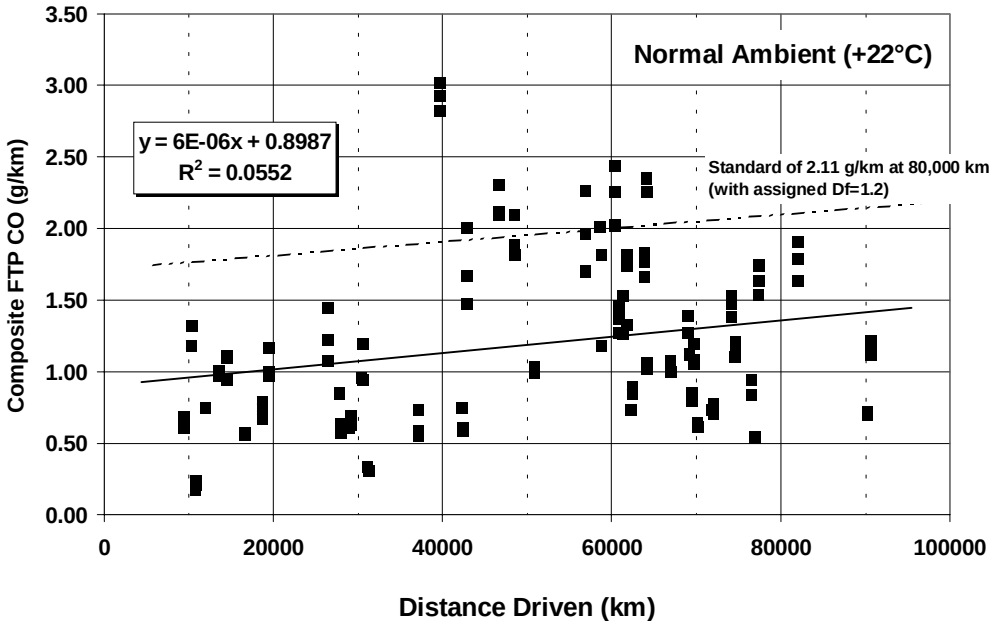

Figure 86 Composite FTP75 CO emissions at normal ambient temperature as a function of total vehicle mileage for cars tested in the In-use study.

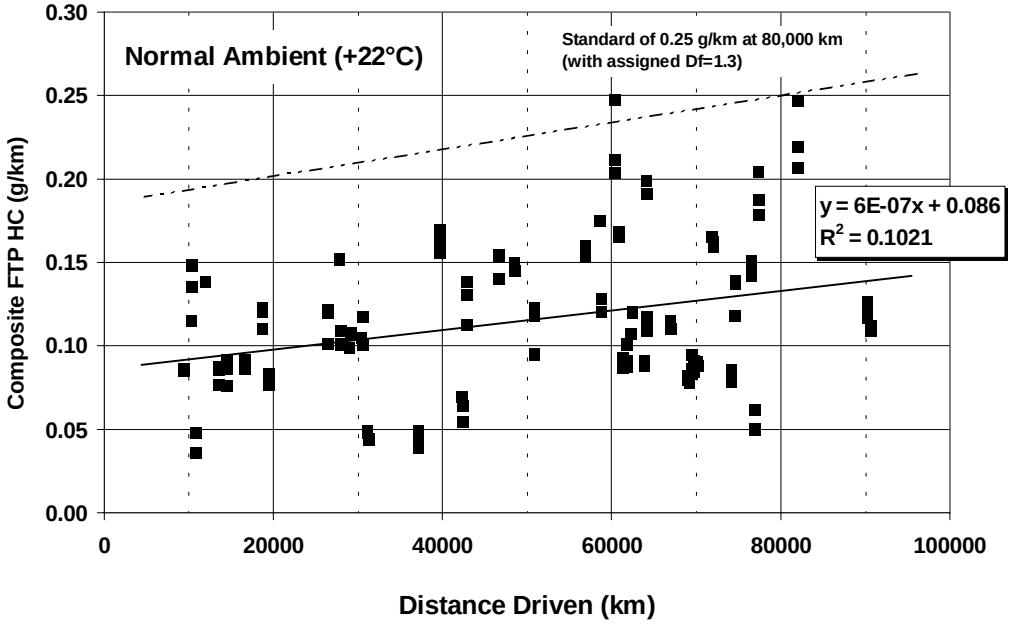

Figure 87 Composite FTP75 HC emissions at normal ambient temperature as a function of total vehicle mileage for cars tested in the In-use study.

derived from a complete durability demonstration test run with one or more vehicles driven up to full 80,000 km.

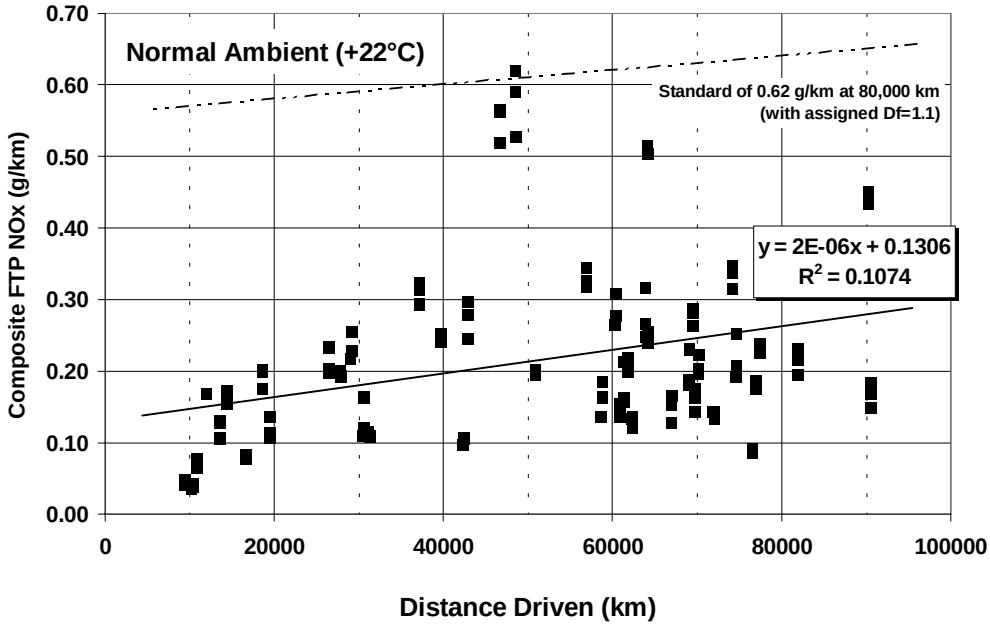

Figure 88 Composite FTP75 NO_x emissions at normal ambient temperature as a function of total vehicle mileage for cars tested in the In-use study.

As an option, the so called assigned factors method has been available in the certification system of the EFTA countries (in the US system this applies only to small-volume manufacturers). These factors are normally much higher than the "true" factors resulting from a test series giving the needed marginal for the evaluation process.

Although the main purpose of this study was not to assess whether the assigned deterioration factors are applicable for this fleet of cars, this kind of analysis can, however, be used to appraise, if the Finnish driving conditions with a lot of cold starts and subsequent low-temperature driving would impose stricter than normal loads on the emission control system and cause deterioration, which is higher than expected. Although this limited analysis should not be taken as a conclusive evidence of the long-term effectiveness of the catalyst-equipped cars in Finnish driving conditions, it gave an interesting insight to what is the real-world performance of in-use vehicles that have mostly been in normal, private ownership service.

For CO emissions, this seemed to be the case, as almost all violations of the certification standard were recorded for this component. Also the trendline fitted to the data shows slightly more progressive deterioration than the line representing the standard with the assigned DF of 1.2. The difference, however, is quite marginal, and because the R^2 value of the least-square fit was only 0.05, it cannot be taken as conclusive evidence. Also the causes of some of the violations of the CO standard have been investigated more thoroughly, and reasons in most of the cases were not directly related to the emission control system, but to other factors

affecting vehicle performance, like binding brakes at driving wheels causing excess road load during testing.

Regarding HC emissions, the situation was more favourable, as only one violation of the standard was registered. Even the trendline fitted to the data lies at about halfway to the limit value and shows less tendency to deterioration than in case of CO. On the other hand, the assigned factor for HC emissions is also somewhat higher (1.3).

In case of NO_X, also only one result of measurement was exceeding the limit value. Overall, the results were much further down from the projected standard line than what was found for the other two components. Nevertheless, when a linear trend-line fit was made to the NO_X data, it showed somewhat steeper inclination than the line drawn with the assigned DF of 1.1.

7.3.3 The effect of vehicle mileage on low-temperature emissions

When the effect of vehicle mileage on cold-start emissions and emissions at low ambient temperature in general were considered, the following figures were used. They plot the emissions measured at -7°C, and similarly to those earlier figures, the emissions are shown as a function of the total distance driven with the test vehicle at the time of testing. Figure 89 outlines CO emissions, Figure 90 is presenting results from HC measurement and finally, Figure 91 introduces a similar plot for NO_X.

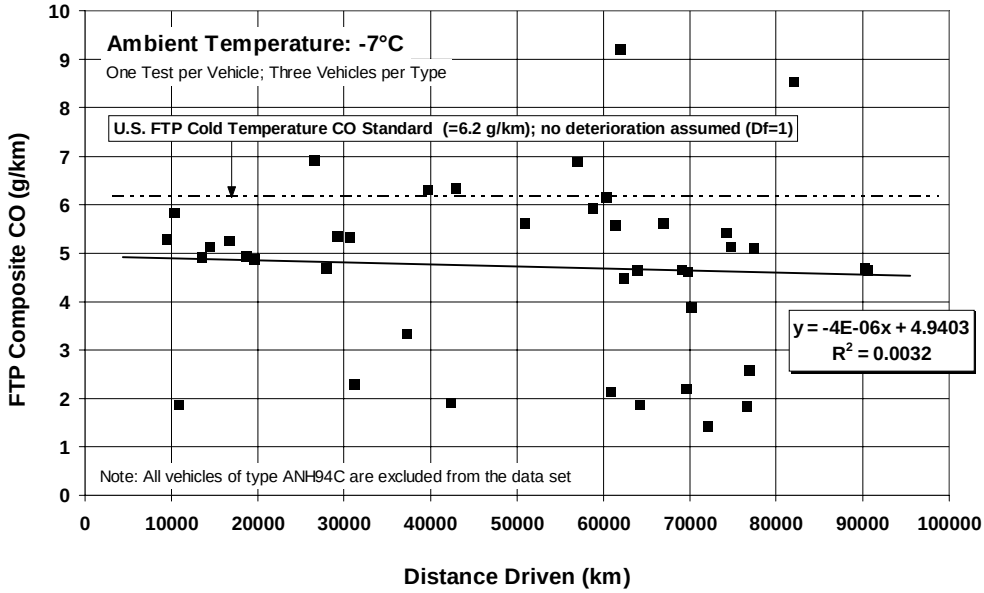

Figure 89 Composite FTP75 CO emissions at -7 °C ambient temperature as a function of vehicle mileage for the cars tested in the In-use study (vehicles of type ANH95C excluded).

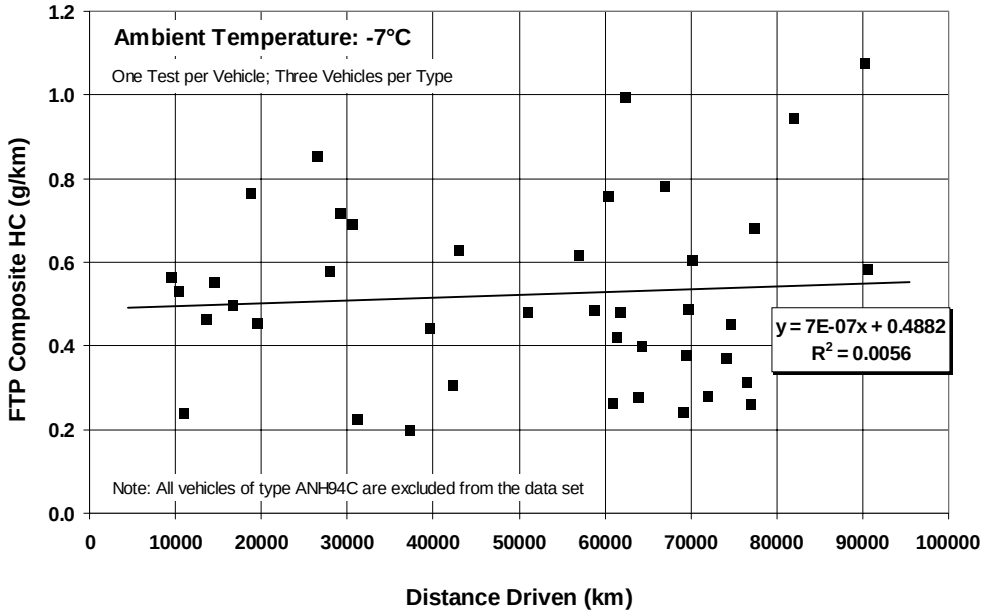

Figure 90 Composite FTP75 HC emissions at -7 °C ambient temperature as a function of vehicle mileage for the cars tested in the In-use study (vehicles of type ANH95C excluded).

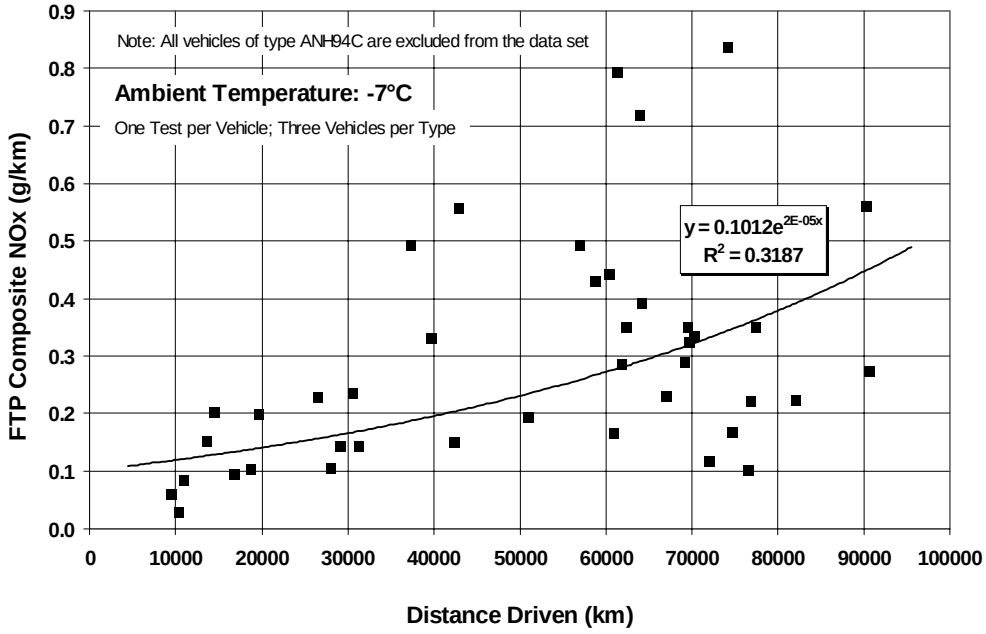

Figure 91 Composite FTP75 NO_x emissions at -7 °C ambient temperature as a function of vehicle mileage for the cars tested in the In-use study (vehicles of type ANH95C excluded).

Because of the poor low-temperature performance of all three cars of type ANH94C, using carburetor for mixture preparation, all the vehicles of that type were excluded from this data set, because they seemed to skew the plots inadvertently.

For CO, composite FTP75 emissions seemed to be almost nondependent of the vehicle mileage. The trendline fitted to the data was almost horizontal, even slightly downwards for higher mileages, and the R^2 value, which represents how well the data fit to the expression, is only 0.003, epitomizing a very, very weak correlation, since $R^2 = 1$ would be a "perfect fit".

Furthermore, HC emissions behaved almost in the same manner as CO. Although somewhat stronger dependence on the distance driven was found now, and the trend line showed a slight increase in emissions as the vehicle mileage increases, the correlation remained rather weak, however, because as seen in the respective figure, R^2 value for the least-square fit was only 0.006.
Only the emissions of NO_X seemed to have some sort of link between the emissions and vehicle mileage. The tendency of increasing emissions with increasing mileage appeared to be even quite strong, as the function best-fitted to the data set was of exponential-type, and R^2 value was as high as 0.32, which was considerably higher than the corresponding values with the other two emissions.

One possible explanation, apart from the obvious one, which was the deactivation of the catalyst, was that the emissions could also be linked with the vehicle age, or rather its model year, since newer vehicles usually employ more sophisticated technology, e.g. in the fuel metering and delivery. Therefore, their emissions tend to be also lower. In an attempt to rule out some of this effect, emissions of NO_X were plotted also as a function of the model year. That plot is seen in Figure 92.

As one can see in this graph, there seemed to be slight tendency of the expected kind as the trendline declines with increasing vehicle mileage. However, the trend is quite a weak representation, as the R^2 value of the fitted function is only 0.03. This is quite understandable, as the vehicle mileage and model year tend to be quite strongly linked, although among the tested fleet, there were vehicles with quite varying annual mileages. Therefore, cars with equal age could have rather different odometer readings.

7.3.4 The effect of vehicle mileage on sensitivity

A further attempt was made to quantify the effect of vehicle mileage on low-temperature sensitivity. This was made by calculating the "sensitivity" as the ratio of emissions measured at -7 °C to baseline emissions measured at +22 °C ambient. In order to more closely portray the role of each of the three phases in the FTP75 driving cycle, results are now discussed as separate bag values and not as

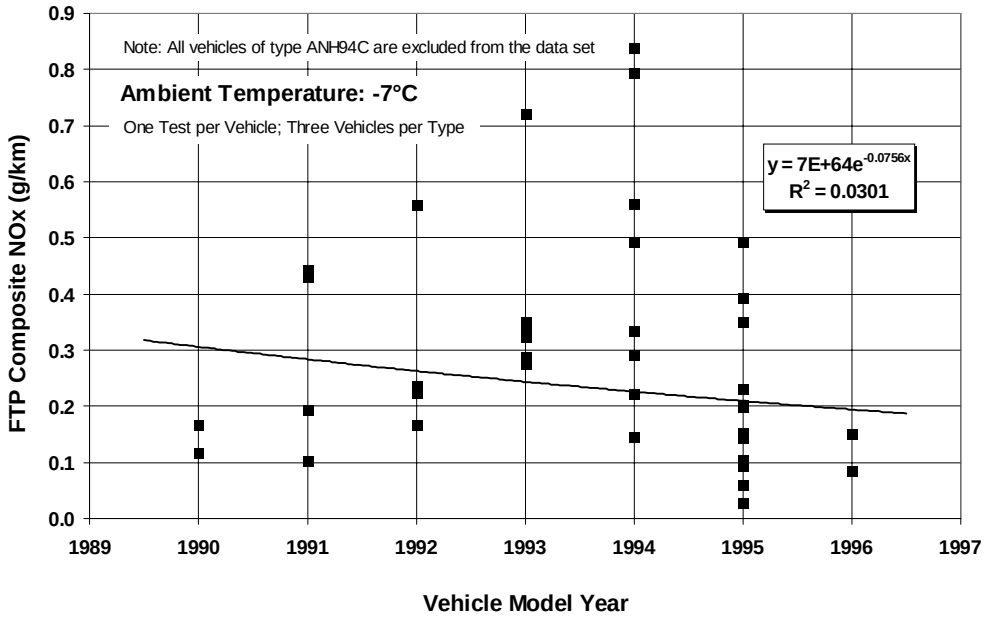

Figure 92 Composite FTP75 NO_x emissions at -7 °C ambient temperature as a function of vehicle model year for cars tested in the In-use study (vehicles of type ANH94C excluded).

composite FTP75 values, like in the previous figures. Figures 93 and 94 plots CO and HC emissions for every individual car in this fleet separately for each of the three bags in an FTP75 test. In addition, a curve was fitted to the data, which would best describe the relationship between the ratio of emissions and total vehicle mileage. Like in previous cases, this was done by employing the procedures available in a computer software package (Microsoft® Excel® 7.0). The choice among available options (linear, logarithmic, exponential, polynomial) was made based on the R^2 calculated for this fit. The one having the highest R^2 value was again considered the best.

As already mentioned, all three cars of type ANH94C presented somewhat abnormal performance at low temperature with extremely high emissions of CO and HC. Therefore, it was felt that including these would unduly skew the data and, therefore, this type was excluded from this analysis. This discrimination was considered valid, because all of the three individual cars of the said type were showing almost identical results. Thus, the behaviour was regarded as type-specific, and not related to vehicle mileage.

Like one can see from these two figures, only bag 1 values presented a meaningful relationship between the mileage and the sensitivity to low ambient temperature. The best fit was achieved using logarithmic formula. In case of CO emissions, the fit was better than with HC, as the R^2 value for CO was 0.487, whereas for HC it was only 0.205.

An attempt to fit any of the available curves also to the data for bags 2 and 3 resulted in R^2 values below 0.05, indicating that there was no correlation. Therefore, these lines are not plotted in the figures.

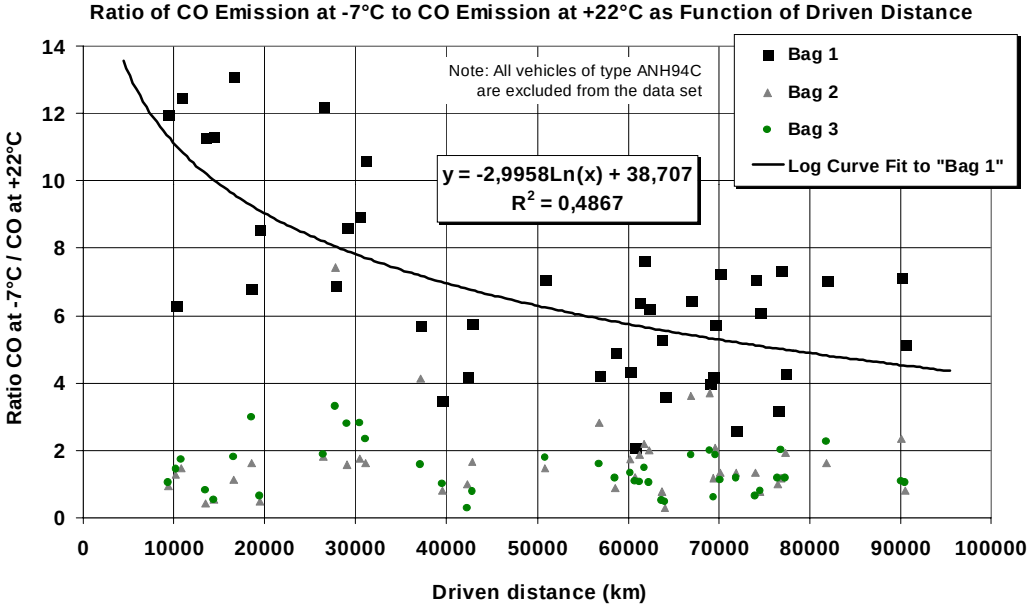

Figure 93 Sensitivity of CO emissions to low ambient temperature expressed as the ratio of emissions measured at -7 °C to baseline emissions (measured at +22 °C) as a function of total vehicle mileage for the cars tested in the In-use study (excluding type ANH94C).

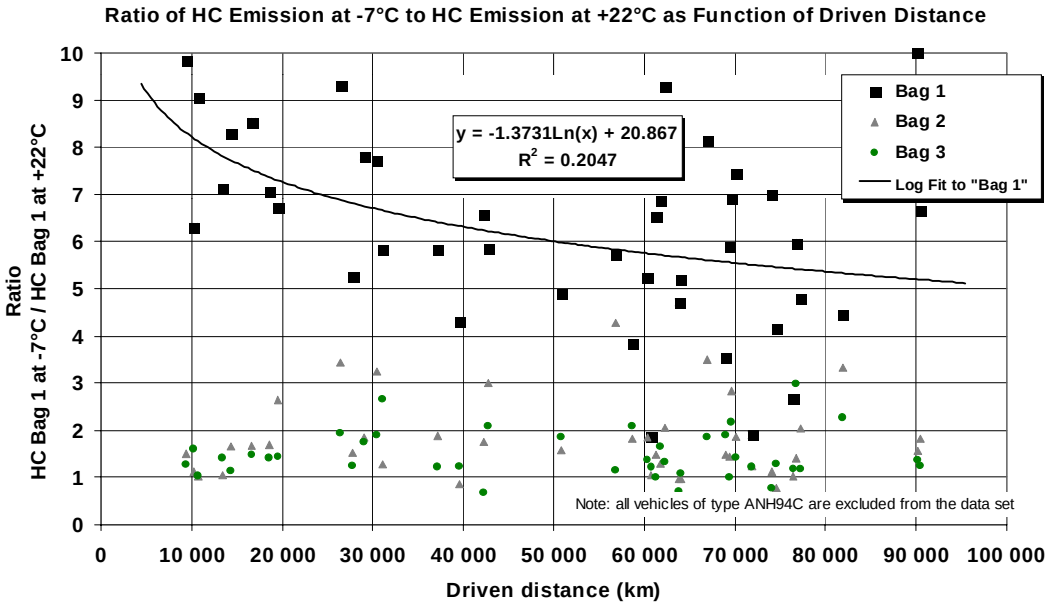

Figure 94 Sensitivity of HC emissions to low ambient temperature expressed as the ratio of emissions measured at -7 °C to baseline emissions (measured at +22 °C) as a function of total vehicle mileage for the cars tested in the In-use study (type ANH94C exluded).

As with both CO and HC the curves describing the sensitivity to low temperature as a function of total vehicle mileage had a negative constant, it means that the sensitivity was actually lowering, when the vehicle mileage was increasing. This was a somewhat unexpected result, because a common assumption has been presented that while the emissions performance of a car at normal ambient temperature is degrading with increasing mileage, as portrayed in Figures 86 to 88, also the cold-emissions performance would deteriorate, when the catalyst is gradually deactivated because of recurring high thermal loads and chemical poisoning. Furthermore, it is well known that, e.g. the light-off temperature is higher in an old converter compared with a fresh one.

Notwhitstanding, these phenomina seemed not to affect emissions at low ambient temperatures, which according to the figures were prominently dependant on bag 1 results, and thus mostly related to cold-start and subsequent warm-up driving in open-loop mode. It was felt that this conclusion can even be used to corroborate the theory that emissions at low ambient temperature actually are more dependant on engine-out emissions and less dependent on catalyst performance.

The circumstances were, however, somewhat different for NO_X. Figure 95 plots the bag-specific sensitivity values for every individual car in this study, except those three of type ANH94C, which were excluded from this evaluation. Again, a curve has been fitted to the data yielding to a logarithmic formula with positive

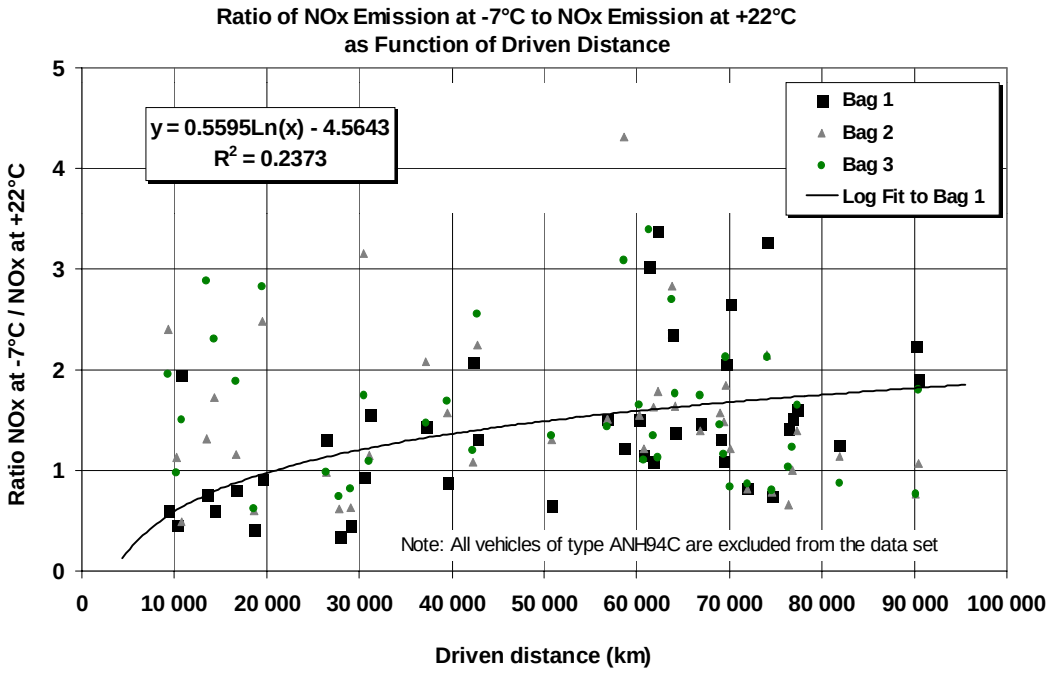

Figure 95 Sensitivity of NO_x emissions to low ambient temperature expressed as the ratio of emissions measured at -7 °C to baseline emissions (measured at +22 °C) as a function of total vehicle mileage for the cars tested in the In-use study (excluding type ANH94C).

constant and R^2 value of 0.237, about the same as with HC emissions. Even in this case it was futile to try to fit any curve to the values for bags 2 and 3.

Because the ln-curve had a positive constant, it meant that with NO_X emissions, the low temperature sensitivity was increasing with increasing vehicle mileage. Actually this finding was almost like an inverted dependance to what was just assumed for CO and even HC. Furthermore, this suggested that even at low ambient temperatures NO_X emissions could be somewhat dependent on catalyst performance, as the degradation in converter efficiency could be the cause for this kind of emissions vs. total vehicle mileage dependance. This conclusion should, however, be taken as indicative, since the judgment was based only on this rather narrow-based vehicle fleet.

7.4 CONCLUSIONS FOR THE IN-USE STUDY

The In-use study was assessing primarily the effect of vehicle mileage upon the low-temperature, cold-start emissions performance. The results could be used to substantiate the following prime conclusions:

- The overall in-use emissions performance was not unduly affected by the cold Finnish driving conditions, but rather followed the average trend, which is expressed in the assigned deterioration factors. Based on this finding, one should expect the emission control systems to last in normal, everyday use in Finnish driving conditions as well as they would do in other countries.

- The emissions of CO and HC recorded at low ambient temperature were almost not dependent on vehicle mileage, but seemed to depend much stronger on vehicle type. When three cars of each type were tested, in most of the cases they usually produced quite similar emissions.

- Furthermore, it could be noted that the emissions of CO and HC in cold-start, low ambient temperature conditions were not a function of catalyst performance, but rather a measure of direct engine-out emissions. Thus, they were probably resulting more from the functioning of the engine itself and not much affected by the exhaust treatment after the engine.

This conclusion was somewhat unanticipated, as the general expectation was that the deactivation of the catalyst as a result of high mileages would raise the light-off temperature of the catalyst, and, therefore, have negative impact upon the cold-start emissions performance. However, this seemed not to be the case, although at normal ambient temperatures, elevated emissions were registered for the high-mileage cars. Only the emissions of nitrogen oxides appeared to be largely dependent on total vehicle mileage, and even in low ambient temperature conditions, closely to follow the trend in performance assessed by the tests at normal temperature.

8 UNREGULATED EMISSIONS MEASURED WITH FTIR AT LOW TEMPERATURES

8.1 GENERAL REMARKS

Parallel to the determination of the typical regulated pollutants discussed in the previous chapter, some of the cars in the In-use study, typically one of each type, were subjected to an additional analysis using the fast FTIR system available at VTT Energy. This multi-component analyser is capable of determining concentrations of some 25 different components directly on-line from raw, undiluted exhaust gas at 1 Hz time resolution. A complete list of components calibrated in the system, as well as further details of its operating principle, performance etc. has been presented in Chapter 5.6.3.

Of the unregulated compounds measured with FTIR, three were chosen for presentation and discussion in this report. These were nitrous oxide (N_2O), because it is a strong greenhouse gas, ammonia (NH_3), being toxic a major component in the acidifying effect of air pollution, and formaldehyde, as it is an extremely reactive species in terms of atmospheric chemistry and ozone formation and even a toxic compound.

The general pattern in the presentation of the results is to give first the total accumulated emissions over the complete FTP75 driving cycle as a function of distance travelled in the cycle at baseline temperature (+22 °C) and at low ambient temperature (-7 °C) for six different vehicle types tested in the In-use study. Because vehicle type ANH95G was represented by two examples (a, b) and other types with just one car, this compiled up a seven-vehicle sub-fleet. In each graph, a reference to the total vehicle mileage is given within the type code. In this reference, "Low" means that the vehicle has been driven less than 20,000 km, "Medium" refers to mileages between 20,000 and 50,000 km, and finally, "High" denotes cars that carry odometer readings over 50,000 km mark. Target speed of the FTP75 driving cycle is also presented in order to help to determine, from which portion of the cycle the emissions are derived.

8.2 EMISSIONS OF NITROUS OXIDE(N_2O)

8.2.1 Accumulated emissions over FTP75

First the profile of emissions accumulated over the FTP75 test cycle is considered. Figure 96 shows the accumulation at normal ambient temperature, and Figure 97 does the same for the emissions measured at the low ambient (-7 °C).

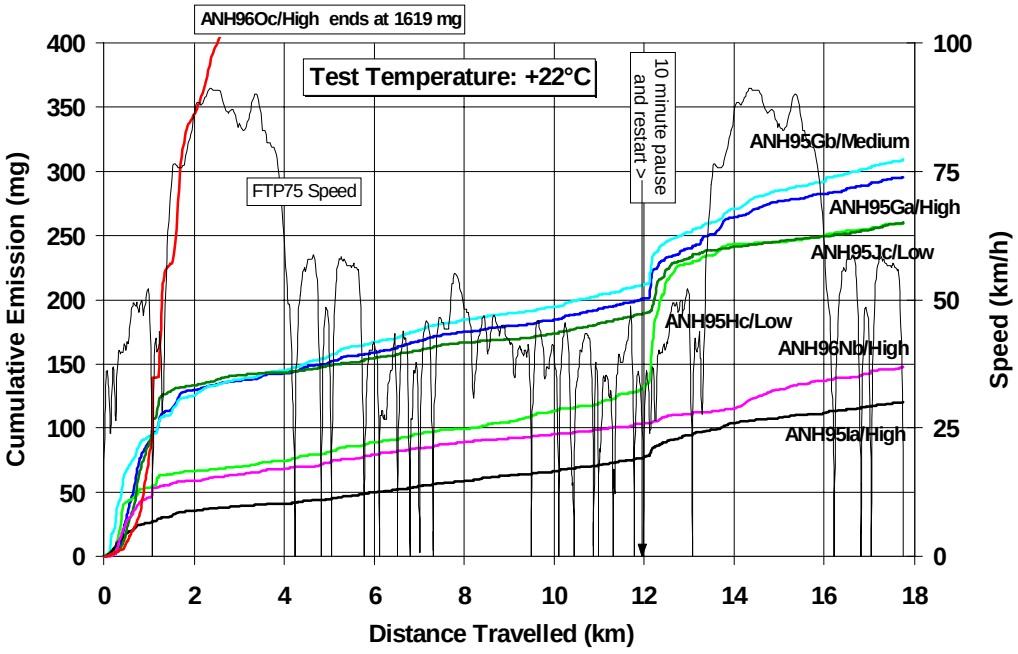

Figure 96 Accumulated emissions of nitrous oxide (N_2O) over FTP75 driving cycle as a function of distance travelled in the cycle for cars tested in the In-use study at +20 ℃ ambient temperature.

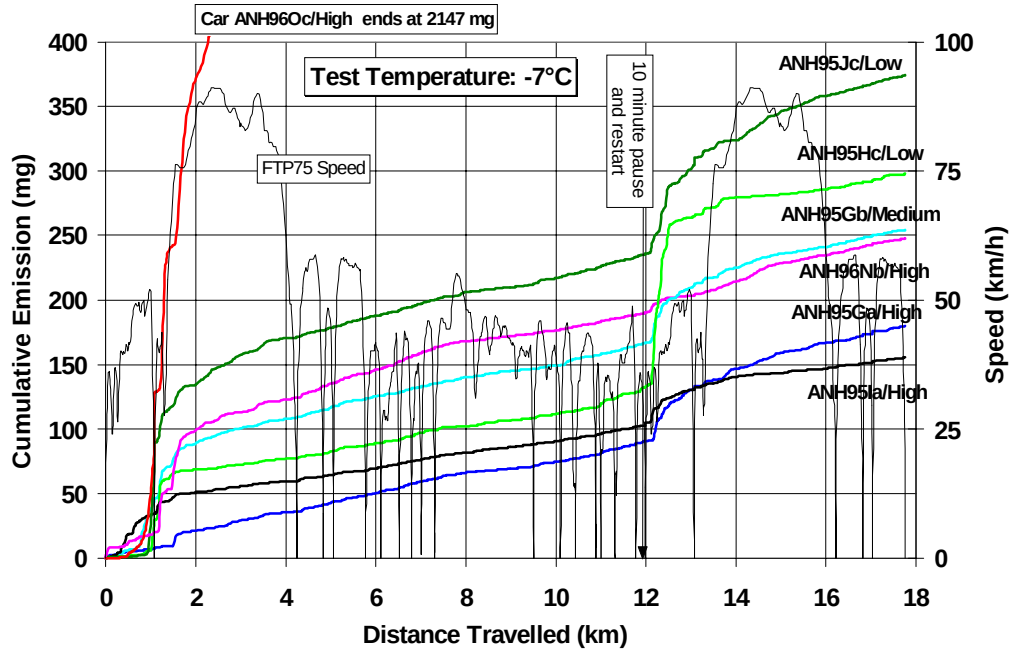

Figure 97 Accumulated emissions of nitrous oxide (N_2O) over FTP75 driving cycle as a function of distance travelled in the cycle for cars tested in the In-use study at -7 ℃ ambient temperature.

According to both of these figures, emission rates were at the highest for a while right after the start-up. This was true even after the "cold start" at normal ambient temperature, as well as after the warm restart after the 10 minute pause between the phases Y_{hs} and Y_{ht}. Furthermore, from Figure 96, it could be noted that the tested cars could be divided into three basic categories: those two having a low total emission, below 150 mg, and those four having a medium output, at about 250 to 300 mg over the complete FTP75 driving schedule, which has a nominal total distance of 17.776 km. One car, however, produced very high emissions totalling up more than 1600 mg at the end of the test. This was the car with code ANH96Oc.

Whilst the test temperature was lowered to -7 °C, the overall outline was, according to Figure 97, somewhat changed, although the car with code ANH96Oc remained still in its own class, as its total output was nearly 2500 mg. This was more than six times the value of 375 mg recorded for the car ANH95Jc with the next highest result. The rest of the cars were quite evenly spread over the range from 150 to 300 mg.

8.2.2 Average emission rates in FTP75

The comparison between the emission performances of different cars in the tested sub-fleet at those two ambient temperatures can also be made using specific emission rates (in mg/km) as the basis. Figure 98 illustrates this comparison. The values portrayed in this figure are analogous to the so called composite FTP75 value, derived from the results for individual sample bags by using different weighting factors for each of the three phases.

Based on this figure, it can be noted that all other cars but those two of type ANH95G emit more nitrous oxide, on average, over the complete FTP75 test run at low ambient temperature compared with their respective baseline values measured at normal ambient temperature. However, considering the relatively low magnitude of the changes, from 15 to 30 %, and the level of inaccuracy in this measurement method (according to [69] detection limit is about 5 mg/km), these variations can only be of indicative nature. Yet they are truly interesting, as data from the emission rates of unregulated pollutants at low ambient temperatures is very scarce. The very high total emissions for the car ANH96Oc are reflected also here in very high, off-scale average rates.

8.2.3 Emissions over the cold-start phase of FTP75 (Bag 1)

Furthermore, the analysis of the emissions performance was extended even to the individual phases of the FTP75 cycle representing different modes of driving. The first phase, known as "cold transient" (Y_{ct}), is the first 505 seconds after the cold start at ambient test temperature. Therefore, as already asserted in earlier discussions of regulated pollutants, it represents the cold-start and subsequent

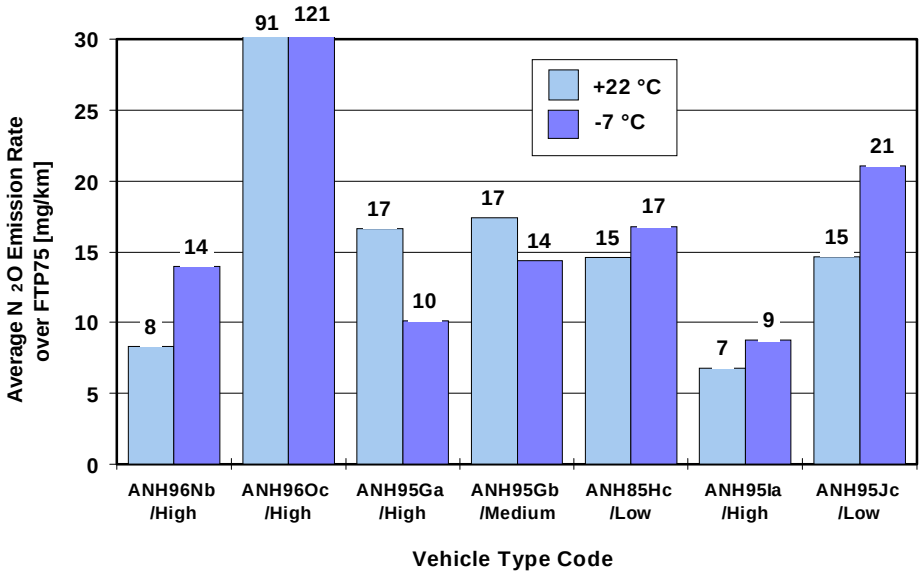

Figure 98 Average overall nitrous oxide emission rates over FTP75 driving cycle at normal and at low ambient temperature for cars tested in the In-use study.

warmup driving. The second phase is officially referred as "hot stabilized" (Y_{hs}). It is a phase, where by definition, the engine and its emission control systems are operating fully in their normal operating temperature range and should, therefore, reach their maximum efficiency, as well. The last phase, "hot transient" (Y_{ht}), is an exact replicate of the first phase, but with a hot engine restart after the 10 minute pause between the last two phases.

First, the results for the cold transient phase, producing the Bag 1 sample in the CVS test procedure, are cited. Figure 99 shows the outcome of measurements at normal ambient and Figure 100 plots the same accumulation for the tests at low ambient temperature. Finally, Figure 101 compares the average emission rates attained during this phase at both of these temperatures.

Comparing first the accumulation of the emissions, it can be noted, how like with the CO and HC emissions, even these nitrous oxide emissions are by large extent produced shortly after the cold-start, despite the ambient temperature. The level of ambient temperature, however, seems to affect to the timing of the peak release rate, as well as its magnitude.

At low ambient temperature, peak rates of emissions occurred somewhat later on the cycle compared with the outcome of the measurements at normal ambient temperature. At +22 °C most of the cars are producing their peak emission rates

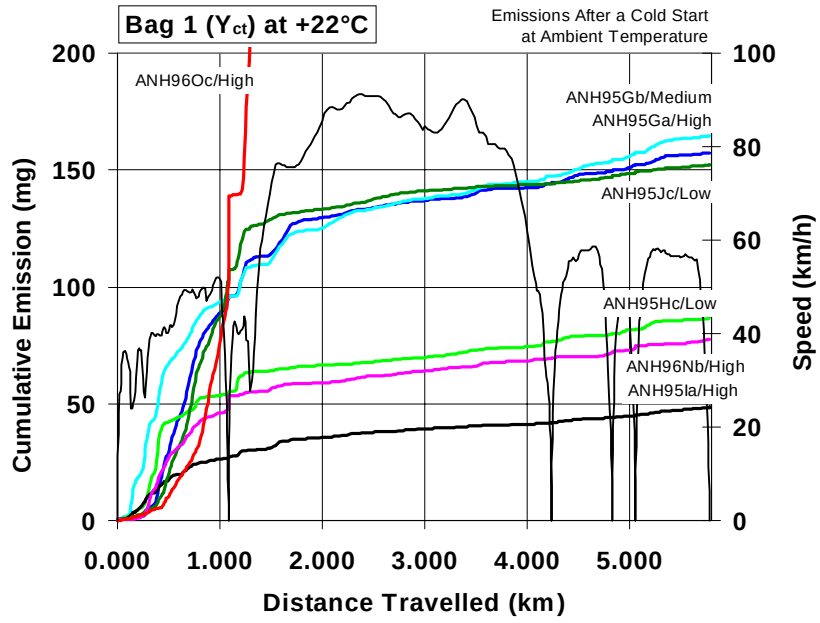

Figure 99 Accumulated emissions of nitrous oxide during phase Y_{ct} of the FTP75 driving cycle as a function of distance travelled in the cycle at normal ambient temperature for cars tested in the In-use study.

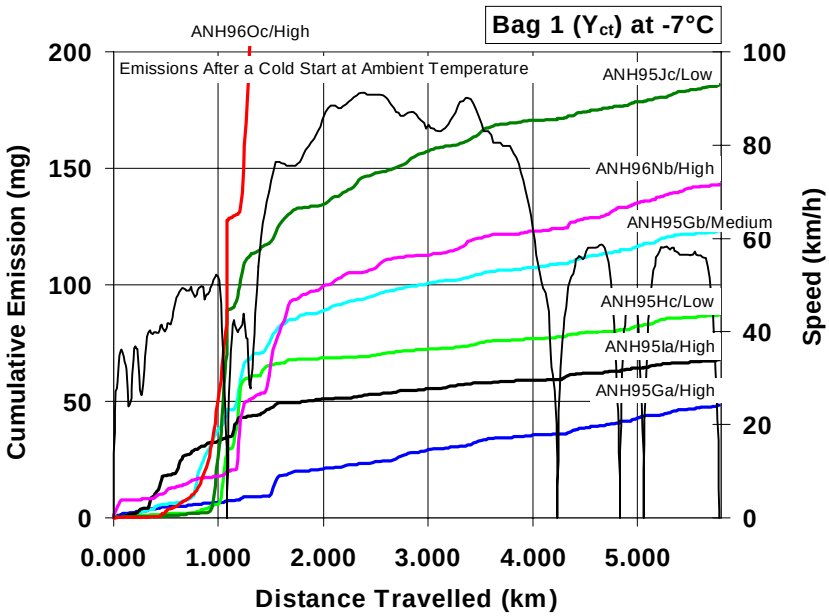

Figure 100 Accumulated emissions of nitrous oxide during phase Y_{ct} of the FTP75 driving cycle as a function of distance travelled in the cycle at low ambient temperature for cars tested in the In-use study.

between 0.5 and 1 km of driving after the cold start. However, at low temperature (-7 °C) this peak occurs somewhat later, between the 1.0 and 1.5 km marks.

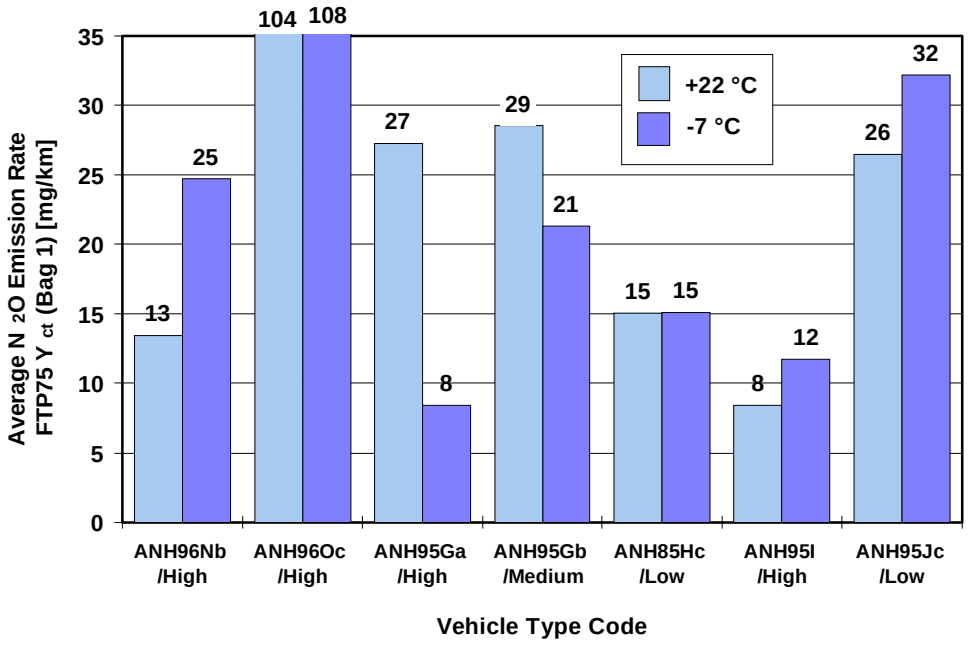

Figure 101 Specific emissions rates of nitrous oxide as average values during Y_{ct} phase of FTP75 for cars tested in the In-use study at normal and at low ambient temperature.

Notwhitstanding, a notable exception to this rule was car ANH96Oc, as already said, when the emission over the total cycle were discussed. It produced nitrous oxide at extremely high rates, and the peaks seemed to occur almost at the same point, at about 1.0 km, regardless of the ambient temperature.

Whereas all other cars produced emissions at low temperature in rates higher or equal than the baseline, both cars of the type ANH95G were emitting less. This phenomenon was already noted, when total emissions were considered. However, this decline was here in the cold-start phase the largest accounted of all the different modes of operation.

8.2.4 Emissions in the stabilized phase of FTP75 (Bag 2)

Like its reference name suggests, the second phase truly seems to be a stabilized phase, as the emission rates attained during this portion of the cycle were more or less nondependent of ambient temperature level. Therefore, specific accumulation plots are not illustrated here, but Figure 102 comprises only the average emission rates, and shows how very little they differed between the two ambient temperature levels. Furthermore, almost all readings were on par with the detection level (about 5 to 10 mg/km). However, the strong difference between car ANH96Oc and the rest of this sub-fleet in this test series remained even here, as it produced emissions at rates about ten times higher than the other vehicles.

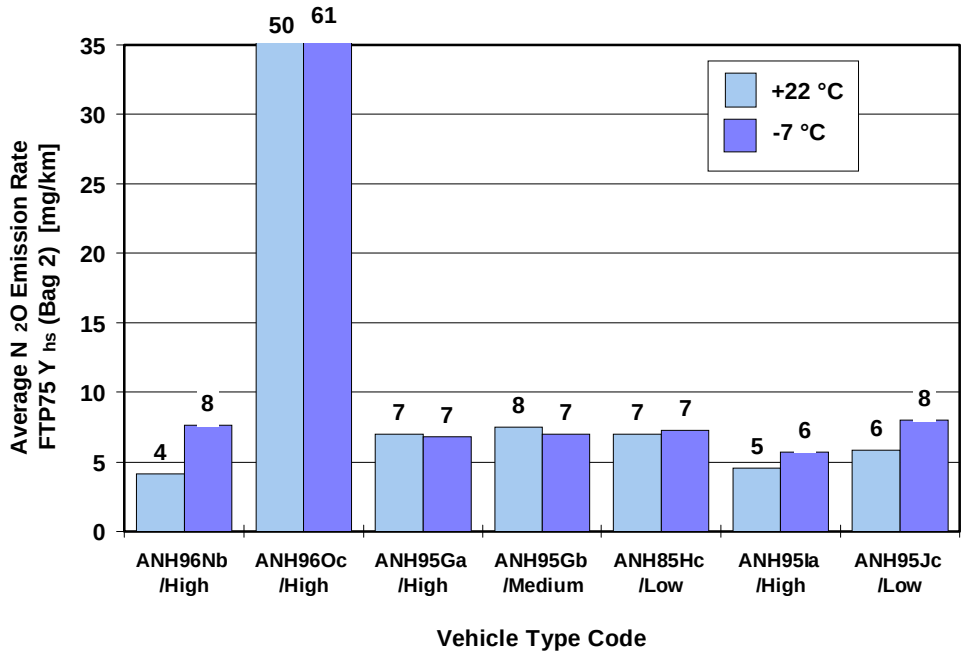

Figure 102 Specific emissions rates of nitrous oxide as average values during Y_{hs} phase of FTP75 for cars tested in the In-use study at normal and at low ambient temperature.

8.2.5 Emissions over the hot restart phase of FTP75 (Bag 3)

Going then further to discuss the results derived from the final, third phase of the FTP75 procedure, which is initiated with a warm engine restart after a 10 minute pause. Figures 103 to 105 replicate the representation already given for the results of the first phase dividing the illustration to accumulation at normal ambient, accumulation at low ambient and the comparison of the average specific emission rates at both of these test temperatures.

The outcome of this evaluation is very similar to what was already noted for the first phase. Peak emission rates were attained for some time right after the start, but as the start now occurred with a warm engine, cooled down only during the 10 minute pause, the peaks were slightly shifted towards the starting point and rose till about 250 to 500 m were travelled.

Overall, the average emission rates seemed to be lower than or similar to what was recorded for the Bag 1 phase. Nevertheless, car ANH95Hc exhibited now higher specific rates. Again, the decline of emissions due to the lowering of the ambient temperature, noted in the case of both cars of type ANH95G, was retained. However, it was only very, very weak at this time, and considering the detection limits for this type of analysis, only indicative, if not totally inconclusive.

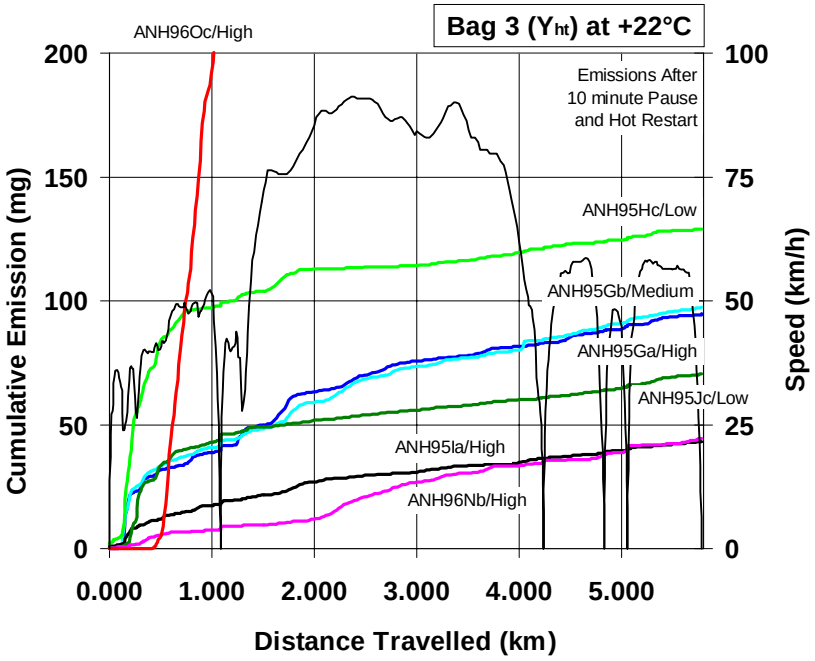

Figure 103 Accumulated emission of nitrous oxide for phase Y_{ht} of FTP75 as a function of distance travelled during cycle for cars tested in the In-use study at normal ambient temperature.

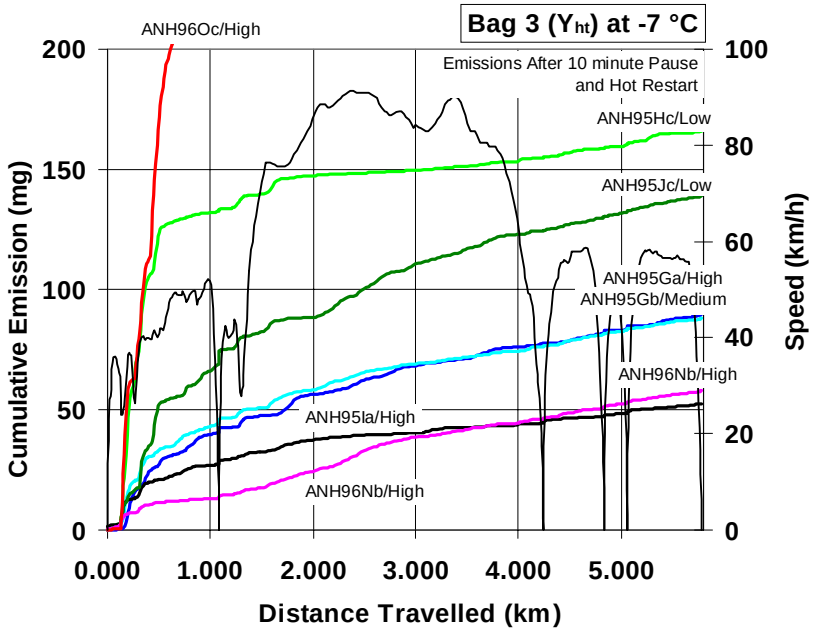

Figure 104 Accumulated emission of nitrous oxide during phase Y_{ht} of FTP75 as a function of distance travelled during cycle for cars tested in the In-use study at at low ambient temperature.

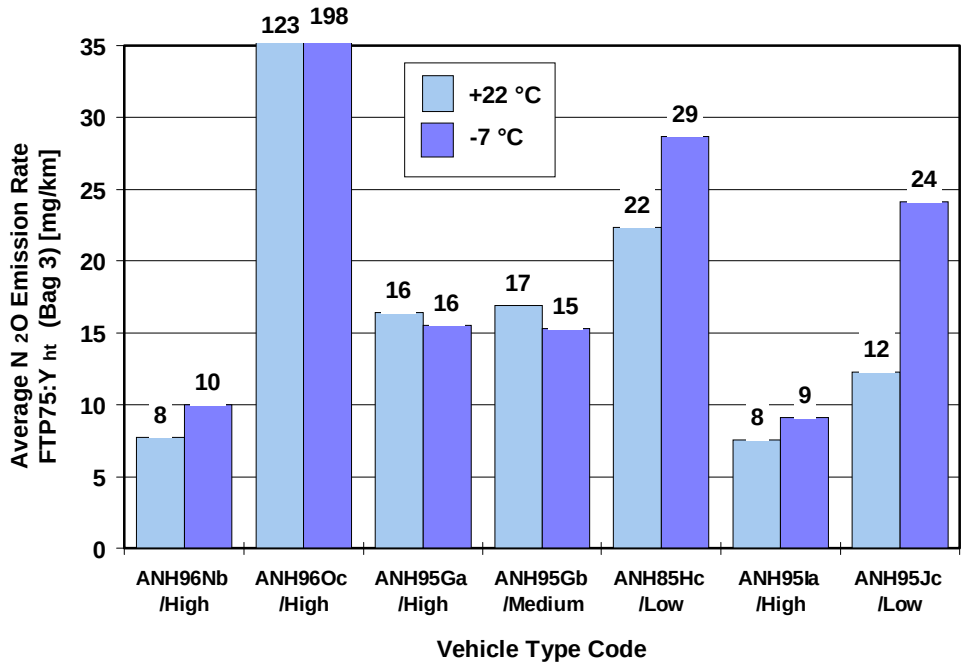

Figure 105 Specific emission of nitrous oxide as average values during phase Y_{ht} of FTP75 cycle for cars tested in the In-use study at normal and at low ambient temperature.

8.2.6 Comparison of two cars with different mileage

Although the test fleet was rather small in size, it contained two cars of the same type (ANH95G). They were, however, of different model years, and with different total vehicle mileages, as one (b) had a medium figure (37,000 km) and the other (a) had a high value (62,000 km) on its odometer. It was felt that due to these differences, they provided an interesting basis for comparison. Therefore, the two cars were evaluated somewhat more in detail.

Figure 106 denotes the accumulated emission as a function of distance travelled during the first phase of the FTP75 cycle just for these two cars at both of the test temperatures. The same kind of illustration is presented in Figure 107 for the individual results attained in the third phase. It was interesting to note, how similar the emissions performance regarding nitrous oxide was in all but one of the four different sub-cases. Effectively the differences in the behaviour all narrowed down to the cold-start at low temperature, whereas in the three other operating modes, a cold-start at normal ambient or a hot restart at both of the temperatures, nitrous oxide was emitted at about the same rate from both of the cars in question.

However, the decline in emission rates at low ambient temperature, already noted previously, was of different magnitude in these two cars. No conclusive reason could be found, although the difference could be linked with the vehic-

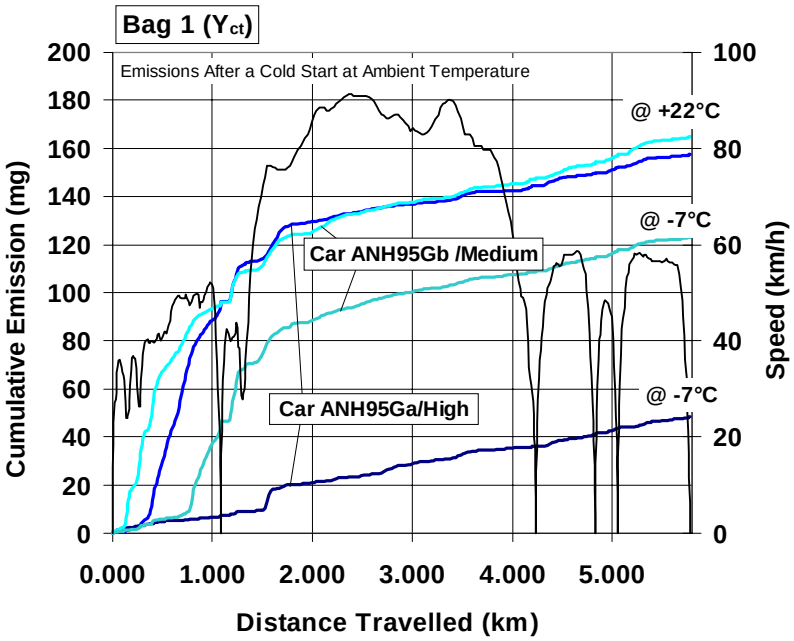

Figure 106 Accumulated emission of nitrous oxide at normal and at low ambient temperature as a function of distance driven during phase Y_{ct} of FTP75 cycle for two individual cars of the same type.

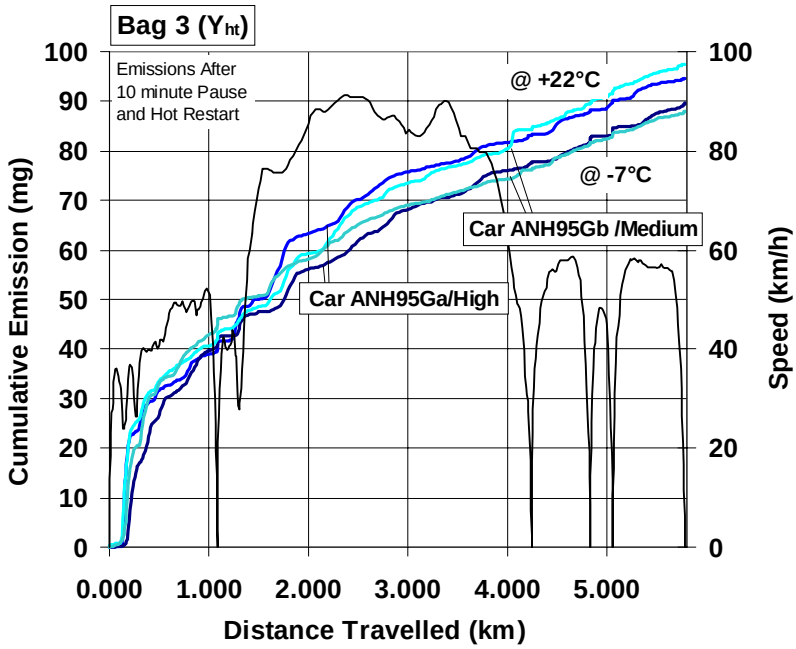

Figure 107 Accumulated emission of nitrous oxide at normal and at low ambient temperature as a function of distance driven during phase Y_t of FTP75 cycle for two individual cars of the same type.

le mileage. However, other reasons were regarded equally likely, since the cars were of different model years (a:1993, b:1995) and unfortunately, not enough details of their technology (air-fuel mixture calibration, catalyst type and formulation etc.) was available to ponder the various possible causes for differences of this kind.

8.2.7 Conclusions for nitrous oxide

According to the basic theories, presented in the literature [72] - [75], for the formation of nitrous oxide in a three-way type of catalytic converter, a three- way catalyst is capable of transforming NO to N_2O during an intermediate phase, when the converter bed temperature is above, but still very close to, the light-off temperature, i.e. around 350 to 450 °C. Because a cold start evidently affects the warm-up of the converter, lowering of the ambient temperature would suggests that the catalyst would be working longer times in the temperature range just referred, thus producing elevated concentrations of nitrous oxide. However, lacking the possibility of in-catalyst temperature measurement, this hypothesis could not be corroborated in this study.

Although the test data was very limited, containing only one-off tests and usually only one car measured of each type, it would be of interest to make an attempt to denote the performance of some individual cars slightly more in detail than what has already been made.

First, the possible reasons for the exceptionally high emission rates recorded for car ANH95Oc should be discussed. This outcome was somewhat surprising, since this car was producing NO_X only on an average level, and NO is considered as a kind of "raw material" for the formation of nitrous oxide. However, this result became even more interesting, because it was known that the car was obtained for testing from a private owner, who was known to have taken this car to continental Europe, especially Germany. Therefore, this particular car could have been subjected to more full-throttle operation and higher temperatures in the catalyst as the rest of this sub-fleet, where no other such vehicles were known to exist.

Unfortunately, there were no parallel measurements for other cars of this type. Therefore, it could not be corroborated, whether this abnormal performance was only some disagreeable by-product of the usage history of this individual car in particular, or a symptom of a wider scale, attached to the catalyst technology used in this car type.

Notwhitstanding, all these differences in emission rates between cars and test cycle phases, if sub-fleet average values are calculated, those escalations and declines denoted previously seemed to counterbalance each other quite effectively. Figure 108 illustrates this comparison, and presents unweighted sub-fleet

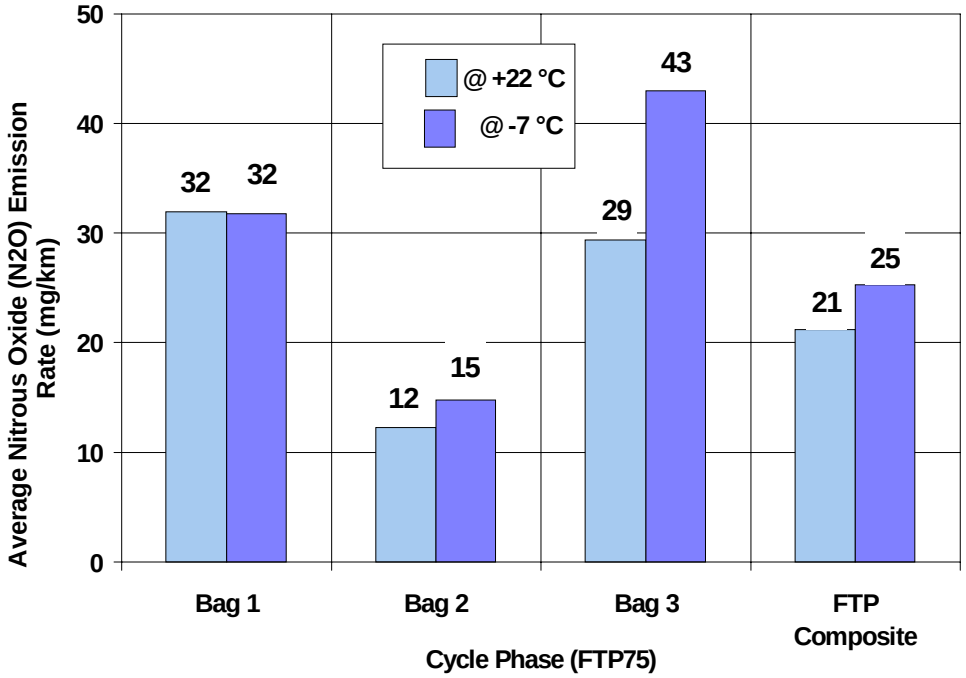

Figure 108 Emission rates for nitrous oxide (N_20) as averages for the tested sub-fleet in different phase of the FTP75 driving cycle at normal and at low ambient temperature; the seven car sub-fleet of the In-use study.

averages for each of the phases in the FTP75 test cycle, as well as for the total, composite FTP values at both of the test temperatures.

As this figure shows, ambient temperature seemed to affect only Bag 3 results in such an extent that the difference could be regarded as meaningful. Furthermore, a very slight tendency towards higher emission rates at low temperatures was present even in Bag 2 values. These two increases together were enough to push also total, composite FTP75 average value up, when the ambient temperature was lowered from the baseline (+22 °C) to low (-7 °C), but only with an almost insignificant amount compared to the level of inaccuracy in this type of analysis. Contrary to expectations, Bag 1 values were, on average, about the same at both ambient temperatures.

Based on the results at hand, it was not possible to link total vehicle mileage to any of the changes in emissions performance conclusively. This was due mainly by the small size of the test fleet and lack of true, parallel measurements with cars of the same type sharing same technology, but differing in total distance travelled.
Furthermore, considering the small size and rather arbitrary composition of this sub-fleet, as well as the inaccuracies in the measurement method (*see 5.6.3*), all these conclusion should be taken only as indicative.

8.3 EMISSIONS OF AMMONIA (NH_3)

8.3.1 Accumulated emissions over FTP75

The emissions of ammonia (NH_3) will be discussed next. Like in the previous case, nitrous oxide, the accumulated emissions over the complete FTP75 driving cycle as a function of distance travelled during the cycle is first quoted. Figure 109 plots the accumulation recorded at baseline temperature (+22 °C) and Figure 110 does the same for results attained at low ambient temperature (-7 °C) for six different vehicle types tested in this In-use study.

Considering first the profile of emissions measured at normal ambient temperature, Figure 109 shows that unlike nitrous oxide, which was displaying elevated rates of emission for some time after the start, especially at low ambient temperatures, the release of ammonia was more evenly dispersed along the distance driven. Furthermore, the tested cars were also more evenly distributed than in the previous case, with total emissions between somewhat below 100 mg up close to 900 mg over the complete FTP75 driving cycle.

The car, which produced the highest emissions was the car with code ANH 95Ga, and the one with the lowest total output was car ANH96Oc. Incidently, this was the very same car that had the absolutely highest emissions of nitrous oxide in this tested sub-fleet.

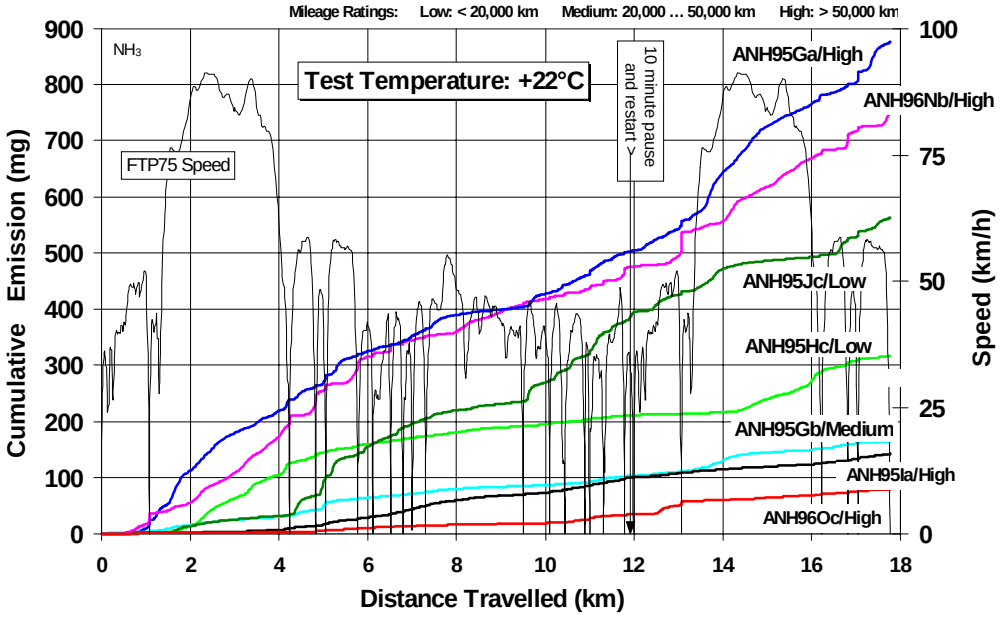

Figure 109 Accumulated emissions of ammonia (NH_3) over FTP75 driving cycle as a function of distance travelled in the cycle for the cars tested in the In-use study at +20 °C ambient temperature.

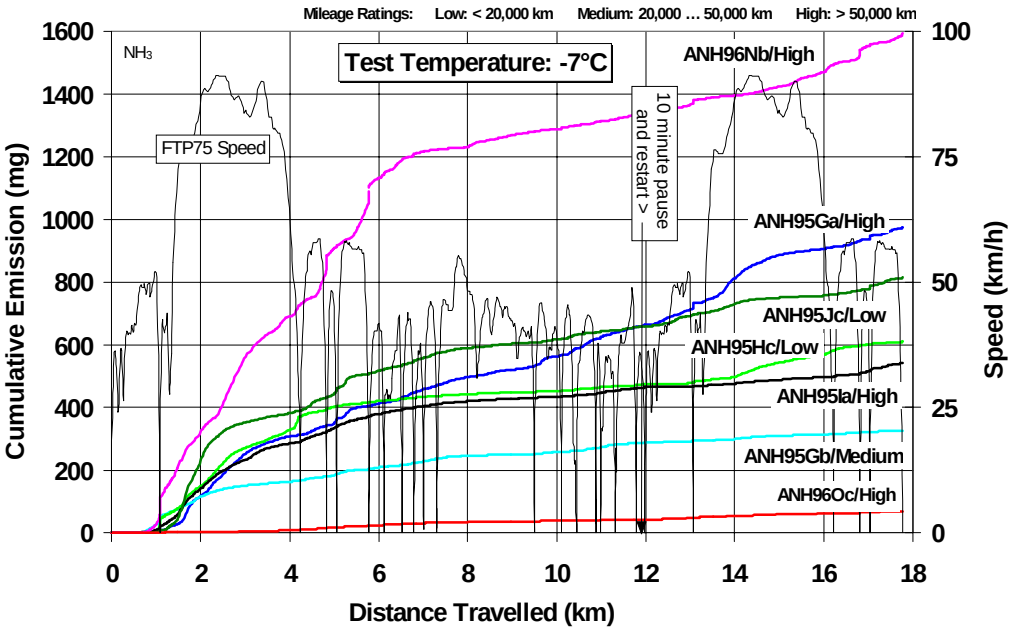

Figure 110 Accumulated emissions of ammonia (NH_3) over FTP75 driving cycle as a function of distance travelled in the cycle for the cars tested in the In-use study at -7 °C ambient temperature.

As seen in Figure 110, lowering the test temperature to -7 °C ambient changed the pattern somewhat. It seems that the cold start affected here the emission rates more than at baseline temperature, as the emissions were now ramping up more steeply. However, the car coded as ANH96Oc remained on a very low level of emissions even here. Furthermore, two notable changes could be recorded. First, the car with code ANH95Ga presented lower total accumulated emissions at this low ambient temperature than at the baseline, whereas the car coded as ANH96Nb seemed to produce ammonia in excess. This high rate continued to the distance of some 6 km, which is about the end of the first phase of the FTP75 driving schedule (Y_{ct}). Notwhitstanding these exceptions, the rest of the tested sub-fleet produced ammonia at low temperature at about the same rates as at baseline temperature.

8.3.2 Average emission rates in FTP75

Like before, this comparison could be best made using specific emission rates (in mg/km) as the rating. The value presented in Figure 111 equals to the so called composite FTP75 value, which is, according to the standardized procedures, calculated from the emissions over individual sub-cycles (Y_{ct}, Y_{hs}, Y_{ht}) by using different weighting factors for each of the three phases.

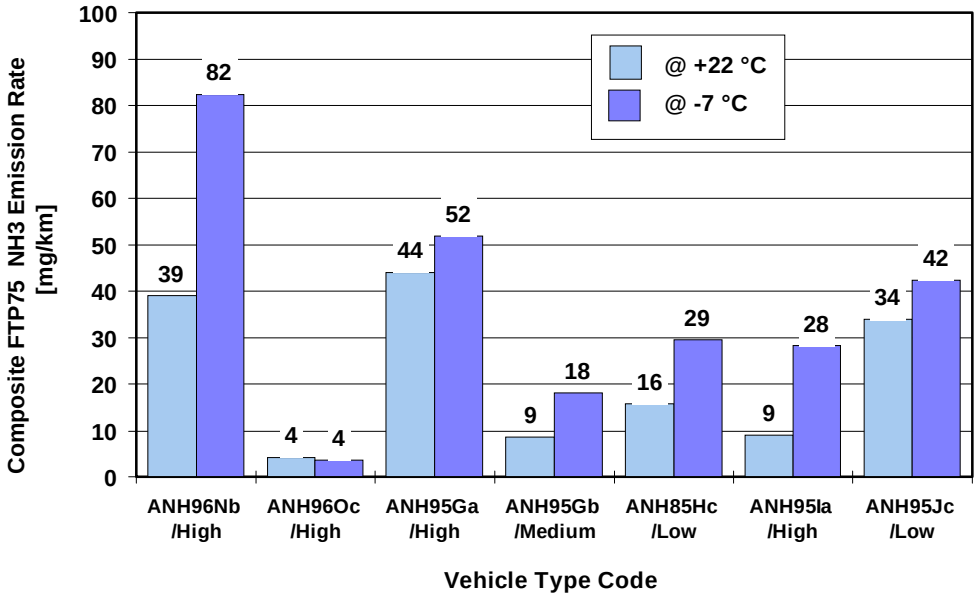

Figure 111 Average overall ammonia emission rates over FTP75 driving cycle at normal and at low ambient temperature for cars tested in the In-use study.

As seen in this figure, it can be seen that all other cars but the one, ANH96Oc, with extremely low emission rates, emit on average more ammonia, over a complete FTP75 test run at low ambient temperature compared with the baseline value measured at normal ambient temperature. However, the magnitude of this elevation varied between the tested cars from only a slight (about 20 %) increase over the baseline to an almost fourfold value measured at low ambient. However, in regard of the level of inaccuracy in this measurement method (*about 2 to 3 mg, see 5.6.3, Table 15*), these variations must be treated more as symptomatic than conclusive. As already noted, those very high nitrous oxide emissions for the car ANH96Oc were reflected here, in the case of ammonia, in extremely low average rates on par with the detection level.

8.3.3 Emissions over the cold-start phase of FTP75 (Bag 1)

According to the previous example, the analysis of the emissions performance was extended to the individual phases of the FTP75 cycle. First, the results for the cold transient phase (Bag 1) are denoted. Figure 112 shows emission accumulation at normal ambient and, furthermore, Figure 113 shows the same for the tests at low ambient temperature. Eventually, Figure 114 compares the average specific emission rates recorded for this phase at both of these ambient conditions.

Comparing first the accumulation of the emissions, it can be noted that the behaviour was now somewhat different from the other unregulated pollutant, nitrous oxide, already discussed previously. Where the nitrous oxide emissions were characterized with strong peaks with quite short duration, ammonia emissions, however, were released much more slowly over the whole cycle,

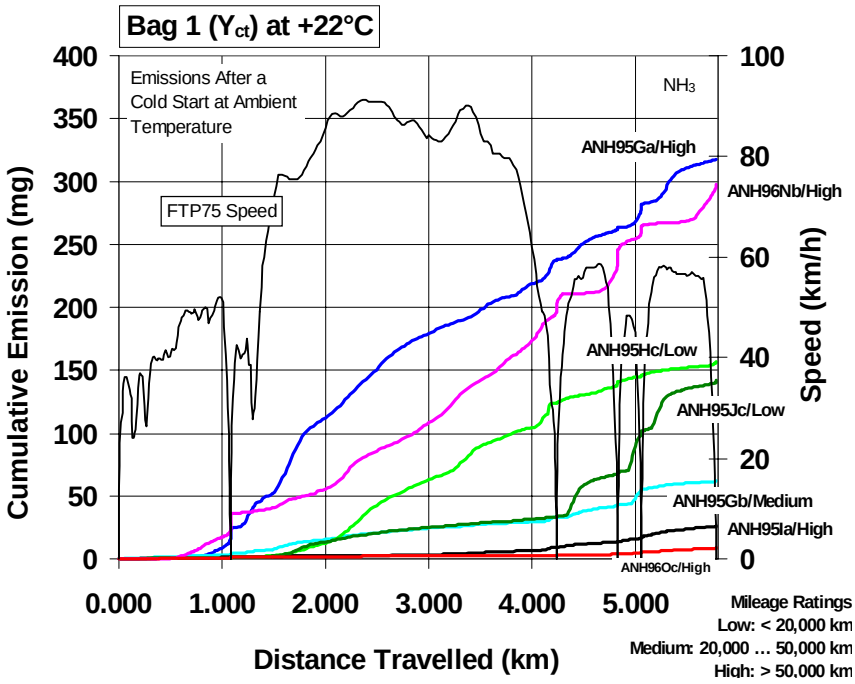

Figure 112 Accumulated emissions of ammonia (NH_3) during phase Y_{ct} of the FTP75 driving cycle as a function of distance travelled in the cycle at normal ambient temperature for cars tested in the In-use study.

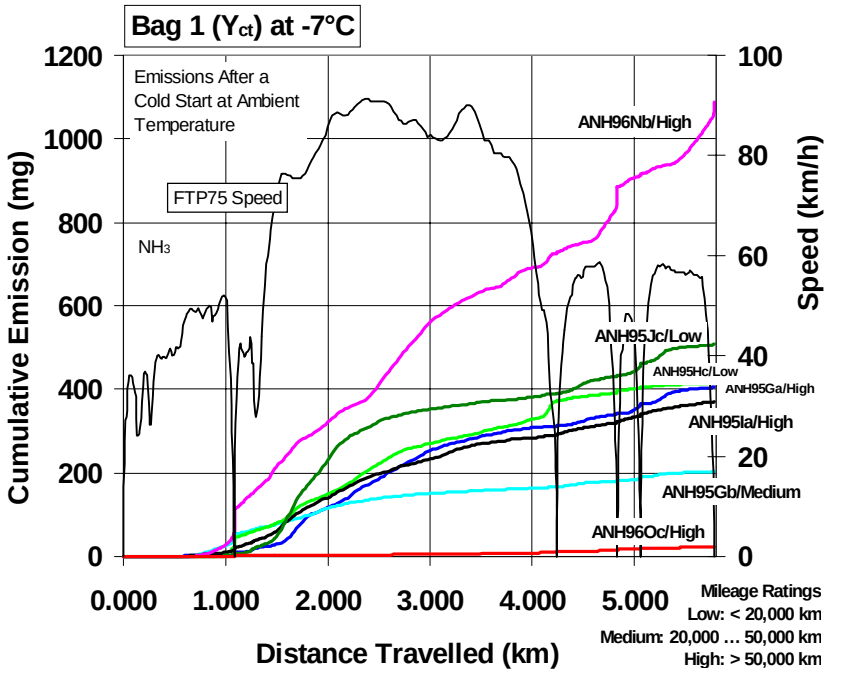

Figure 113 Accumulated emissions of ammonia (NH_3) during phase Y_{ct} of the FTP75 driving cycle as a function of distance travelled in the cycle at low ambient temperature for cars tested in the In-use study.

particularly at the baseline temperature case. However, Figure 113 shows how at low ambient temperature, elevated emission rates were recorded for the car being the extreme case (ANH96Nb) already shortly after the cold-start, at about 1 km, and a second burst was detected further up till the end of the test phase discussed here, at about 4.7 km of driving distance.

From all the tested vehicles, the car that was coded as ANH96Nb appeared to be the most sensitive to the lowering of the ambient temperature, as was already indicated, when the emissions over the total cycle were discussed. According to the Figure 114, it produced ammonia at extremely high rates, nearly 200 mg/km, where the next highest rate was substantially below 100 mg/km.

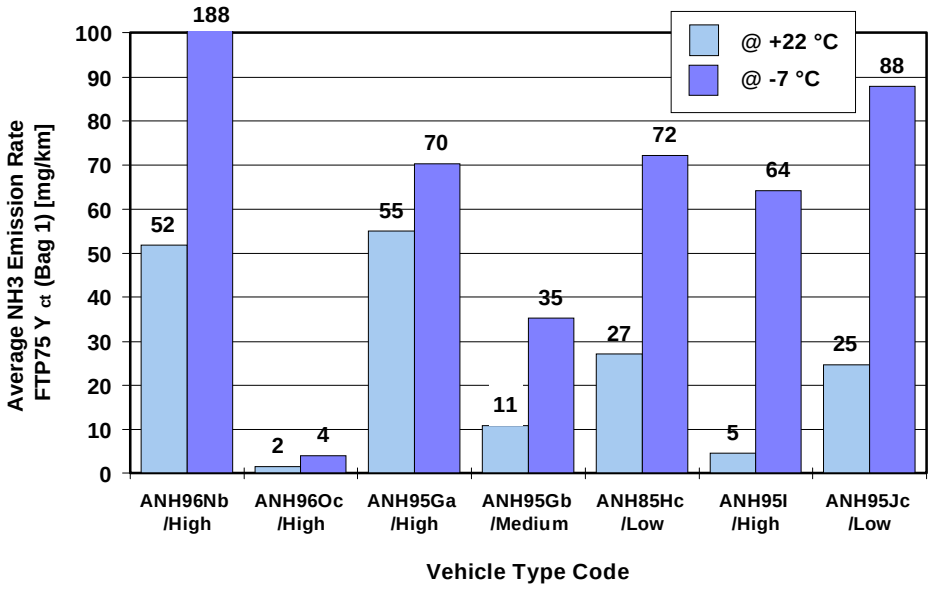

Figure 114 Specific emission rates of ammonia (NH_3) as average values during Y_{ct} phase FTP75 for cars tested in the In-use study at normal and at low ambient temperature.

Considering the level of inaccuracy at this kind of measurement (about 2.5 mg/km), all cars produced emissions of ammonia in rates higher than the baseline at low ambient temperature. The change in the rate, however, was very different from one car to another. On average, three times higher rates compared with the baseline were recorded at low ambient. Aside, the lowest increase was only some 30 %, whereas the strongest change was as high as 12 times more emissions at -7 °C compared with baseline level attained at +22 °C. It was car ANH95Ia that produced this extreme case. Although this was a high-mileage vehicle, the total mileage was evidently not strongly affecting this aspect of emissions performance. This assumption was based on the observation that the lowest change was also attributed to a high-mileage vehicle (ANH95Ga), and its parallel car (ANH95Gb), with much less kilometres on the odometer, suffered from the effect of low ambient temperature much more, because the specific emission rate for this particular car was changed from 11 to 35 mg/km.

8.3.4 Emissions in the stabilized phase of FTP75 (Bag 2)

The analysis is then continued to the second, stabilized phase. Figure 115 comprises the average emission rates for this portion of the cycle. It appears, that the changes in emission rates because of the lowering of the ambient temperature were here much less dramatic than in the previous phase. Furthermore, the average emissions level was only about half of what was the average level in Bag 1. However, the rather striking dissimilarity between car ANH96Oc and the rest of the sub-fleet was retained, as it produced emissions at rates far below the numbers attributed to the other vehicles.

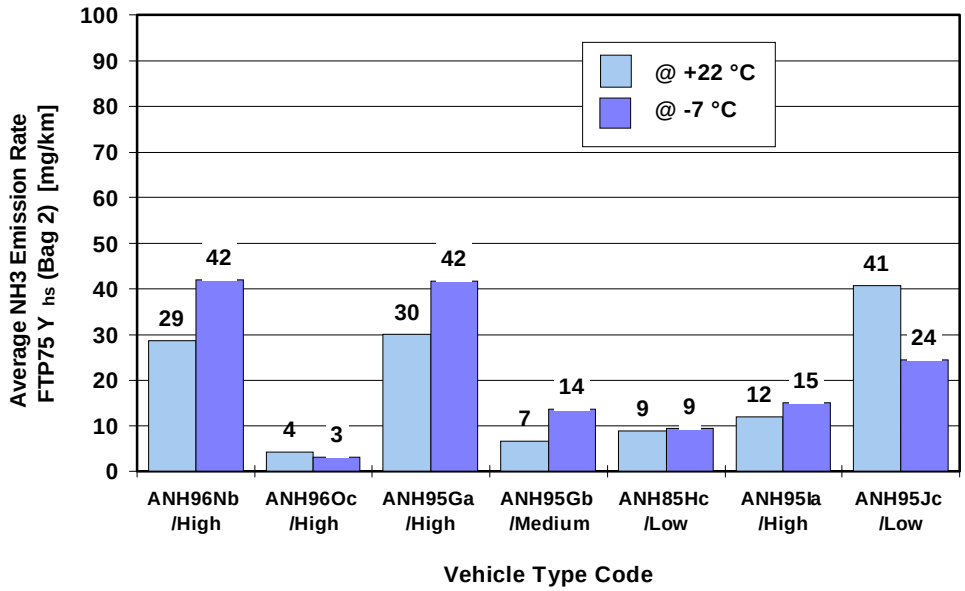

Figure 115 Specific emission rates for ammonia (NH_3) as average values during Y_{hs} phase of FTP75 cycle for cars tested in the In-use study at normal and a low ambient temperature.

8.3.5 Emissions over the hot restart phase of FTP75 (Bag 3)

Lastly, results derived from the third phase of the FTP75 procedure are commented. Figures 116 to 118 duplicate the representation given for the results of the first phase illustrating the accumulation at normal ambient, at low ambient and then presenting the comparison of the average specific emission rates at both of the tested temperatures.

In this portion of the driving schedule low ambient temperature seemed to have less effect on the emission rates than during the very first phase, right after a cold start. Almost the same kind of accumulation of emissions was registered at both of the tested temperatures.

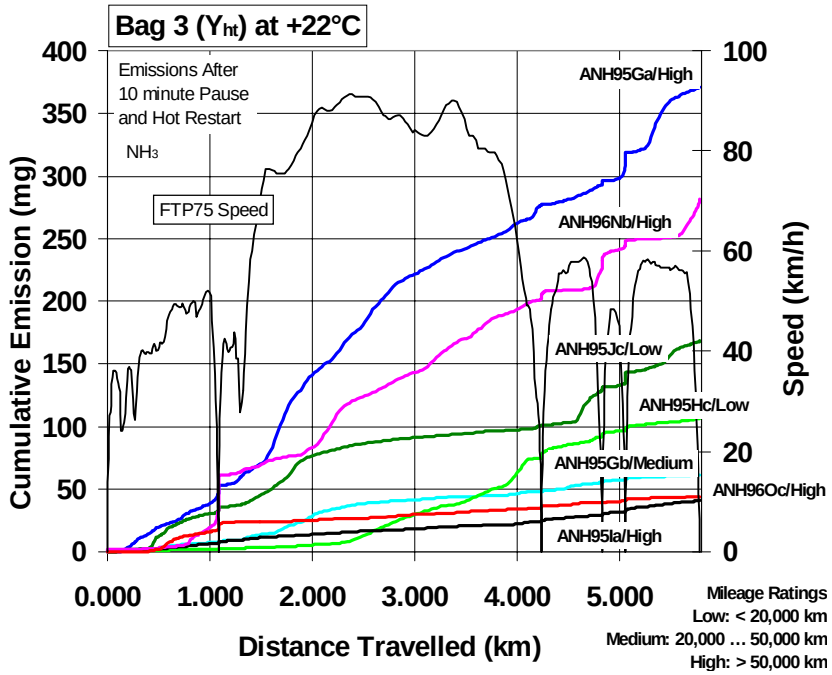

Figure 116 Accumulated emission rates of ammonia (NH_3) for phase Y_{ht} of FTP75 as a function fo distance travelled during the cycle for cars tested in the In-use study at normal ambient temperature.

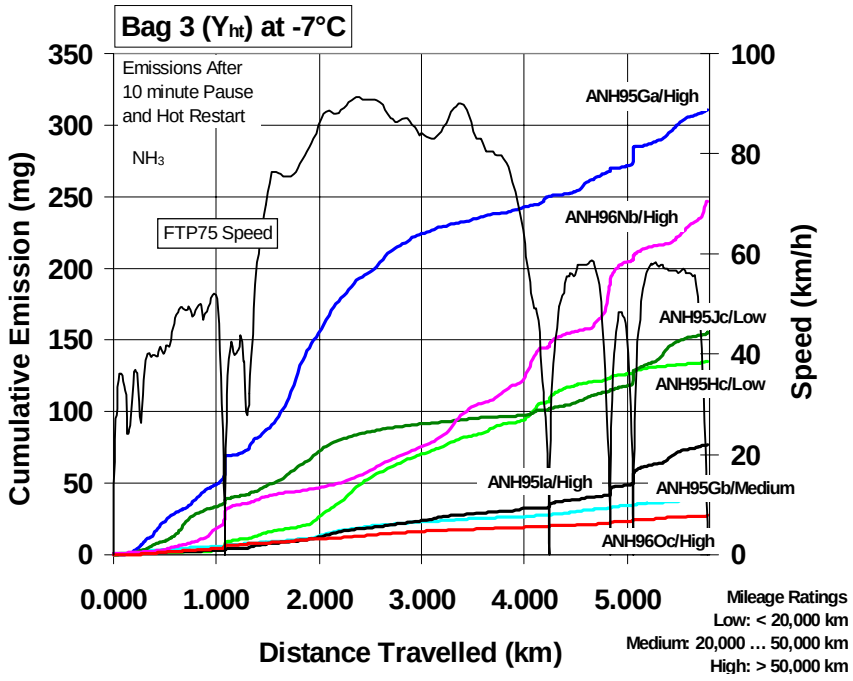

Figure 117 Accumulated emission rates of ammonia (NH_3) for phase Y_{ht} of FTP75 as a function fo distance travelled during the cycle for cars tested in the In-use study at low ambient temperature.

The release of ammonia, however, started in this phase much sooner, only at about 200 to 500 m distance from the start, than in case of the first phase, where it was in most of the cases delayed until about 1 km or some more distance was collected.

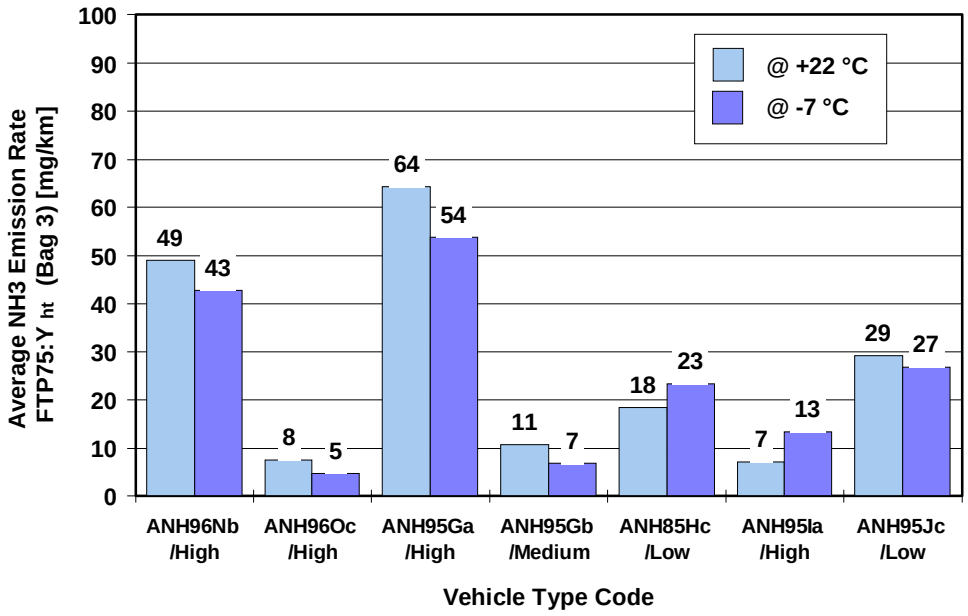

Figure 118 Specific emission rates of ammonia (NH_3) as average values during phase Y_{ht} of FTP75 cycle for cars tested in the In-use study at normal and at low ambient temperature.

As seen from Figure 118, the average emission rates for the Bag 3 phase (Y_{ht}) were in all but two of the tested cars lower than the baseline at the lower ambient temperature. These declines were, however, quite mild, which was the case also with those increases detected for two cars. Furthermore, considering the accuracy of this measurement, neither of these changes can be attributed to be other than indicative.

8.3.6 Comparison of two cars with different mileage

Finally, results for those two cars of the same type (ANH95G) are compared also for ammonia. Figure 119 denotes the accumulated emission as a function of distance travelled during the first phase of the FTP75 cycle just for these two cars at both of the test temperatures. The same kind of illustration is presented in Figure 120 for the individual results attained in the third phase. Considering first those Bag 1 results, one can see, how dissimilar the release and accumulation of the ammonia were in these two cars. The car coded as ANH95Ga had at baseline temperature substantially higher emissions than its counterpart, ANH95Gb, of the same type. About fivefold total accumulation of ammonia was recorded for the car (a) compared with the car (b).

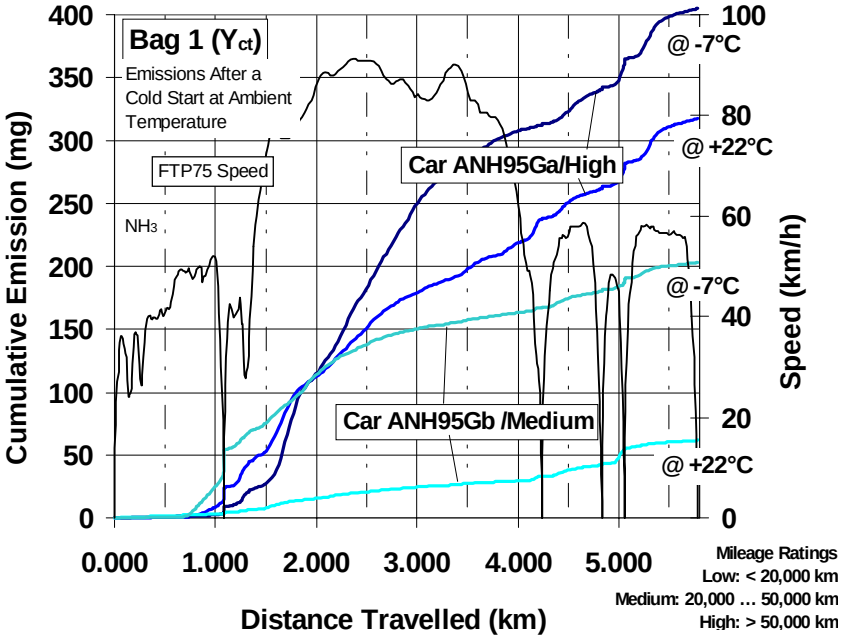

Figure 119 Accumulated emission of ammonia (NH_3) at normal and at low ambient temperature as a function of distance driven during phase Y_{ct} of FTP75 cycle for two individual cars of the same type, ANH95G, from the tested sub-fleet in the In-use study.

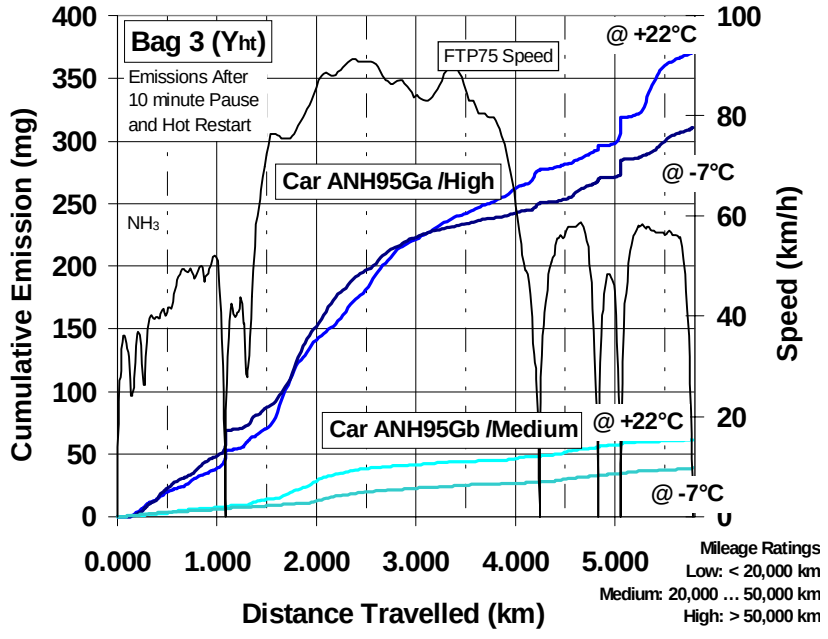

Figure 120 Accumulated emission of ammonia (NH_3) at normal and at low ambient temperature as a function of distance driven during phase Y_{ht} of FTP75 e for two individual cars of the same type, ANH95G, from the tested sub-fleet in the In-use study.

However, at low ambient temperature this difference was much less, as car (a) with higher total mileage seemed to be less sensitive to ambient temperature, as total output figure for the car (a) was only about twice as high as the value accounted for the car (b).

The emissions performance appeared to be slightly different in case of the phase Y_{ht} corresponding to Bag 3 of the FTP75 driving cycle. For both of these cars almost identical trace to that of Bag 1 was recorded also for Bag 3 in tests at +22 °C. However, at low ambient temperature both of the cars presented a decline in emissions, which was in direct contrast to what was just discussed for Bag 1.

This difference between cars in Bag 3 results was somewhat surprising, because as the corresponding figure already showed, both of the cars emitted nitrous oxide at about the same magnitude, and these two compounds are both essentially derived from the NO_X conversion. Furthermore, as already mentioned in 8.2.6, it was all too difficult to determine, what was causing this kind of difference in operation, because not enough details of technology were available.

8.3.7 Conclusions for ammonia

As just discussed, emissions of ammonia were overall differing rather strongly from one car type to another and between different phases of the cycle. They were, to a certain level, also quite dependent on ambient temperature. However, average values for the whole fleet were not very different from another, even regarding ambient conditions. This can be seen in Figure 121, which illustrates these averages for the results in each of the sub-phases of the FTP75 test cycle, as well as for the total, composite FTP values. These averages are calculated as unweighted values for the sub-fleet in question.

As seen in the figure, quite surprisingly in all but only two cases the average rate of ammonia emission was 23 mg/km (range from 19 to 27). The only two contrasting cases were Bag 1 at low ambient temperature, which was about three times as high as this overall average. This high value in Bag 1 was affecting also to the total, composite FTP value to the extent that it rose to a level half of that high peak and about 1.5 times the overall level. Thus, this evaluation duly underlines the cold start effect seen in short trips at low ambient temperature. However, considering the quite minute size and entirely random compilation of the sub-fleet, and also the relative error contained in the measurement method, all previous resolutions should be taken only as indicative.

Based on the results for this rather limited sub-fleet, no conclusive dependence between ammonia emissions and total vehicle mileage could be corro-

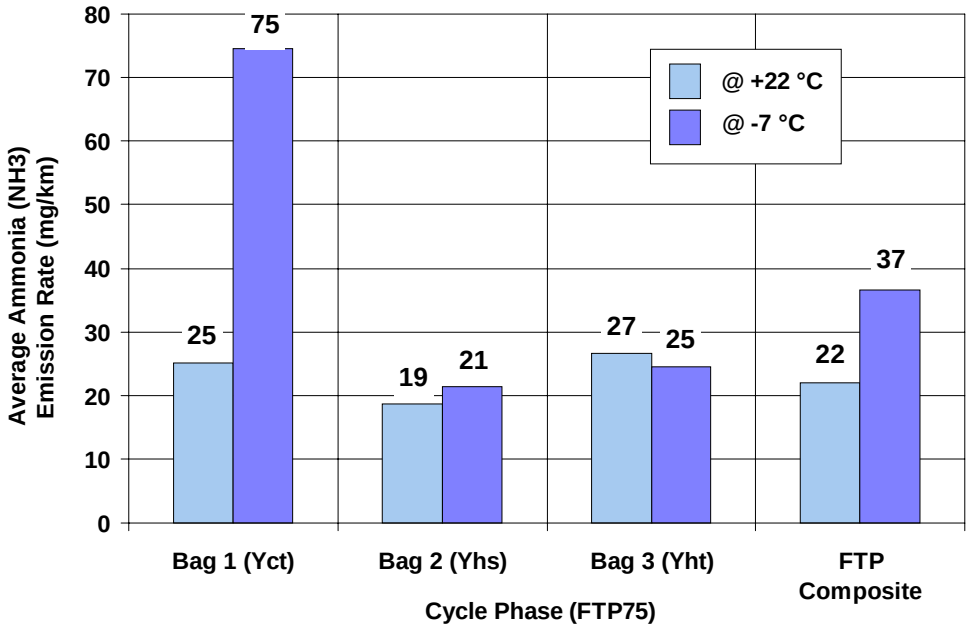

Figure 121 Emission rates for ammonia (NH_3) as averages for the tested sub-fleet in different phase of the FTP75 driving cycle at normal and at low ambient temperature; seven car sub-fleet in the In-use study.

borated. Other parameters discussed here had, by far, stronger effect. Of these, vehicle type seemed to be the overruling factor. Like in the case of nitrous oxide, the lack of true parallel measurement of identical cars with variable mileages was the main inhibiting factor for making any truly definite comments on this subject.

8.4 EMISSIONS OF FORMALDEHYDE

8.4.1 Accumulated emissions over FTP75

Of the unregulated emissions measured with FTIR, formaldehyde is discussed as last. Parallel to the previous cases, Figures 122 and 123 show the accumulated emissions over the complete FTP75 driving cycle as a function of distance travelled during the cycle at baseline temperature (+22 °C) and at low ambient temperature (-7 °C) for the sub-fleet tested for unregulated pollutants in the In-use study. Likewise, total vehicle mileage is noted in connection to the type code using the same references as before. Equally, target speed of the FTP75 driving cycle is included to make possible to detect different phases of the cycle.

Judging first the accumulation of emissions at normal ambient temperature, one can see from Figure 121, that in most of the tested cars formaldehyde emissions started right after the cold start. This was somewhat in contrast to nitrous oxide or especially ammonia, which were both released only after

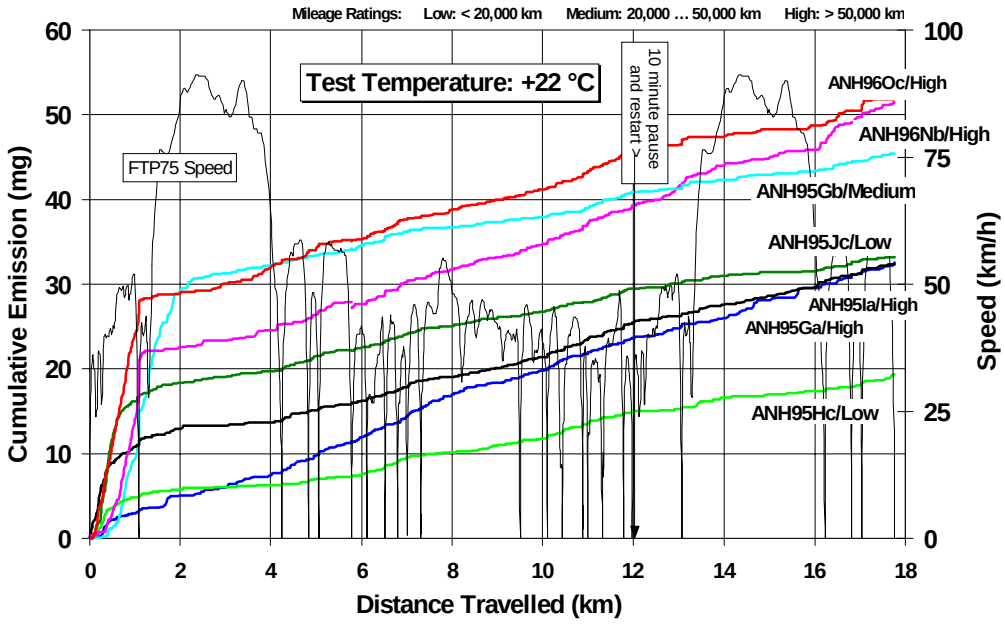

Figure 122 Accumulated emissions of formaldehyde over FTP75 driving cycle as a function of distance travelled in the cycle for cars tested in the In-use study at +22 °C ambient temperature.

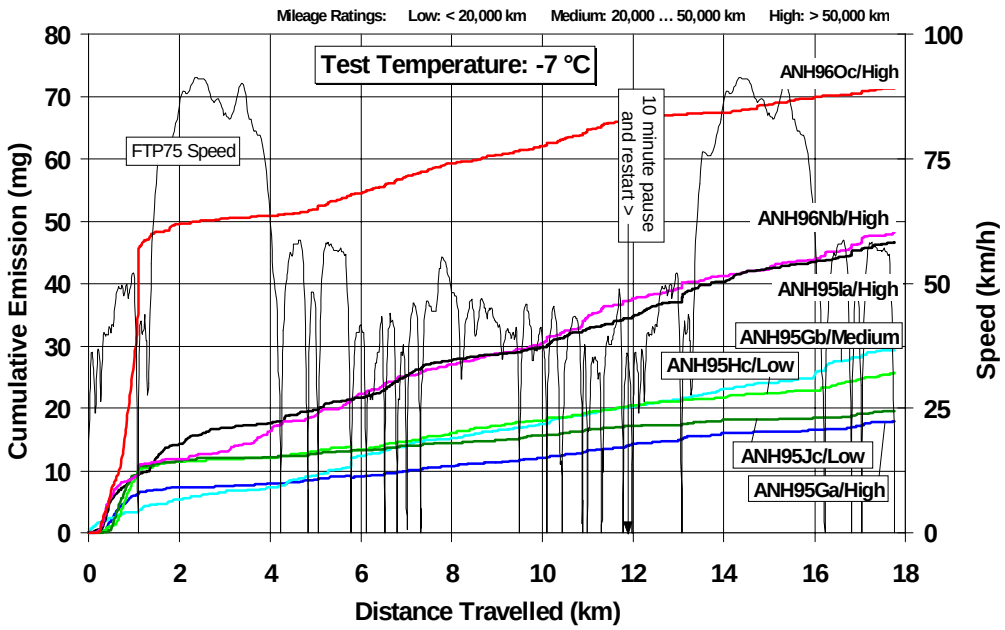

Figure 123 Accumulated emissions of formaldehyde over FTP75 driving cycle as a function of distance travelled in the cycle for cars tested in the In-use study at -7 °C ambient temperature.

some time and distance was completed after the cold start. Most of the cars were also producing quite similar emission rates up to the point, where the enrichment of the fuel-air mixture supposedly phases out and the engine assumes stoichiometric

operation. This was happening in the fastest reacting car at about 500 m and in the slowest one at the distance of 2 km from the start. Thereafter, the emission rates were much smaller, and again quite similar from one car to another. Not even the restart after the pause seemed to affect markedly.

One car (ANH95Ga), however, had quite different performance, because it produced only negligible emissions at the start, but emitted formaldehyde at higher rates than the rest of the cars in this sub-fleet, cumulating a total output similar to that of cars with much higher emissions at initial start-up. Based on the total output of formaldehyde at normal ambient temperature (+22 °C) over the complete FTP75 driving cycle, which is nearly 18 km in length, the cars fell into three groups: those three (O, N, Gb) having total emission around 50 mg, those three (Ga, I, J) totalling slightly above 30 mg, and the one (H) having the lowest total output of the whole sub-fleet yielding to a figure below 20 mg.

As seen in Figure 123, lowering the test temperature to -7 °C ambient created somewhat different results. Release of formaldehyde seemed to start slightly later than in the baseline case. However, in most of the cases the levelling of the emissions occurred again before 2 km mark, equalling the performance at normal ambient. Thus, the cold start affected the emission rates less than at baseline temperature, because many cars produced almost equal or in some of the cases even lower emission rates at low temperature compared with the baseline figure. However, some of the cars, notably the one coded as ANH 96Oc, presented higher levels of emissions even here, especially during the first 1 km of the FTP75 driving schedule (Y_{ct}). Incidently, this highest-emitting car was the very same car that had also the absolutely highest emissions of nitrous oxide in this tested sub-fleet.

8.4.2 Average emission rates in FTP75

As before, comparison of average emision rates was made also using specific emission rates (in mg/km). The results of such an assessment are presented in Figure 124. In analogy with the previous instances, the values in this figure are calculated as composite FTP75 value, which is a weighted sum from the emissions over individual sub-cycles (Y_{ct}, Y_{hs}, Y_{ht}).

Based on this figure, the performance in this tested sub-fleet did not vary much as for overall formaldehyde emissions. Even the effect of low ambient temperature was rather mild. Only three of the tested cars, namely ANH 96Oc, ANH95Ga and ANH95Ia, showed elevated rates, when the test temperature was lowered. However, taking the low level of emissions in relation to the sensitivity of the measurement method (*about 7 mg/km; see 5.6.3*) into consideration, all of these changes should be taken as indicative only, if not totally inconclusive.

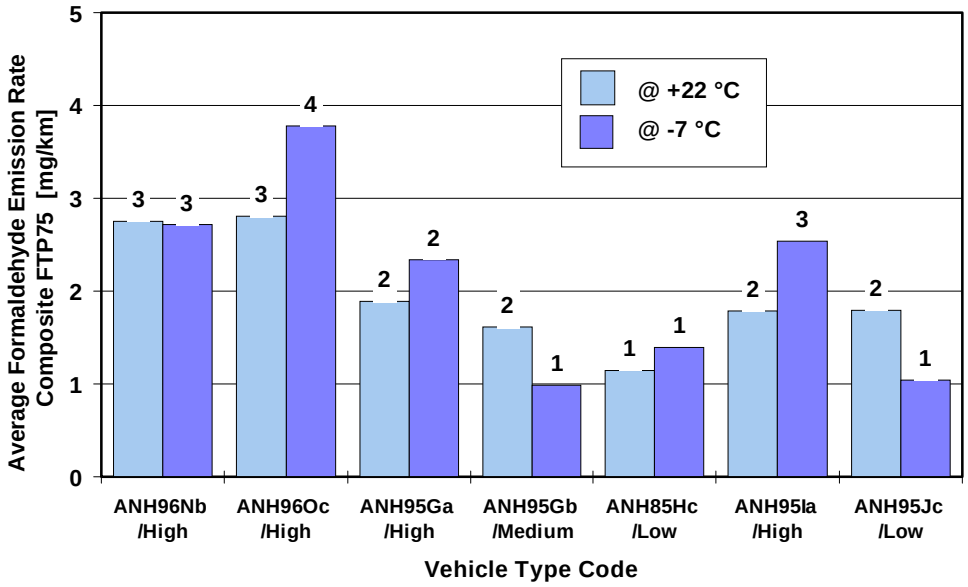

Figure 124 Average overall formaldehyde emission rates over FTP75 driving cycle at normal and at low ambient temperature for cars tested in the In-use study.

Formaldehyde can be classified also among the regulated pollutants, as CARB has imposed a certification standard for formaldehyde emissions in their current Low-Emission Vehicle Program. The test is a regular FTP75 at normal ambient temperature, and the limit values are 0.015 g/mile for TLEV and LEV class of vehicles, and 0.008 g/mile for vehicles certified as ULEV's. Expressed as [mg/km] these values become 9.3 and 5.0, respectively. However, this restriction is applicable to methanol-fuelled vehicles only, and petrol fuelled cars do not need to comply with it. Notwhitstanding, all these tested cars passed this guideline.

8.4.3 Emissions over the cold-start phase of FTP75 (Bag 1)

Again, the emissions performance was assessed also separately for each of the individual phases of the FTP75 driving schedule. The most interesting, by far, are the results for the cold transient phase (Bag 1). Figure 125 shows the accumulation of formaldehyde emissions at normal ambient and, furthermore, Figure 126 shows the same for the tests at low ambient temperature. Consequently, Figure 127 compares the average specific emission rates registered for this portion of the cycle at both of these ambient temperatures.

The difference in cold-start emissions, which was already discussed previously, can clearly be noted here by comparing Figure 125 with Figure 126. At normal ambient temperature the cars are rather evenly spread over the scale at the end of this first phase (Y_{ct}) totalling to figures ranging from below 10 mg

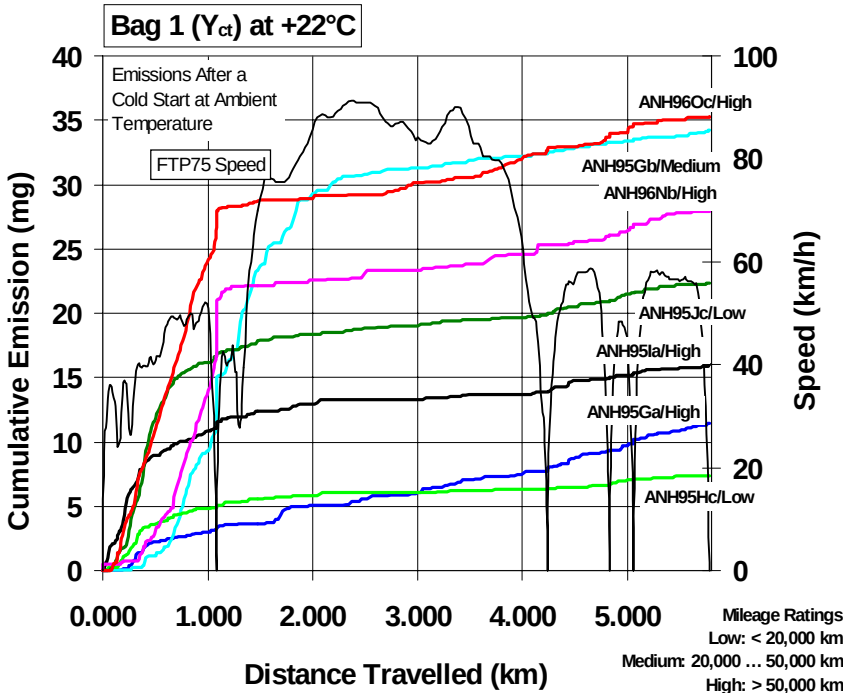

Figure 125 Accumulated emissions of formaldehyde during phase Y_{ct} of the FTP75 driving cycle as a function of distance travelled in the cycle at normal ambient temperature for cars tested in the In-use study.

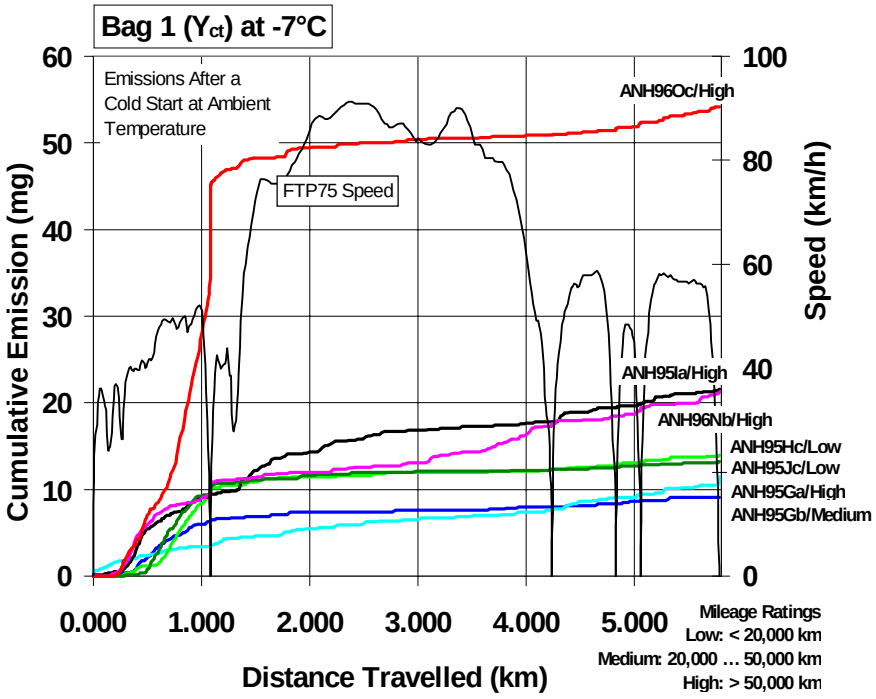

Figure 126 Accumulated emissions of formaldehyde during phase Y_{ct} of the FTP75 driving cycle as a function of distance travelled in the cycle at low ambient temperature for cars tested in the In-use study.

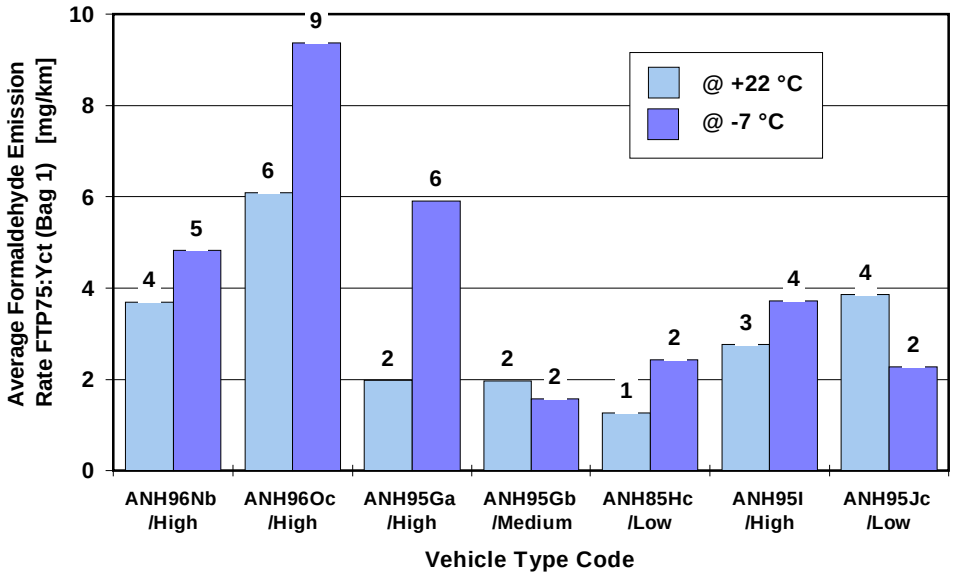

Figure 127 Specific emission rates for formaldehyde as average values during Y_{ct} phase of FTP75 cycle for cars tested in the In-use study at normal and at low ambient temperature.

up to 35 mg. At low ambient temperature, however, the whole sub-fleet, other than car ANH96Oc, produced formaldehyde about 10 to 20 mg in this nearly 6-km long trip. The anomalous behaviour of the car ANH96Oc placed it in its own class with a total output figure of some 55 mg, which is more than twice of the typical value for the rest of the sub-fleet. Even if this kind of phenomenon was typical for this car even in terms of nitrous oxide, not enough details were available about the vehicle to facilitate the making of conclusions of the reasons for this kind of performance. However, since the vehicle was known to employ a lean mixture setting at part-load and different kind of catalyst concept compared with the rest of the sub-fleet, it might have affected the results.

Notwhitstanding, the aforementioned car was seemingly not the most sensitive to the lowering of the ambient temperature. According to the Figure 127, it produced formaldehyde at higher rates, between 6 and 9 mg/km, than any other car. However, in case of car ANH95Ga, lowering of the test temperature produced emissions at rates that were about three times the baseline value recorded at normal ambient temperature. In the rest of the cases lowering of the ambient temperature seemed hardly to make any effect, especially if the level of inaccuracy in this method is taken into consideration.

8.4.4 Emissions in the stabilized phase of FTP75 (Bag 2)

As before, the analysis was then carried over to the second, stabilized phase. Figure 128 comprises the average emission rates for this portion of the cycle. Because apart form the exceptional vehicle ANH96Oc, the figures are all on the

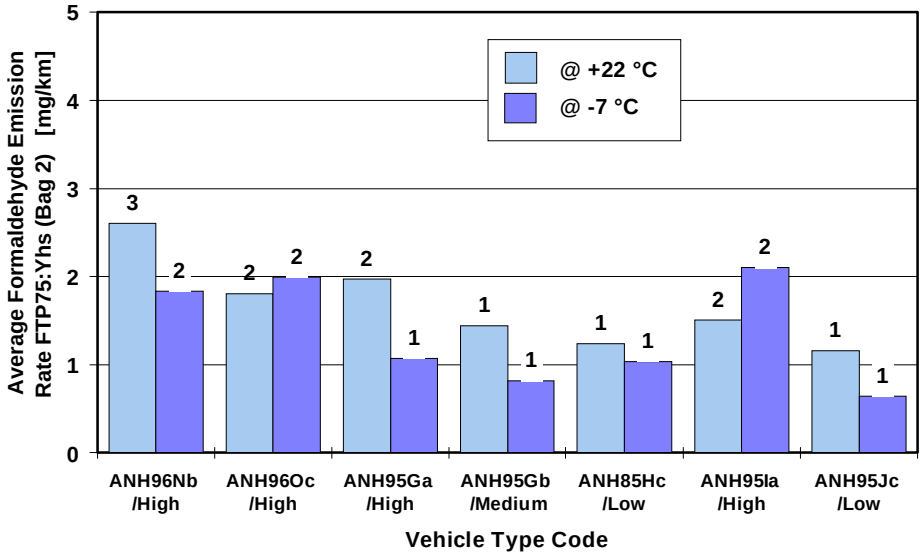

Figure 128 Specific emissions rate for formaldehyde as average values during Y_{hs} phase of FTP75 cycle for cars tested in the In-use study at normal and at low ambient temperature.

same level with the lowest detection limit (about 5 - 7 mg/km, according to [69]), they need not to be commented further.

8.4.5 Emissions over the hot restart phase of FTP75 (Bag 3)

Lastly, results derived from the third phase of the FTP75 procedure are commented. First, Figures 129 and 130 illustrate the accumulation at normal ambient and at low ambient. Then Figure 131 is presenting the comparison of the average specific emission rates at both of the tested temperatures.

As can be noted from these graphs, here the lowering of the ambient temperature did not affect the emission rates like it did in the very first phase, right after a cold start. Formaldehyde was produced at an almost constant rate over the sub-cycle in all cars, The rates, however, varied from car to car, but remained at all cases so low that the differences could only be taken as indicative, or totally inconclusive, as they were even lower than rates in Bag 2 and very close to the lowest detection limit.

8.4.6 Comparison of vehicles with different mileage

The final analysis for formaldehyde was made using results for those two parallel cars of the same type (ANH95G). Figure 132 denotes the accumulated emission as a function of distance travelled just for these two cars at both of the test temperatures during the first phase (Y_{ct}) of the FTP75 cycle, which

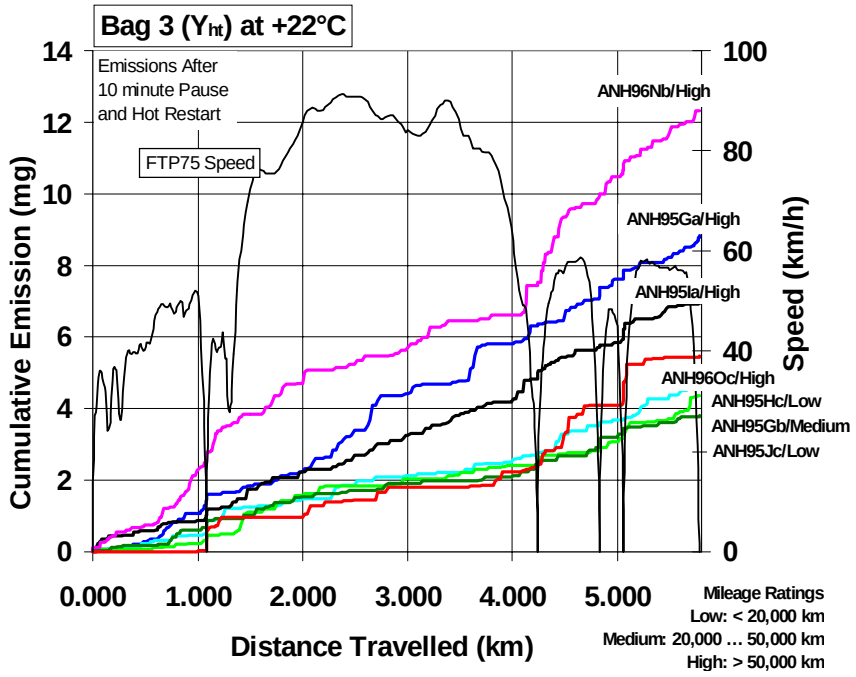

Figure 129 Accumulated emission of formaldehyde for phase Y_{ht} of FTP75 as a function of distance travelled during cycle for cars tested in the In-use study at normal ambient temperature.

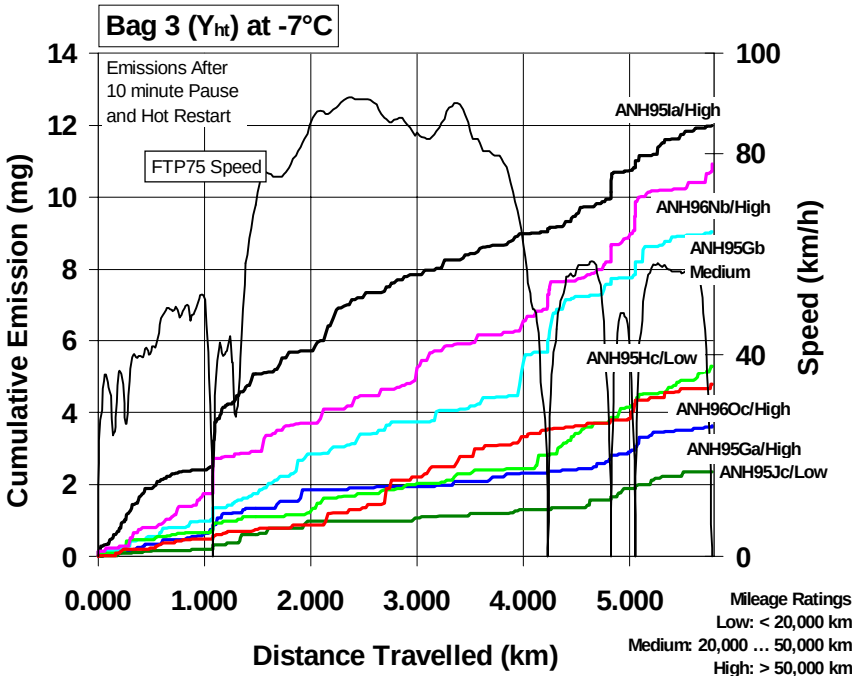

Figure 130 Accumulated emission of formaldehyde for phase Y_{ht} of FTP75 as a function of distance travelled during the cycle for cars tested in the In-use study at low ambient temperature.

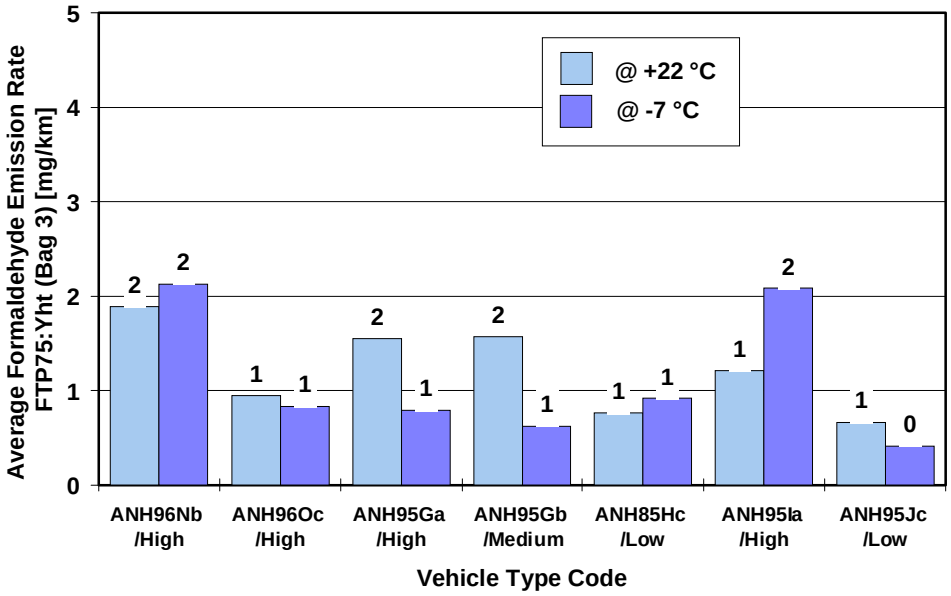

Figure 131 Specific emission rates of formaldehyde as average values during phase Y_{ht} of FTP75 cycle for cars tested in the In-use study at normal and at low ambient temperature.

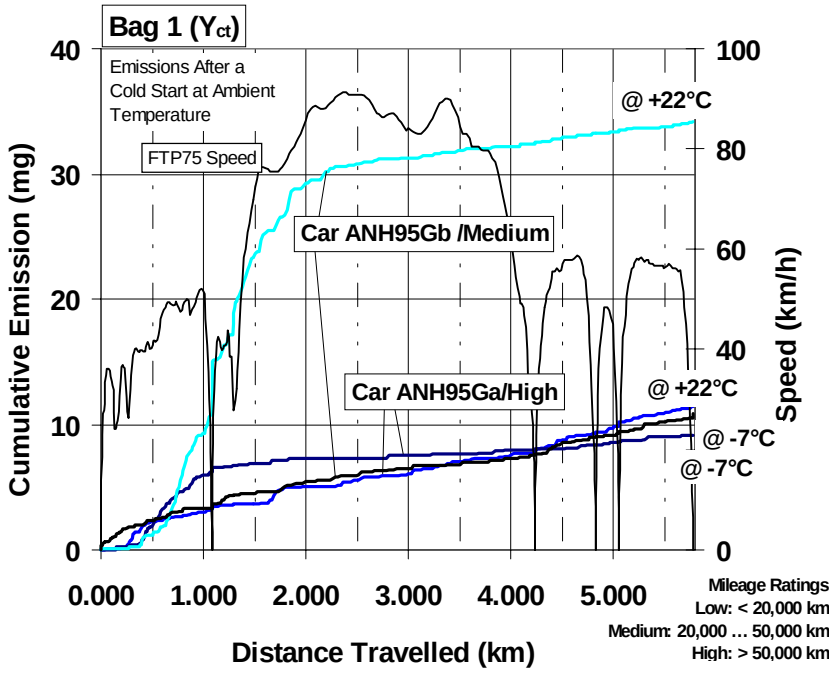

Figure 132 Accumulated emission of formaldehyde at normal and at low ambient temperature as a function of distance driven during phase Y_{ct} of FTP75 cycle for two individual cars of the same type from the tested sub-fleet in the In-use study.

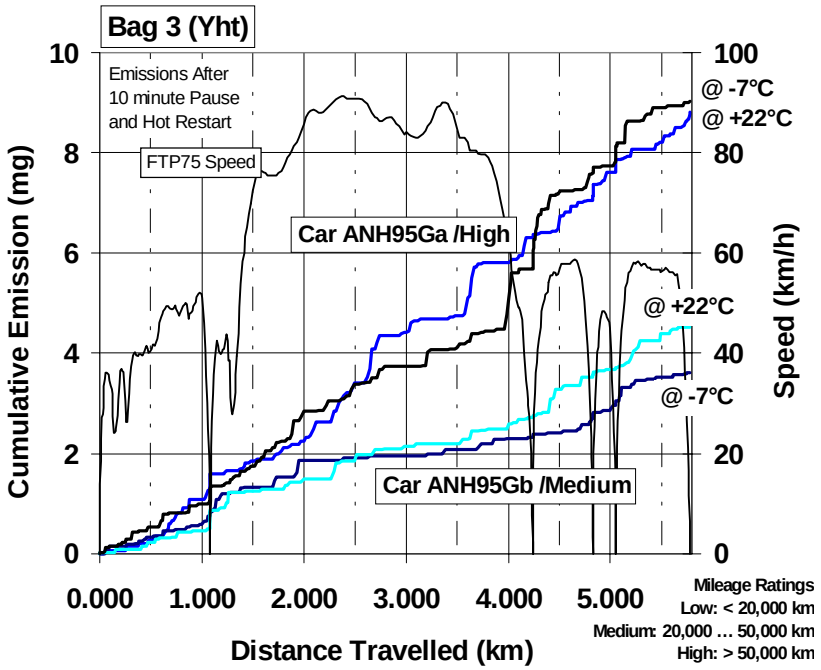

Figure 133 Accumulated emission of formaldehyde at normal and at low ambient temperature as a function of distance driven during phase Y_{ht} of FTP75 for two individual cars of the same type from the tested sub-fleet in the In-use study.

starts with a cold engine. The same kind of illustration is presented in Figure 133 for the individual results attained in the third phase (Y_{ht}), which replicates the same target speed over time as the first phase, but starts with a warm engine restart after the 10 min pause.

The strongest difference between these two cars was noted in Bag 1 results, where the medium-mileage car coded as ANH95Gb had at the baseline temperature substantially higher emissions than its high-mileage counterpart with the code ANH95Ga. There, about fourfold total accumulation of formaldehyde was recorded for the car (b) compared to the car (a). Incidently, this was in direct contrast with the case of ammonia, where the same kind of difference in magnitude was recorded, but the cars were in opposite positions with the car (a) being the high-emitting one.

In Bag 3 results the low ambient temperature hardly had any effect, but somewhat stronger difference was recorded between the two individual cars. Now the high-mileage one was exceeding the emissions of the medium-mileage one, but both were on a level very close to the detection limit.

8.4.7 Conclusions for formaldehyde

Because the levels of formaldehyde emissions were in most cases very low and sometimes even on par with the detection limit of the FTIR system for this

pollutant, it was almost inappropriate to try to make any conclusions. Aside, like in the cases of previous unregulated pollutants, averages were calculated for the sub-fleet per rates recorded in each of the phases in the FTP75 driving schedule, and also for the total, composite FTP results. These values are illustrated in Figure 134. The outcome of this perusal is that on average, only Bag 1 results show somewhat higher values, when the ambient temperature is lowered. However, this could be taken only as weakly indicative, as it remains so close to the limit of detection.

Because of the very low level of the results for formaldehyde in this rather limited sub-fleet, no conclusive dependence between emissions and total vehicle mileage could be corroborated.

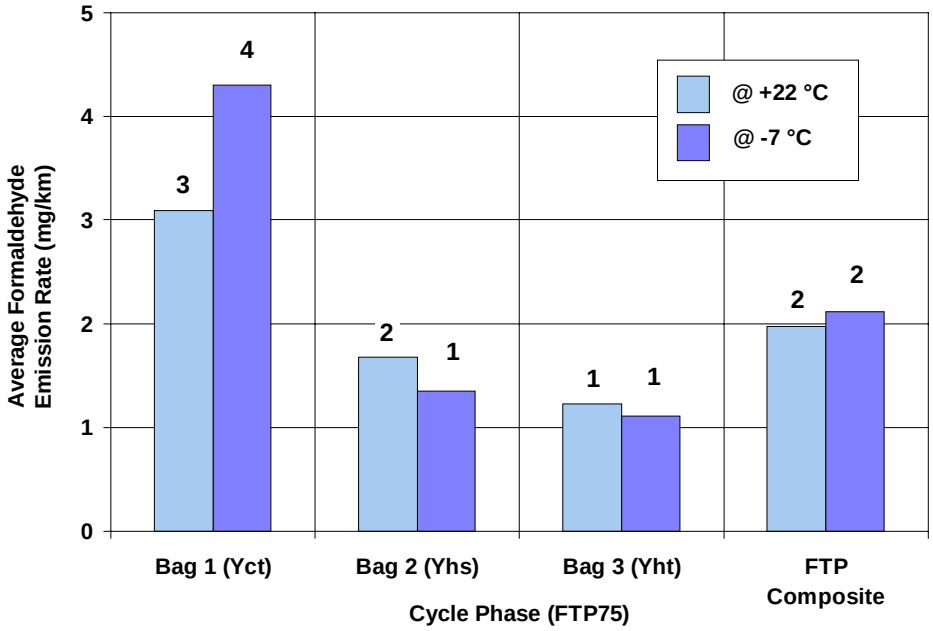

Figure 134 Emission rates for formaldehyde as averages for the tested sub-fleet in different phases of the FTP75 driving cycle at normal and at low ambient temperature; the seven car sub-fleet of the In-use study.

9 EMISSIONS OF SOME HYDROCARBONS AT LOW AMBIENT TEMPERATURES

9.1 GENERAL DESCRIPTION OF THE STUDY

A number of individual C_1-C_8 hydrocarbon species were determined in a study referred here as the Catalyst study, which was initiated in 1995 with KEMIRA Metalkat Oy, a manufacturer of automotive catalytic converters. The mission of this study was to investigate cold-start emissions performance of different new catalyst formulations. For this purpose, three different experimental converters were prepared by the manufacturer. The original, OEM converter of each of the three test vehicles was used as a primary reference. In addition, a similar OEM converter unit was acquired as a secondary, fresh reference, since the total vehicle mileages of the test cars were somewhat different, and the experimental converters were also unaged.

Because of the proprietary nature of the experimental catalysts, the results of this study have previously been reported only to the catalyst manufacturer as a confidential report, and no public report has been released. Therefore, the commenting of the results here is also restricted to the fresh OEM converters.

9.2 TEST PROCEDURES AND PROGRAM

9.2.1 Test vehicles and fuel

Three normal petrol cars were employed as test vehicles for this study. Table 19 gives some information of these cars that were normal, private in-service vehicles leased from their importing agents. Further details of the vehicles are given in Appendix 2.

Table 19 Test vehicles in the Catalyst study.

Vehicle Code	Displ. (dm^3)	Model Year	Test inertia (kg)	Odometer [1] (km)	Fuel delivery system; emission control devices
KK95A	1.59	1994	1010	44318	MPFI; TWC; CL
KK95B	1.29	1995	910	9473	MPFI; TWC; CL
KK95C	1.58	1995	1060	12028	MPFI; TWC; CL

[1] Note: the converter was fresh, aged only for 0.5 h
MPFI = multi-point fuel injection TWC = three-way catalyst
CL = closed-loop control of AFR (assuming stoichiometric operation)

Test fuel in compliance with standard reference petrol was used for fuel in all the tests. The fuel fulfilled the requirements determined in CEC RF-08-A-85 specification. A copy of the analysis report for the batch used is given in Appendix

3. Again, what was commented in Chapter 6.2.2. of the use of this fuel at low ambient temperatures, applies also here.

9.2.2 Converters and their preparation

All the fresh OEM converters acquired as standard replacement parts were used with just a minimal stabilizing use, which consisted of some 30 minutes of driving on the chassis dynamometer at about 80 km/h speed.

Because further details of the composition or precious metal loadings of these converters were not available, no attempt was made to characterize their design and formulation. Thus, it was not possible to match any attributes of their performance to a particular design or catalyst formulation. Therefore, the results should then be taken only as indicative values of which kind of levels of emissions for individual hydrocarbons could be expected of modern three-way catalyst-equipped cars at normal and especially at low ambient temperatures.

9.2.3 Test temperatures, driving cycles and exhaust sampling

The test program consisted of two ambient temperatures, +22 °C as the baseline, and -7 °C as the low ambient. Both US FTP75 and the new European test cycle, often referred as NEDC, consisting of ECE15 and EUDC cycles, were employed. Both of the cycles were initiated as prescribed in their current specifications, which for the FTP75 cycle meant a simultaneous start of the engine and sampling. However, with the NEDC procedure, the current specification (in directive 91/441/EEC) determines that the engine was started first and put on idle for 40 seconds before the exhaust sampling was engaged. Therefore, part of the emissions was escaping the sampling, and the results are not directly comparable with the results obtained using the US FTP75 procedure. As already described, the European procedure will most probably be revised in the near future to omit this idle period.

The exhaust sampling and determination of the different hydrocarbon species were carried out as described in Chapter 6.6.2.

9.2.4 Test program

Each of the three vehicles was tested with five different converters, namely with each of the prototype converters, with the original OEM converter and also with a fresh OEM converter. Using two different driving schedules and two ambient temperatures, as just described, brought the number of tests per vehicle up to 20. Normally, only one single test per case was performed, but a few additional

duplicate tests were done to obtain some information of the repeatability of the measurements.

9.3 MAIN RESULTS

9.3.1 General format of the presentation of the results

Overall, results for individual speciated hydrocarbons (or for a group species) are presented in figures, which give the values separately for each of the test vehicles and both test cycles. Separate graphs were drawn also for both of the ambient temperatures. Because screening of the results showed that in most of the cases meaningful levels of emission were detected only from the samples collected in Bag 1 (phase Y_{ct} in the US FTP and ECE 15:1-2 in the NEDC), the results for the other two bags are neither presented nor discussed in this context. Besides the individual compounds, a total HC sum (determined with a FID analyser) is presented as a reference.

Individual results were determined for 12 different C_1-C_8 species. Table 20 lists the names of all these compounds. Calculation of these results was carried out according to the procedures outlined in the standards for regulated components (*see Appendix 4*). Only the concentrations and the respective molar masses were adjusted to the species in question.

Table 20 Speciated hydrocarbons determined in the Catalyst study

Name of the compound	Chemical composition	Molec. weight	HC Group
methane	CH_4	16	parafines
ethane	C_2H_6	30	parafines
iso-butene	C_4H_8	56	parafines
iso-pentane	C_5H_{12}	72	parafines
ethene	C_2H_4	28	olefines
propene	C_3H_6	42	olefines
1,3 butadiene	C_4H_6	54	olefines
benzene	C_6H_6	78	aromatics
toluene	C_7H_8	92	aromatics
m- & p-xylene	C_8H_{10}	106	aromatics
o-xylene	C_8H_{10}	106	aromatics
ethyl benzene	C_8H_{10}	106	aromatics

The results are at first presented as specific emission rates (in mg/km) for each of the selected emissions and in each test case (i.e. driving cycle and ambient temperature). Both averages calculated from the results for these three individual

car as well as standard deviations are presented. Later on, a summary is made illustrating the selected emissions also as mg/test, which makes it is easier to compare driving cycles with different accumulated distance, such as ECE15:1-2 and FTP75:1.

9.3.2 Emissions of methane

Methane (CH_4) is the most simple of all the gaseous hydrocarbons. It is not regarded as particularly harmful, because it is not reactive in terms of atmospheric formation of ozone, for instance. Its maximum incremental reactivity (MIR) value is only 0.015 [69, Appendix 1]. Therefore, it is currently excluded from the sum of total hydrocarbons, as well as from the applicable standards in the US and Californian certification procedures, where the limit values are expressed as non-methane HC (NMHC) or non-methane organic gases (NMOG). However, it is a greenhouse gas with an equivalence factor of 35 to CO_2.

Figure 135 presents the emission rates of methane in each of the different test cases according to the general format described previously.

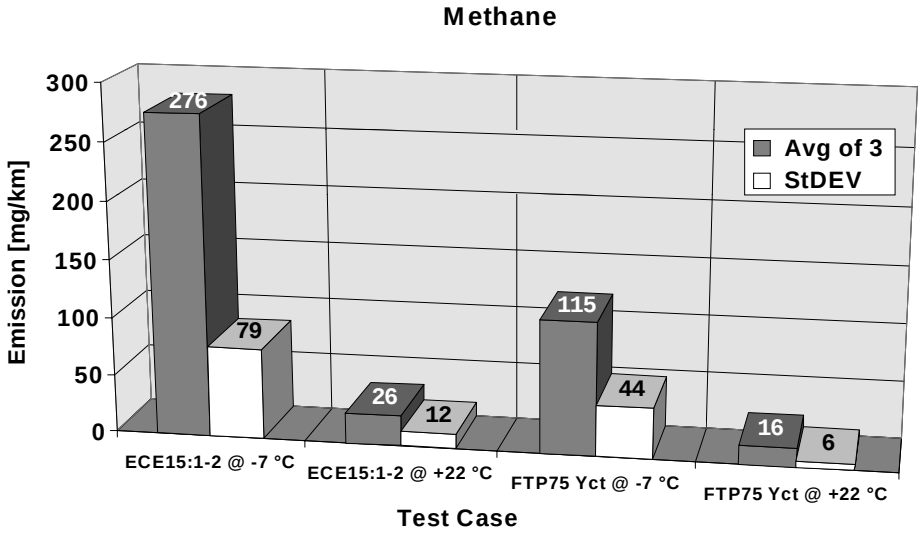

Figure 135 Emission rates of methane in Bag 1 at +22 and at -7 °C ambient temperature; average value and standard deviation for the three-car fleet in Catalyst study when using fresh OEM converters.

As the height of the bars in this figure suggest, the average rate of methane emission was some 7 times higher at low ambient temperatures than in baseline conditions, if the FTP75 test cycle was used to assess the performance. However, in the case of the ECE15 cycle, even stronger rise was recorded, as the emissions at -7 °C were more than 10 times higher than baseline figures.

Furthermore, the three tested cars seemed to perform rather differently in terms of methane emission, as standard deviations is each of the cases were between som 30 to almost 50 % of the nominal (average) value.

9.3.3 Emissions of iso-butene

Figure 136 displays average the results for iso-butene measurements. Iso-butene is, like methane, a simple hydrocarbon structure, but is much more reactive in atmospheric chemistry. Its relative reactivity index in the MIR scale is about 350, if the value of methane is adjusted to 1.0. Therefore, it is much more harmful than methane.

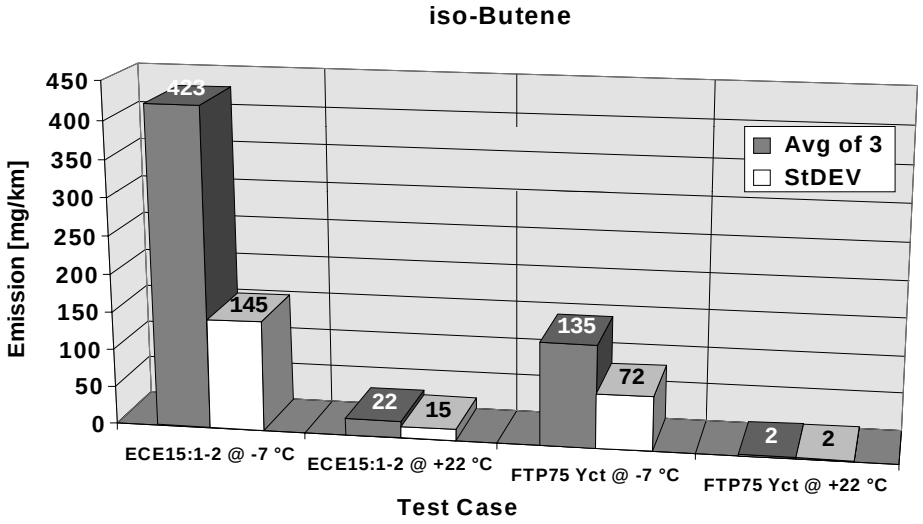

Figure 136 Emission rates of Iso-Butene in Bag 1 at +22 and at -7 °C ambient temperature; average value and standard deviation for the three-car fleet in Catalyst study when using fresh OEM converters.

As the figure shows, the lowering of the ambient temperature had a striking effect on the emission rates. The three-car average rate was in the case of the ECE15:1-2 results nearly 20 times above the level measured in normal ambient conditions. Again, differences among the three tested vehicles were striking, because the standard deviations ranged from some 30 to nearly 100 % of the nominal value.

9.3.4 Emissions of ethene

Ethene is already a hydrocarbon species with more complicated structure. It belongs to the group of olefines, together with such compounds like propene. Basically, olefines are rather aggressive in terms of acute toxicity. Furthermore,

they are reactive in atmospheric chemistry, and they are classified among the main contributors in ozone forming potential of automotive HC emissions. In a relative MIR scale, ethene has a value almost 500 times the value of methane.

Figure 137 graph the results for ethene according to the pattern used here for the presentation of these speciated hydrocarbon compounds. Again, very different emissions performances and sensitivities to low ambient temperature were encountered form car to car, as the values for standard deviations were ranging between 70 and 80 % of the average suggesting quite strong spread in the results. For the ECE15 test, almost six times higher emission rates were recorded, on average, at low ambient temperature compared to the baseline. In the case of the FTP75 dricving schedule, the rise was slighly less, because emission rates about fivefold to baseline were measured in low ambient temperature tests.

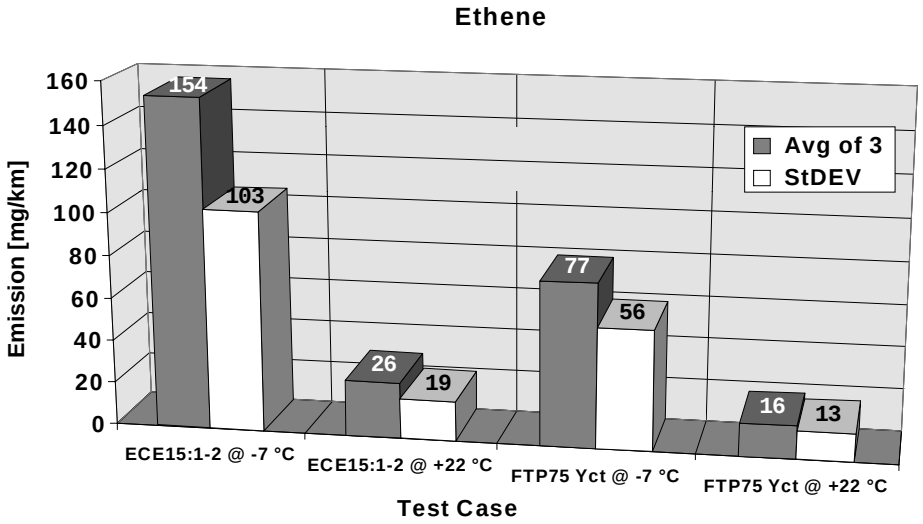

Figure 137 Emission rates of ethene in Bag 1 at +22 and at -7 °C ambient temperature; average value and standard deviation for the three-car fleet in Catalyst study when using fresh OEM converters.

9.3.5 Emissions of 1,3 butadiene

Figure 138 portrays the results for the measurements of 1,3 butadiene. It is also an olefine-type hydrocarbon species, and rated among the primary air toxics by the US EPA. It is also highly reactive, as its relative MIR-value is over 700. Therefore, the emissions should be kept to an absolute minimum.

When those fresh OEM-type three-way converters were used, average emission rates for Bag 1 at baseline temperature seemed to be about 11 mg/km, when the ECE cycle was used, but markedly less, only about 2 mg/km, if the US FTP75 driving schedule was employed. At low temperatures, however, these rates rose sharply. The overall average level recorded for Bag 1 in ECE15 tests was about 80 mg/km, but in those US FTP75 tests it was less, somewhat below 50 mg/km. However, the latter case presented much higher low-temperature sensitivity, as the ratio ranged between seven and over 20 times of the baseline value. Furthermore, the differences between the test vehicles seemed to be smaller when ECE15 test was used compared to what was registered for the FTP75 test results.

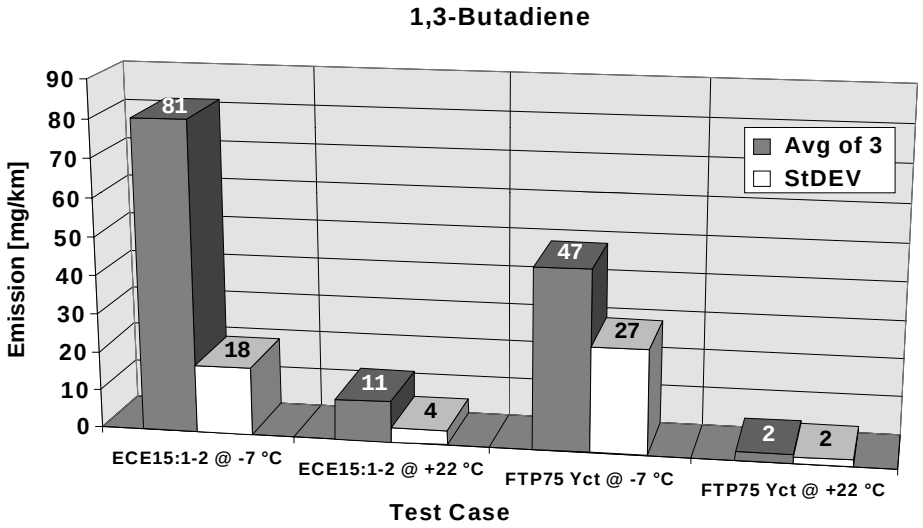

Figure 138 Emission rates of 1,3-butadiene in Bag 1 at +22 and at -7 °C ambient temperature; average value and standard deviation for the three-car fleet in Catalyst study when using fresh OEM converters.

9.3.6 Emissions of benzene, toluene and xylene (BTX)

Benzene, toluene and different xylenes (in this case m-, p-, and o- types) are all aromatic compounds. They are assessed as possible human carcinogens, especially benzene, and present toxicity upon long-term immission.

The general fashion of presenting the results is again followed in Figure 139, which introduces the sum of emissions of these aromatic compounds in all the different cases discussed here. The pattern, which this figure portray, copies quite well the pattern already recorded for the emissions of 1,3 butadiene. Slightly lower sensitivity, however, was noted, as the average overall emission level rose from the value of 60 mg/km (in an FTP75) to 120 mg/km (in ECE15:1-2) in

baseline conditions up to between some 300 mg/km (in an FTP75) to about 600 mg/km (in an ECE test) at the low ambient temperature, thus corresponding some five fold emissions at -7 °C over the baseline performance.

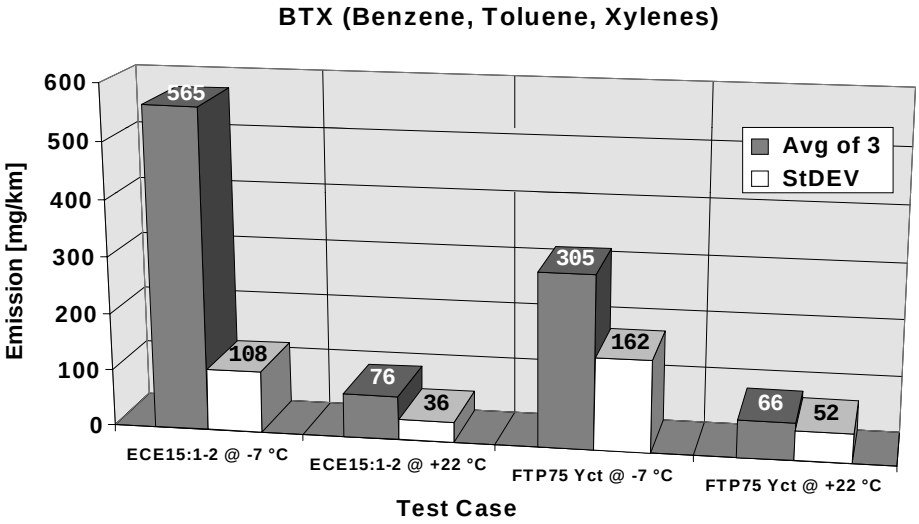

Figure 139 Emission rates of BTX (sum of benzene, toluene and xylenes) in Bag 1 at +22 and at -7 °C ambient temperature; average value and standard deviation for the three-car fleet in Catalyst study when using fresh OEM converters.

Furthermore, it is worth noting how vehicle KK95C seemed to be particularly insensitive to converter type at both temperatures, especially when the emissions were measured using the US FTP75 driving schedule. Overall, the differences between the various cases were smaller in US FTP75 tests than if the corresponding European cycle was employed.

9.3.7 Emissions of ethyl benzene

Another aromatic species rather abundant in exhausts from petrol-fuelled cars, even with a three-way catalyst, is ethyl benzene. Figure 140 displays the results for this compound in the same fashion as the other speciated hydrocarbons previously.

Comparing the results for ethyl benzene at baseline temperature with the BTX emissions at the same temperature (Figure 139), it can be seen, how closely they are matching each others as the pattern of BTX performance is almost replicated in the case of ethyl benzene. The only notable exception was that the fresh OEM converters used in these test cars seemed to be performing very efficiently in

terms of ethyl benzene in FTP75 tests at normal ambient temperature. However, since the relative pattern of emissions in other test cases was almost the same as for BTX emissions, the aforementioned outcome remains as a kind of anomaly.

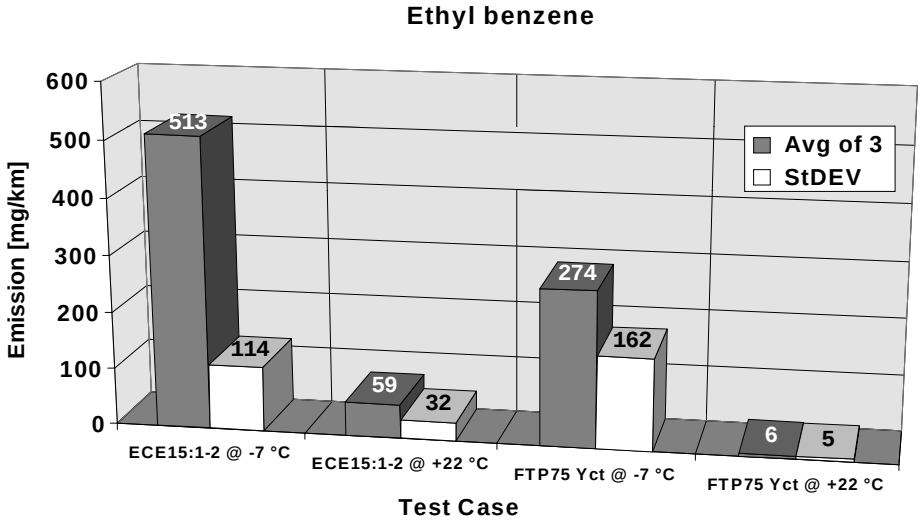

Figure 140 Emission rates of ethybenzene in Bag 1 at +22 and at -7 °C ambient temperature; average value and standard deviation for the three-car fleet in Catalyst study when using fresh OEM converters.

9.3.8 Share of GC sum of total hydrocarbon emissions

The share of the sum of these individual hydrocarbon species (determined with GC) of the total hydrocarbon value (determined with FID) is presented in Figure 141.

According to the figure, this share seemed to be somewhat higher in both of the cases using ECE15 driving cycle. The difference, however was only very small and must be regarded highly inconclusive, as the values for individual test cars varied some ± 10 % of the nominal, average value.

9.3.9 Emissions of selected hydrocarbons as [mg/test] values

Emissions of selected individual hydrocarbon species are presented in Figures 142 (ECE15:1-2 cycle) and 143 (FTP75 cycle).

The values portrayed in these two figures enable a valid comparison between the two cycles, as it is generally felt that the emissions over a total test cycle are

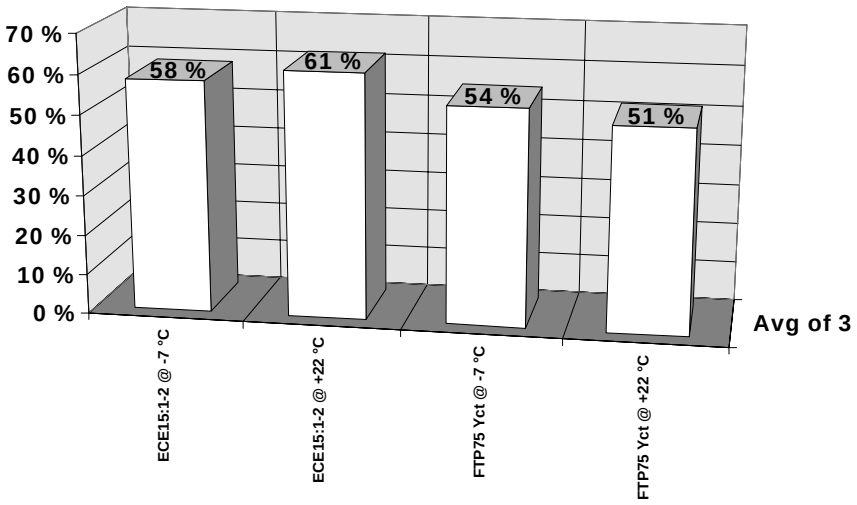

Figure 141 The relative share of the sum of all 12 individual hydrocarbon species determined with CG in this study of the respective total HC value determined with FID; average values for the three-car fleet in the Catalyst study in each of the tes cases.

generated strongly up front, and are more related to the cold start, even at this normal ambient temperature, than to the driving itself. Therefore, dividing the test total with the distance travelled over the whole test cycle gives undue bias to the

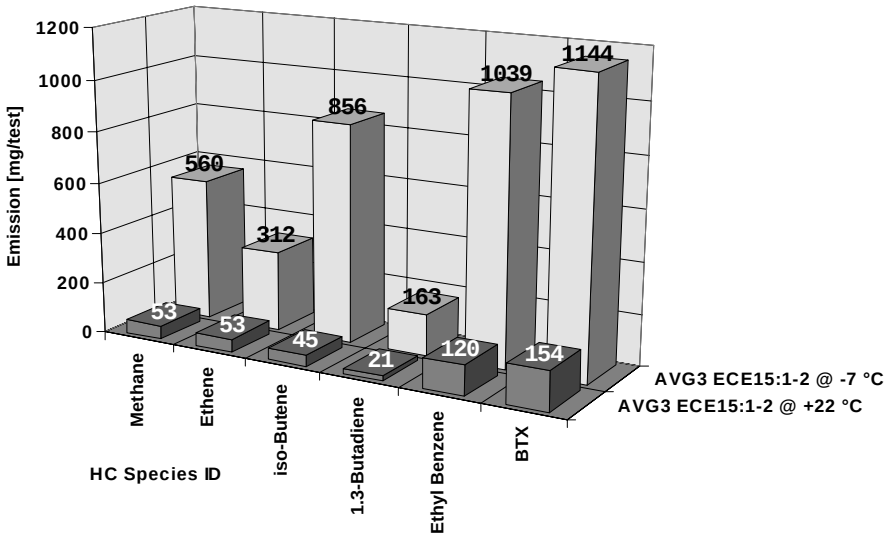

Figure 142 Average Bag 1 emission of selected hydrocarbon species for the three-car fleed in the Catalyst study at +22 and at -7 °C ambient temperature; fresh OEM converters and modified ECE15 driving cycle use.

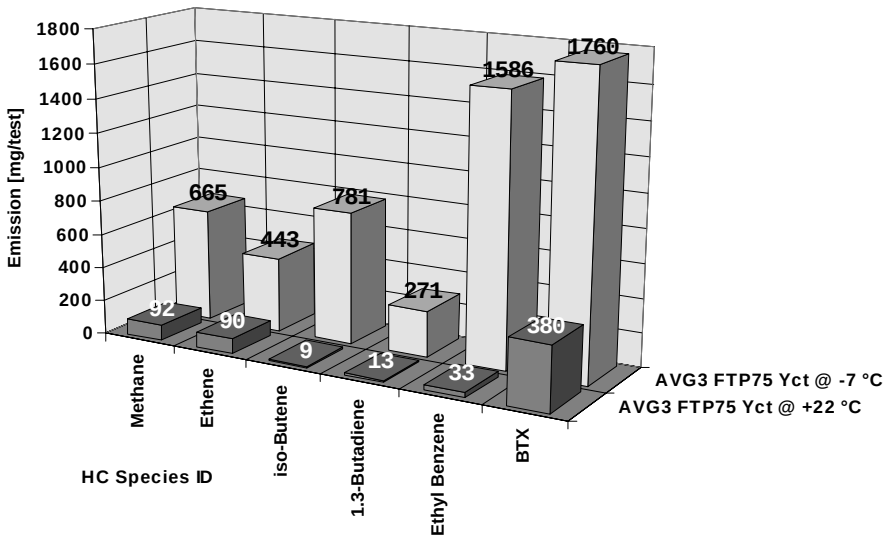

Figure 143 Average Bag 1 emissions of selected hydrocarbons for the three-car fleet in Catalyst study at +22 and at -7 °C ambient temperature; fresh OEM converters and FTP75 driving cycle used.

European test, as the ECE15:1-2 sub-cycle is only 2.01 km, and the corresponding distance is 5.765 km in FTP75 Y_{ct}. Therefore, the emission rates expressed as mg/km become higher in the European test, even if the absolute emission in mg would be about the same.

9.4 CONCLUSIONS FOR HYDROCARBONS

It has been quite difficult to draw any conclusions for the emissions of these speciated hydrocarbons as the test methods and conditions (driving cycle, ambient temperature) used to assess the performance seemed to place different cases into different order. Overall sensitivity to the lowering of the ambient temperature seemed in case of most of these compounds to follow, at least loosely, the sensitivity recorded for total HC, which was about seven. In some of the cases it was, however, much higher. This was true especially, if the FTP75 driving cycle was used. Furthermore, differences recorded in the performance of the test vehicles, expressed in the form of a standard deviation, were in most of the cases close to what was the average for this three-car test fleet. This suggests that strong conclusions should be avoided.

Lastly, Table 21 presenting some average levels of specific emission of different HC species is introduced. Taking into consideration the very small number of cars tested, the fresh (unaged) state of the catalytic converters involved and sometimes

rather different performance recorded for the two driving cycles used, these values must, however, be regarded only as indicative. Furthermore, subsequent testing to support the outcome of this study is highly recommended.

Table 21 Typical emission rates of some selected hydrocarbon species dtermined in the Catalyst study using fresh OEM converters.

test case species	average emission rate ECE15:1-2 [mg/km]		average emission rate FTP75:1 [mg/km]	
	+22 °C	-7 °C	+22 °C	-7 °C
methane	25 ± 10	270 ± 80	16 ± 5	115 ± 40
iso-butene	20 ± 15	400 ± 150	2 ± 2	135 ± 70
ethene	25 ± 20	150 ± 100	15 ± 10	75 ± 50
1,3 butadiene	10 ± 5	80 ± 20	2 ± 2	45 ± 25
BTX	75 ± 35	560 ± 100	70 ± 50	300 ± 160
ethyl benzene	60 ± 30	500 ± 110	6 ± 5	275 ± 160

10 AVERAGE LEVELS OF EMISSIONS AS A FUNCTION OF AMBIENT TEMPERATURE

10.1 GENERAL OVERVIEW

It was felt that the studies discussed in this report gave a reasonable foundation to assess the average emissions levels attained at various levels of ambient temperature. Producing such estimates would give a first-hand, practical outcome for this study, and they could prove to be invaluable tools, when assessing the contribution of the motor vehicle emissions to the air pollution, especially in an urban environment and in low ambient temperature conditions.

By far the greatest number of results were available for the main, regulated pollutants (CO, total HC and NO_X), because all tests have encompassed such determinations. Therefore, the averages produced for these three substances should give a sound estimate of their occurrence.

In addition, a number of unregulated constituents have been measured. However, the supportive basis of this part of the work was far more narrow than what was available for the regulated pollutant, mainly because of the limited number of vehicles involved. In spite of this fact, the results should be used to give only a first appraisal of the level of the occurrence of these compounds at low ambient temperatures in the exhaust gases from petrol-fuelled passenger cars with three-way catalytic emission control. More work in this area is certainly called for to corroborate these early findings.

10.2 REGULATED EMISSIONS (CO, HC, NO_X)

Table 22 combines the average values attained at various ambient temperatures for the three regulated pollutants. Apart from the averages, range from the lowest to the highest occurrence in each case has been recorded. The values are expressed as emission in [g/trip], because the specific emissions levels, expressed in g/km, that were used throughout this report to scale the emissions, were to an extent somewhat misleading, because the driving cycle used to assess the emissions performance affected the results. However, it was felt that the influence was not much related to the different speed vs. time profile of the cycles. Rather, it was mainly because the cycles cover different theoretical distances. Therefore, even if the actual amounts of emissions in [g/test] were equal, the specific emissions in [g/km] were different, simply because the distances driven per test were different. For this reason, it would be advisable to relate emissions generated at low ambient temperatures more to the cold-start event itself rather than to the driving in general.

Table 22 Average values for the emission of carbon monoxide (CO), total hydrocarbons (HC) and oxides of nitrogen (NO_x) at different ambient temperatures during a trip consisting of a cold-start and subsequent driving depending on the cycle; ECE15:1-2 ~ 2 km, FTP 75:1 ~ 6 km.

Ambient temperature	+22 °C [g/trip]		± 0 °C [g/trip]		-7 °C [g/trip]		-20 °C [g/trip]	
Source study (no of cars)	Co-Nordic (10)		n/a		Co-Nordic (10)		Co-Nordic (10)	
ECE15:1-2	avg	range			avg	range	avg	range
CO	**19**	3-31			**116**	18-166	**168**	122-202
total HC	**2.3**	1-5			**13**	4-26	**32**	12-59
NO_X	**1.3**	0.8-1.5			**1.4**	0.6-2.2	**1.2**	0.4-1.5
Source Study (no of cars)	In-Use study (44)		TM study (55)		In-Use study (44)		n/a	
FTP75:1	avg	range	avg	range	avg	range		
CO	**19**	3-44	**98**	30-280	**135**	27-430		
total HC	**2.2**	1-6	**7.5**	2-17	**14**	5-29		
NO_X	**1.4**	0.5-7	**0.9**	0.3-9	**1.8**	0.3-10		

avg = average for the whole fleet
range = lowest - highest within the whole fleet n/a = data not available

This approach was also strongly supported by the findings of the sub-study on the allocation of the emissions along the distance travelled. It showed that especially for CO and HC, more than 90 % of the excess emissions generated over a given cycle were released already during the first 1 km of driving. After that, the emission control devices seemed to work quite well even at low ambient temperatures, as soon as the engine had reached its normal operating temperatures and the mixture enrichment has been phased out.

Notwhitstanding, the values are presented in the table separately for both of the driving cycles used. Such way they represent a short, about 2 km long, and a medium, about 6 km long, urban trips. Such cases cover a great majority of the urban driving, because the average trip length in the urban environments of most the European countries tends to be quite short, in the range of four to five kilometres.

The average values contained in Table 23 has been used to produce a series of graphs that illustrate the dependence of each of the three pollutants from the ambient temperature level. Figure 144 is for CO, Figure 145 for HC and Figure 146 for NO_X, respectively. Apart from the individual averages for each of the cases, i.e. a temperature and driving cycle, a trend line is fitted to the data as a

whole, to produce a mathematical expression of the dependencies in general. Like before, this procedure was done on a personal computer, and from the options provided by the computer software (Microsoft® Excel® 7), the one giving the highest R^2 value was chosen. For CO, the best fit was linear, but for HC and NO_X exponential type of function gave better results. The latter, however, being a quite poor representation, because even for this best case, the R^2 value attained was below 0.03.

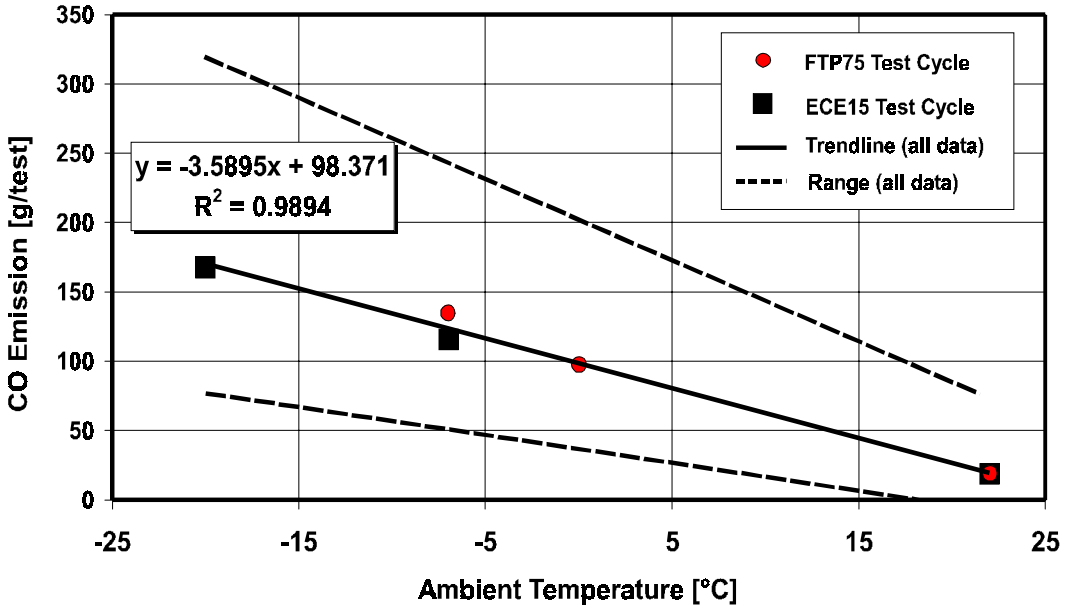

Figure 144 The emission of carbon monoxide (CO) as a function of ambient temperature. Tests initiated with cold start and using either ECE 15:1-2 (modified, no 40 s idle) or US FTP75:1 (Y_{ct}) driving cycles.

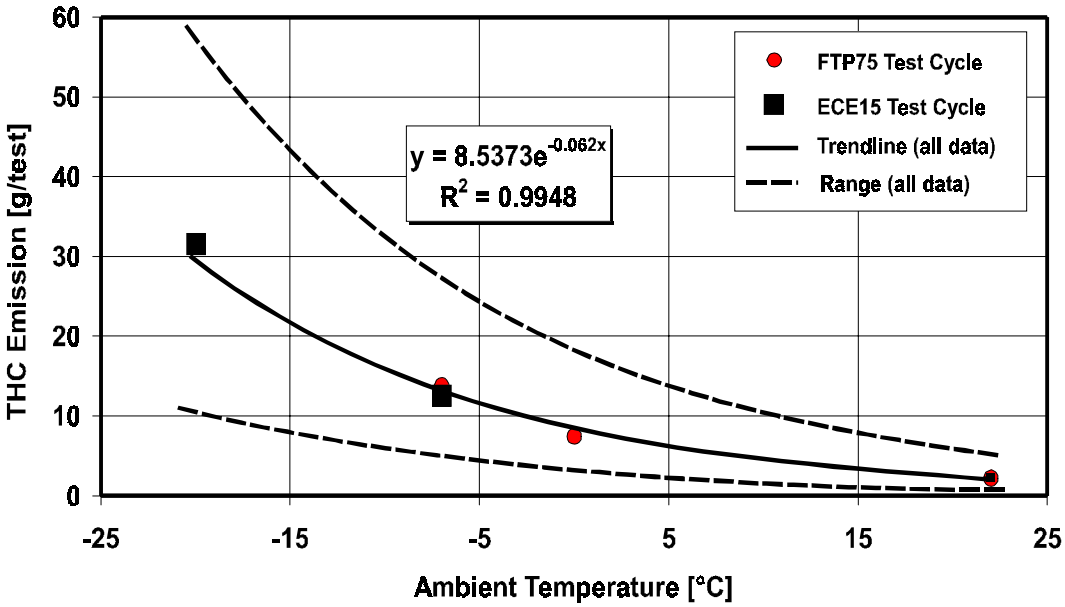

Figure 145 The emission of unburned hydrocarbons (HC) as a function of ambient temperature. Tests initiated with cold start and using either ECE 15:1-2 (modified, no 40 s idle) or US FTP75:1 (Y_{ct}) driving cycles.

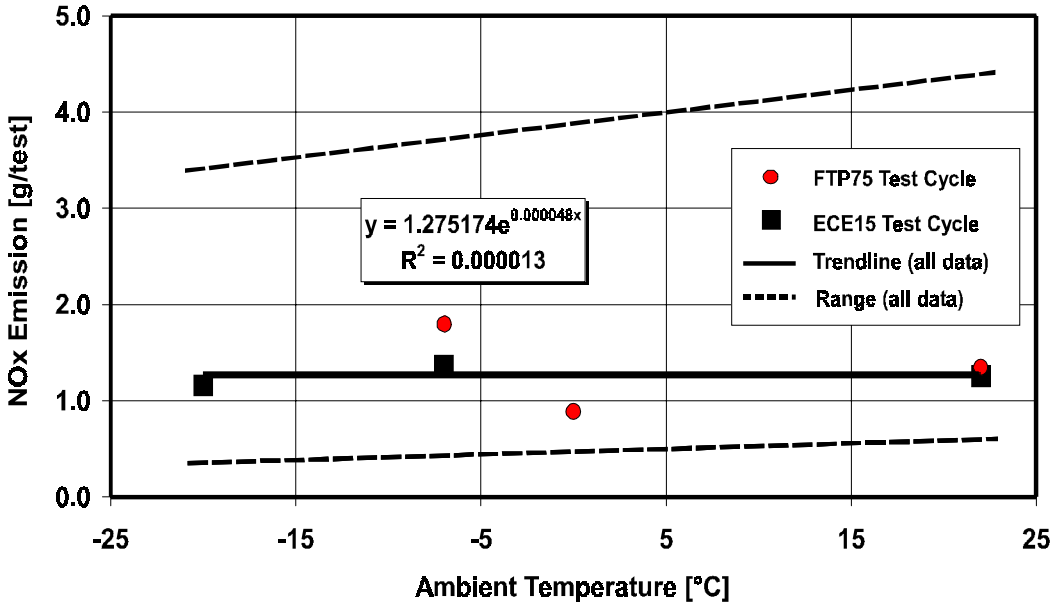

Figure 146 Emissions of nitrogen oxides (NO_x) as a function of ambient temperature. Tests initiated with cold start and using either ECE 15:1-2 (modified, no 40 s idle) or US FTP75:1 (Y_{ct}) driving cycles.

As Figure 144 shows, a fairly good linear dependence of the ambient temperature was achieved for the CO emissions within the tested temperature range (from +22 down to -20 °C). Furthermore, judging from the positions of the individual case values plotted in this figure, a reasonably good agreement was found between the two driving cycles, as the points sharing the same test temperature were falling quite close to one another. This was true not just for CO, but for HC emissions, as well, which can be seen in Figure 145. However, here more of an exponential dependence of the average emissions from the ambient temperature was attained. The function produced by the computer software was even quite well fitted, as the R^2 value was as high as 0.995, whereas for CO, it was slightly lower (0.985).

Notwhitstanding, as already mentioned, rather poor concordance was recorded for the emissions of NO_X. As Figure 146 clearly shows, the emissions seemed to be quite nondependant of the ambient temperature, but more dependant on the driving cycle used to assess the emissions. Higher amounts of emissions seemed to be produced in the US FTP75 cycle at each of the tested ambient temperatures. There is, however, a certain logic in this phenomenon. The fact is that the CO and HC emissions are by a large extent produced up front in the cycle, during the first 1 km of the trip, whereas NO_X is derived more evenly from the whole distance. Hence, it is more dependant on trip length that those two other pollutants, and not just cold-start related emissions, like in the cases of CO and HC.

10.3 UNREGULATED EMISSIONS WITH FTIR

The unregulated compounds measured with FTIR and discussed in this report were nitrous oxide (N_2O), a strong greenhouse gas, ammonia (NH_3), a major component in the acidifying and irritating effect of air pollution, and formaldehyde, an extremely reactive species in terms of atmospheric chemistry and ozone formation and even a toxic compound. Table 23 comprises the results averaged for the seven cars sub-fleet of the In-use study. As before, even a range from the lowest to the highest occurrence has been included.

Graphs have also been produced individually for each compound. Figure 147 shows the averages for nitrous oxide (N_2O) emissions with the lowest and highest values recorded. Figure 148 comprises the same representation for ammonia (NH_3) and finally, Figure 149 portrays the results for formaldehyde.

The average emissions of nitrous oxide seemed not to be dependant on ambient temperature. Not even the range of emissions was sensitive to temperature. The reason was, what was already said in Chapter 8.2.1, when this emission was first discussed. The emission level seemed to be largely nondependant on the ambient temperature and the variations resulting from the lowering of the temperature seemed occur into both directions, depending on the vehicle, seemingly compensating each other rather efficiently.

Table 23 Average values for the emissions of various unregulated exhaust consistens at different ambient temperatures during a trip consisting of a cold-start and subsequent driving FTP75:1 ~ 6 km.

Ambient temperature	+22 °C	[mg/trip]	-7 °C	[mg/trip]
	average	range	**average**	range
Source study: In-Use No of Cars: 7 Analysis from Raw Exhaust with FTIR				
N_2O	**185**	50-600	**185**	50-630
NH_3	**145**	12-317	**435**	23-1100
formaldehyde	**18**	6-35	**25**	12-52

average = average for the whole fleet
range = lowest - highest within the whole fleet

All this, however, was not true for ammonia, as by far the strongest elevation in average emissions level within this group of compounds was recorded for this pollutant as a result for the drop in the ambient temperature. Even the range from the lowest to the highest value was much wider at low ambient, when compared with the one recorded for the cases measured at normal ambient temperature.

The levels of emission for formaldehyde were at both tested temperatures substantially lower compared with those nitrous compounds just discussed.

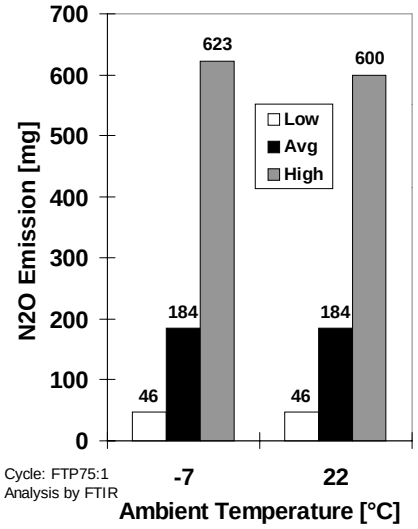

Figure 147 Average emissions of nitrous oxides (N_2O); 7 cars in the In-use study.

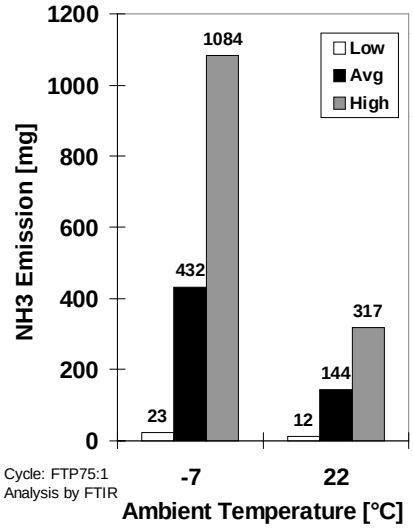

Figure 148 Average emissions of ammonia (NH_3); 7 cars in the In-use study.

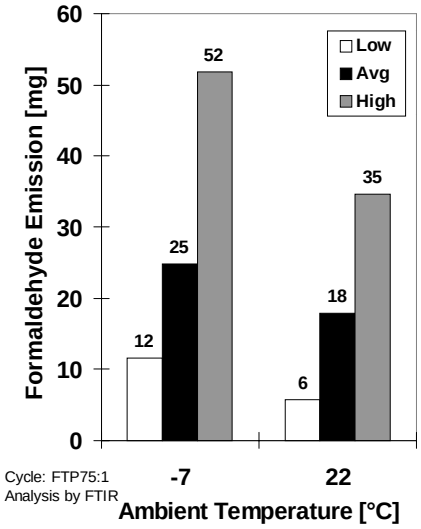

Figure 149 Average emissions of formaldehyde; 7 cars in the In-use study.

Aside, a slight increase in average emission level was recorded as a consequence of the lowering of the ambient temperature. The range from low to high, however, was in relative terms about the same at both temperatures.

Although some kinds of average values were presented here for these unregulated emissions, one must strongly bear in mind when using these estimates in some calculations, e.g. for emission inventories, the rather limited vehicle base used in this sub-study. Because of quite strong variations observed in the emissions performance from vehicle to vehicle, another kind of choice for the test fleet or even weighting of these results to reflect the average composition of the current total vehicle park better, would probably have rendered totally different results.

10.4 SPECIATED HYDROCARBONS

The last group of emissions determined in this work was speciated hydrocarbons. Of those 13 C_1-C_8 compounds available, those with either high emission levels or with known strong adverse effects were discussed. Table 24 comprises average values for these six species. Because the level of total hydrocarbon emission is very relevant in this context, it is also included as a value determined by the FID type of analyser. In addition, the relative share of the sum of all these 13 C_1-C_8 compounds analysed of this total HC value is presented. It indicates, what sort of share this group represents of all the exhaust hydrocarbons detectable with a FID type of analyser.

Overall the relative changes resulting from the lowering of the ambient temperature followed the trend set by total HC emissions, which rose by a factor of seven to eight, when the temperature fell from normal ambient to the low of -7 °C. However, as Figures 150 to 152 show, slight variations from compound to compound was detected. The most simple kind of structures, methane and iso-butene, were somewhat more sensitive to the temperature than hydrocarbons on overall, as the emission level of these two rose by a factor of about 10 to 11, when the temperature was lowered. The emissions of the two types of olefine compounds discussed here (ethene and 1,3 butadiene) were closely following the rate of increase for total the HC sum, whereas the emissions of aromatic compounds (BTX sum and ethyl benzene), were slightly underrating the change, as their average was only five to six times higher at low temperature to what was recorded at the baseline.

Table 24 Average values for the emission of various hydrocarbon species at different ambient temperatures in a trip consisting of a cold-start and subsequent driving either with ECE15:1-2 (~2 km), or FTP75:1 (~6 km) cycle.

Ambient temperature	+22 °C [mg/trip]				-7 °C [mg/trip]			
Source: Catalyst study No of Cars: 3 Analysis from Bag Sampling with Gas Chromatography								
Cycle	ECE15:1-2		FTP75:1		ECE15:1-2		FTP75:1	
Species	avg	range	avg	range	avg	range	avg	range
total HC (FID)	**815**	± 440	**1600**	± 1300	**7500**	± 2100	**11000**	± 6300
methane	**55**	±25	**90**	± 30	**560**	± 160	**670**	± 250
iso-butene	**45**	±30	**9**	± 9	**860**	± 300	**780**	± 420
ethene	**55**	± 40	**90**	± 80	**310**	± 210	**440**	± 330
1,3 butadiene	**21**	± 7	**13**	± 10	**160**	± 40	**270**	± 160
BTX	**150**	± 70	**380**	± 300	**1140**	± 220	**1760**	± 930
ethylbenzene	**120**	± 65	**33**	± 30	**1040**	± 230	**1590**	± 940
Sum of all 13 C1-C8 of total HC	**61 %**	± 6 %	**51%**	± 6	**58 %**	± 5	**54 %**	± 5%

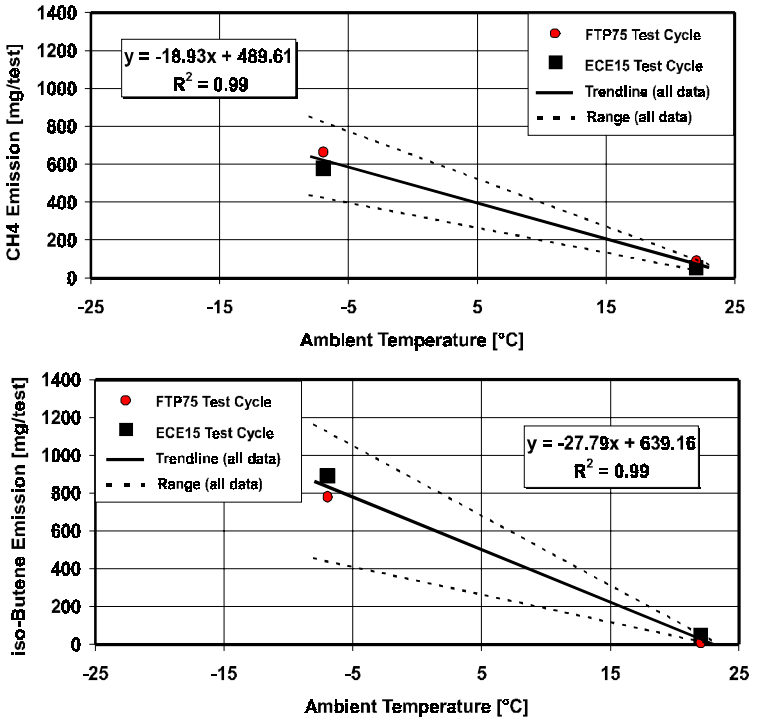

Figure 150 Average emissions of methane (CH_4) and iso-butene as a function of ambient temperature; the three-car fleet of the Catalyst study.

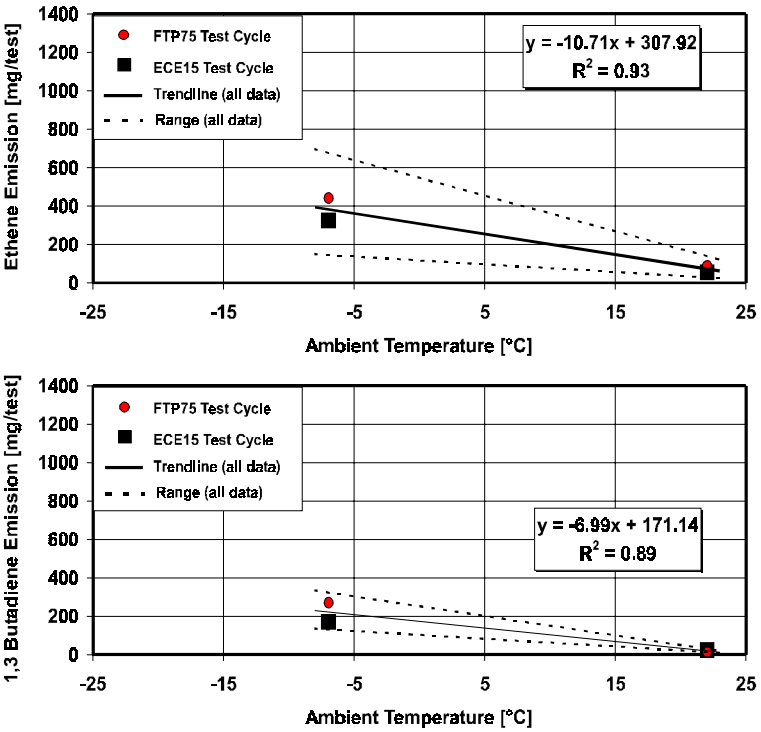

Figure 151 Average emissions of ethene and 1,3 butadiene as a function of ambient temperature; the three-car fleet of the Catlalyst study.

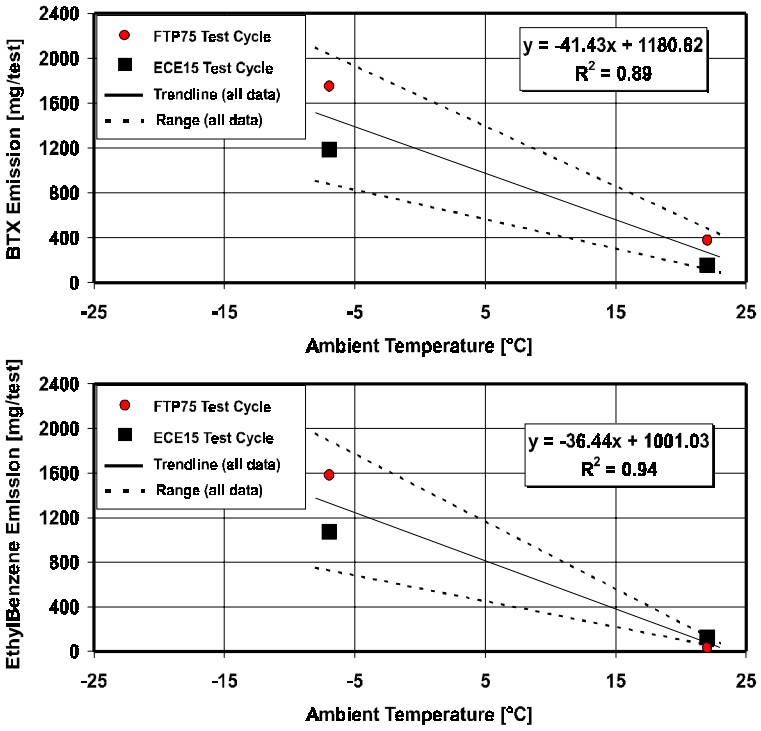

Figure 152 Average emissions of methane BXT (bentzene toluene and xylenes) and ethyl benzene as a function of ambient temperature; the three-car fleet of the Catlalyst study.

Furthermore, a relatively good agreement was existing between the values derived from the ECE15:1-2 cycle and those obtained using the US FTP75 cycle. Overall, the relative share of sum of these 13 C_1-C_8 compounds analysed of the total HC (FID) value was slightly smaller, about 55 %, at low ambient temperature than what was computed for the baseline case, about 70%. This suggested that the amount of the species heavier than C_8 was increasing in the HC emission rather strongly, more than those C_1-C_8 compounds.

One must not, however, neglect the fact that these findings were all based on a very narrow vehicle base, as they were results from tests involving only three cars and even some experimental types of catalytic converters. Therefore, their value as a typical representation of the emissions levels attained at low ambient temperatures remains quite low, and the rates of changes must be taken only as indicative. Much broader base of vehicles should to be tested, before making any firm conclusions.

11 DISCUSSION

11.1 PERFORMANCE EVALUATION OF THE CURRENT-LEVEL TECHNOLOGY

The experimental results presented in this report gave firm ground for a discussion and a number of final conclusions could be made. First, the basic studies showed that elevated levels for the emissions of carbon monoxide (CO) and unburned hydrocarbons (HC) were measured at low ambient temperatures. The emissions of nitrogen oxides (NO_X), however, were on average unaffected, but fairly large variations from one car type to another were registered.

Furthermore, it became quite evident that cars having a three-way catalytic exhaust emission control system were more susceptible to the influence of low ambient temperature at cold-start than regular cars without any external exhaust treatment. In this respect the findings corroborated well the outcome of the earlier studies. Notwhitstanding, the fact that the sensitivity of cars with a TWC system to the adverse effects of low temperatures was on average much greater than with a conventional car, their actual emission levels attained at low temperatures did not, however, exceed those measured for their non-TWC counterpart, but were about 50 to 75 % lower even at the most extreme low ambient (-20 °C) temperature used in this study.

Although only a few cars having more advanced emissions control than the present-day average, a simple TWC system, were involved in this study, it could be seen that their sensitivity to show high emissions at low ambient temperatures was equal or even greater than what was recorded to the average vehicle. This clearly suggests that good performance and low emissions in normal ambient conditions are not necessarily reflected in low emissions at low temperatures, as well. This finding gives a further emphasis to the necessity of a separate low-temperature test in order to curb real-world emissions really effectively. Setting strict standards at normal temperature is no more effective alone, but needs to be accompanied with additional requirements for good performance in conditions closer to the everyday use of cars.

Furthermore, the results proved that emissions of carbon monoxide (CO) and unburned hydrocarbons (HC) were not necessarily strongly interlinked every time, although both were measured at elevated rates at low ambient temperatures. Sometimes, when low or moderate CO values were measured, HC emissions remained still rather high. However, quite the opposite performance was also encountered. Therefore, separate standards should be set for both of these compounds, if really effective control of these emissions is sought after.

The results presented here, as well as most of the conclusions and recommendations, have already been weighed and employed in a practical application, as most of these findings have been reported and presented to the expert working groups, GRPE of UNECE and MVEG of EC, in charge of preparing the future European emission regulations. They were used to support the inclusion of an additional low-temperature test with separate limit values for CO and HC as part of future amendments for the directive of the European Union covering exhaust emissions from motor cars (70/220/EEC). This kind of initiative was made by some of the member states (Sweden, Finland, Austria, Germany and the Netherlands), and a joint research effort combining expert resource from Sweden, Finland and the Netherlands was undertaken to provide necessary information promoting the initiative. The work discussed here was a part of that venture. As a successful result for all these deliberations, the Environment Council of the European Union has in June 1997, found a common position with the Commission, and preliminarily agreement was reached upon the introduction of a low-temperature test with applicable limit values.

11.2 THE EFFECT OF VEHICLE MILEAGE

The results and findings of the studies involving new or low-mileage cars have in many cases provided first-hand information of the performance of current or near-future technology in low-temperature conditions, which had not been available before. Perhaps the greatest novelty, however, was contained in the outcome of the In-use study, because such an approach has never been taken before with equally broad-based test fleet including parallel test vehicles with identical or almost-identical specifications.

Based on previous research and practical experience, total vehicle mileage was expected to affect cold-start emissions, mainly because it is known that the light-off temperature in a catalytic converter tends to elevate due to chemical poisoning and thermal deactivation of the catalyst. To prove this presumption and to show its magnitude was among the main aims for this sub-study on in-use vehicles. However, the outcome of the investigation was more or less in direct contrast to these anticipations.

Two main conclusions were reached in this sub-study. The first of them suggested that the overall emissions performance was not unduly affected by the Finnish driving conditions. This assumption was based on the finding that in spite of the cold climate, the deterioration of the emissions performance in the tested cars, which had all been in normal private ownership service, followed quite closely to the deterioration prescribed in the emissions regulations as the assigned deterioration factors (DF).

The other conclusion was that the emissions of CO and hydrocarbons in cold-start, low ambient temperature conditions did not depend on catalyst performance. Moreover, they were resulting from the functioning of the engine itself and, therefore, were more a measure of direct engine-out emissions.

This latter conclusion was an outcome of the overall analysis of the cold-start emissions measured at low ambient temperature, which suggested that the emissions of CO and HC were not dependent on total vehicle mileage, but rather dependant on vehicle type. It was found that vehicles of identical make and model, differing from each other only in terms of total distance driven, had in most of the cases similar emissions output, when measured at a low ambient temperature. If measured at normal temperatures, however, emissions performance was much more dependant on vehicle mileage.

Furthermore, this non-dependence was taken also as an evidence that in low temperature conditions engine performance and direct, engine-out emissions were an overruling factor and the catalyst performance was only a minor element. Subsequently, this assumption was supported by the fact that the deactivation of the catalyst, which was clearly registered in tests at normal ambient temperature, did not markedly affect the result of cold-start tests at low ambient temperature.

However, this was not true for the emissions of nitrogen oxides, as those were, even in low ambient temperature conditions, largely dependent on total vehicle mileage, quite closely following the deterioration trend set by the performance assessed in normal, baseline temperature.

11.3 AVERAGE LEVELS OF SPECIFIC EMISSIONS

Based on the results from a number of sub-studies, the average levels of regulated and some unregulated emissions attained at low ambient temperatures could be established. Table 25 combines all these values.

The values in this combined table are all expressed as emission in [g/trip], because it was found more advisable to relate emissions generated at low ambient temperatures to the cold-start event or to a complete trip, rather than to the driving itself, which is the more common way of expressing the emission output (in [g/km]).

It is important to note that the level of certainty varies here form one group of emissions to another quite substantially. For the emissions of regulated components (CO, HC and NO_X), the greatest number of results was available, because all tests have encompassed such determinations. Therefore, the averages calculated for these three substances should give rather sound estimate of their occurrence.

Furthermore, it was noted that the dependence of the emissions of CO on ambient temperature was best described with a linear function, whereas the output of unburned hydrocarbons (HC) more closely followed an exponential curve, when

Table 25 Average values for the emission of various exhaust constituents at different ambient temperatures during a trip consisting of a cold-start and subsequent driving edpending on the cycle; ECE15:1-2 ~ 2 km, FTP75:1 ~ 6 km.

Ambient temperature / Species	+22 °C [g/trip]		± 0 °C [g/trip]		-7 °C [g/trip]		-20 °C [g/trip]	
Source study (No of cars)	Co-Nordic (10)		n/a		Co-Nordic (10)		Co-Nordic (10)	
ECE15:1-2	avg	range			avg	range	avg	range
CO	**19**	3-31			**116**	18-166	**168**	122-202
total HC	**2.3**	1-5			**13**	4-26	**32**	12-59
NO_X	**1.3**	0.8-1.5			**1.4**	0.6-2.2	**1.2**	0.4-1.5
Source study (No of cars)	In-Use Study (44)		TM-study (55)		In-Use study (44)		n/a	
FTP75:1	avg	range	avg	range	avg	range		
CO	**19**	3-44	**98**	30-280	**135**	27-430		
total HC	**2.2**	1-6	**7.5**	2-17	**14**	5-29		
NO_X	**1.4**	0.5-7	**0.9**	0.3-9	**1.8**	0.3-10		

Source study: In-Use No of Cars: 7 (of 44) Analysis from Raw Exhaust with FTIR				
	+22 °C [mg/trip]		-7 °C [mg/trip]	
FTP75:1	average	range	average	range
N_2O	**185**	50-600	**185**	50-630
NH_3	**145**	12-317	**435**	23-1100
HCHO	**18**	6-35	**25**	12-52
Ambient temperature	+22 °C [mg/trip]		-7 °C [mg/trip]	

Source: Catalyst study No of Cars: 3 Analysis from Bag Sampling with Gas Chromatography								
Cycle	ECE15:1-2		FTP75:1		ECE15:1-2		FTP75:1	
Species	avg	range	avg	range	avg	range	avg	range
total HC (FID)	**815**	± 440	**1600**	± 1300	**7500**	± 2100	**11000**	± 6300
methane	**55**	±25	**90**	± 30	**560**	± 160	**670**	± 250
iso-butene	**45**	±30	**9**	± 9	**860**	± 300	**780**	± 420
ethene	**55**	± 40	**90**	± 80	**310**	± 210	**440**	± 330
1,3 butadiene	**21**	± 7	**13**	± 10	**160**	± 40	**270**	± 160
BTX	**150**	± 70	**380**	± 300	**1140**	± 220	**1760**	± 930
ethylbenzene	**120**	± 65	**33**	± 30	**1040**	± 230	**1590**	± 940
Sum of all 13 C1-C8 of total HC	**61 %**	± 6 %	**51%**	± 6	**58 %**	± 5	**54 %**	± 5%

avg = average for the whole fleet
range = lowest - highest within the whole fleet n/a = data not available

the test temperature was lowered from the normal range of +20 to +30 °C to sub-zero values.

The supportive basis of results for the determination of the average emission levels for the unregulated constituents was much narrower than what was available for the regulated pollutants, mainly because of the limited number of vehicles involved. In spite of this fact, however, the results could be used to give a first appraisal of the level of these compounds found at low ambient temperatures in the exhaust gases from petrol-fuelled passenger cars with three-way catalytic emission control. Notwhitstanding, more work in this area is certainly needed to corroborate these early findings.

11.4 REAL-TIME ANALYSIS OF THE EMISSIONS

As already mentioned, it was found to be advisable to express emissions originating from a trip initiated with a cold start at low ambient temperatures as a single, temperature dependant portion related more to the cold-start event, rather than to the driving itself. This kind of approach was strongly supported by the findings of the sub-study on the allocation of the emissions along the distance travelled. It showed that in most of the cases, especially at low ambient temperatures, more than 90 % of the excess emissions generated over a given cycle were released during the first 1 km of driving. After that, and almost irrespectively of the driving schedule used, the emission control system starts to work efficiently reducing the emissions substantially. A very low level of emissions was attained even in low ambient temperature conditions, once the engine and emission control system had reached their normal operating temperatures. This conclusion further accentuates the role of cold-starts and the negative effect that the break-down of the driving to very short trips has on total emissions.

This kind of dynamic, time resolved analysis gave support to some other important conclusions, too. One of them was that the enrichment used to guarantee the driveability of the cars and the subsequent effect it had on the emissions of CO and HC was on average proportional to the ambient temperature. However, this effect was phased out almost after the same distance was reached at both of the sub-zero temperatures (-7 and -20 °C) included in the study.

Taking into consideration the aforesaid conclusions and what had been said in Chapter 2.3 of the functioning of an SI engine and a three-way catalyst, future deliberations to lower the emissions of CO and HC in low ambient temperature conditions should preferably be targeted towards better engine performance and lowering the engine-out emissions achieved by engine preheating or less enrichment of the fuel-air mixture, rather than trying to increase catalyst performance by means of, e.g. heated converters.

12 FINAL CONCLUSIONS

The studies discussed in this report supported a number of conclusions. They are listed below in a condensed form, and not necessarily in any order of importance, but rather in context to the sub-study on whose outcome they were based on.

From the basic study with a non-catalyst vs. catalyst cars and the performance evaluation of the current-level three-way catalytic emission control technology, the following conclusions were made:

1) Low ambient temperature caused elevated emission levels for carbon monoxide (CO) and unburned hydrocarbons (HC). The emissions of nitrogen oxides (NO_X), however, were largely unaffected.

2) Cars with a TWC system were, on average, more sensitive to the adverse effects of low temperatures than conventional cars without exhaust aftertreatment. However, the emission levels measured for TWC cars at low temperatures did not exceed those recorded for their non-catalyst counterparts

The main outcome of the In-use study on the effect of vehicle mileage can be expressed in four prime conclusions:

3) The overall in-use emissions performance was not unduly affected by the cold Finnish driving conditions, but followed the average trend expressed in the assigned deterioration factors.

4) The emissions of CO and HC recorded at low ambient temperature were almost not dependent on vehicle mileage, but depended much stronger on vehicle type, and

5) The emissions of CO and hydrocarbons (HC) in cold-start, low ambient temperature conditions were not a function of catalyst performance, but rather a measure of direct engine-out emissions and were probably more resulting from the functioning of the engine itself.

6) The emissions of nitrogen oxides were largely dependent on total vehicle mileage, and even in low ambient temperature conditions, closely following the trend in performance assessed at normal temperature.

Furthermore, the average levels of emissions attained at different ambient temperatures could be established for regulated and even for some unregulated compounds. The validity and credibility of these estimates, however, differ from one group of emissions to another, because the estimates are based on a variable number of tests and quite arbitrary selection of test vehicles.

For the emissions of regulated components (CO, HC and NO_X), by far the greatest number of results were available. Therefore, the averages produced for these three substances should give quite a sound estimate of their occurrence. The number of results available to determine average emission levels for unregulated constituents was much lower than what was obtainable for the regulated pollutants, mainly because of the limited number of vehicles involved. In spite of this deficit, the results could be used to give a first appraisal of the level of these compounds at low ambient temperatures in the exhaust gases from petrol-fuelled passenger cars with three-way catalytic emission control. However, more work in this area is certainly needed to corroborate these early findings.

Regarding the average emissions, the following facts were also inscribed:

7) It is recommended to express the values for cold-start emissions in [g/trip], because the emissions generated at low ambient temperatures are mainly derived from the cold-start event rather than to the driving itself.

8) The dependence of the emissions of CO on ambient temperature was best described with a linear function, whereas the output of unburned hydrocarbons (HC) vs. ambient temperature more closely followed an exponential curve.

9) The average emission level for oxides of nitrogen (NO_X) was nearly non-dependent of ambient temperature.

Based on the dynamic, time-resolved analysis of the emissions output, the following three conclusions were made:

10) In most of the cases, especially at low ambient temperatures, more than 90 % of the excess emissions generated over a given driving cycle were released during the first 1 km of driving.

11) The emission control system works efficiently despite ambient temperature conditions once the engine and emission control system has reached their normal operating temperatures.

12) The enrichment was on average proportional to the ambient temperature, but was phased out almost after the same distance, about 1.6 km, was reached at both of the sub-zero temperatures (-7 and -20 °C) studied.

Taking into consideration the aforesaid conclusions and what had been said in Chapter 2.3 of the functioning of an SI engine and a three-way catalyst, a final recommendation was formulated:

13) Future deliberations to lower the emissions of CO and HC in low ambient temperature conditions should preferably be targeted towards better engine performance and lowering the engine-out emissions achieved by engine preheating or less enrichment of the fuel-air mixture, rather than trying to increase catalyst performance by means of, e.g. heated converters.

13 SUMMARY

The implications of the wide use of catalytic exhaust treatment to curb harmful and unwanted exhaust emissions from petrol-fuelled passenger cars have been quite extensive. A dramatic decline in the level of emissions from new motor cars has been achieved, as the three-way converter, when working at its best, is capable of reducing the amount of the regulated pollutants (CO, HC and NO_X) by more than 90 %.

Although the forecast for the decrease in emissions has been quite promising, the real-world situation has proved to be less fortunate. The levels of monitored ambient air pollution have not always been improving at equal pace with the decline predicted for the emissions. Strong increase in traffic volumes has surely ingested some of the advantages of lower new-car pollution levels. However, another very important factor has been that to some degree, this projection was based on theoretical rather than practical, real-world achievements. Actual circumstances of car use, which affet the emissions, have not been adequately reflected in those test procedures that form the basis for the regulations, with due effect also for the research and development work targeted for their fulfilment. Setting too narrow-based conditions for the assessment of emissions performance has allured us to think that the technology is more capable than it actually is.

The first criticism towards the effectivity of the certification system to address the problem was raised in the late 1980's, when it was found that despite of wide use of catalytic converters, high ambient CO levels persisted during wintertime in those areas of the United States, where sub-zero ambient temperatures prevail over that season. This criticism was supported by some early research showing that cars, which were clean in very normal conditions, could, however, emit substantially higher levels of CO and HC when tested at low ambient temperature. Thus, it became evident that although the driving cycles used in a regulatory test had been revised and updated over the years to reflect the evolution of the real-world traffic situations, neglecting the influence of the ambient conditions and upholding the traditional temperature range, originally set by the first Californian rule in 1960's, had been almost a crucial mistake.

In order to quantify and address this problem, the US EPA carried out in the late 1980's a wide-scale study of the emissions from former non-catalyst and present-day catalyst-equipped cars at low ambient temperatures. Subsequently, an extension to the certification regulation was promulgated, which called for additional emissions testing at 20 °F (appr. -7 °C) with separate standard for CO. This rule was implemented in a three-year phase-in starting from model year 1994 and extending to model year 1996.

Parallel to this exertion by the US EPA, many European countries were engaged in a discussion of substantially increasing the stringency of their emission regulations to a level that would request the use of catalytic converters. Among these countries were Sweden, Norway and Finland, which share more or less the same Nordic climate with low ambient temperatures. The question was raised, whether the current system would quarantee adequate performance of new cars even in these circumstances. Subsequently, research work was initiated to address this question. The studies described in this report are descendants for that work, which started in Finland at VTT in 1986.

The early, basic studies in the Nordic countries were more or less corroborating the findings of the American work and proving that the problem was still pertinent in cars with technology targeted for the European market, and not only restricted to those designated for North-America. The issue was brought to the attention of both expert working groups (GRPE and MVEG), which are in charge of preparing the future European emission regulations.

The initiative was given added strenght, when Sweden, Finland and Austria joined the European Union in 1995. The effort was supported by some of the old member states, particularly Germany, Denmark and the Netherlands, and quite extensive research efforts combining their expert resources with Sweden and Finland to provide necessary information promoting the initiative were undertaken. The work discussed here was a part of that venture. As a successful result for all these deliberations, the Environment Council of the European Union has in June 1997 preliminarily agreed upon the issue of introducing a low-temperature test with applicable limit values.

The various sub-studies described in this report have employed more than 120 individual passenger cars of model years 1992 to 1997. They represented more than 50 different makes and models typical for the Finnish market as well as other EC countries. All of them were normal, series produced cars, and if they were not new vehicles, they had been in normal private ownership use. Almost exclusively, the cars utilized today's predominant emission control technology in its most simple form: a single, underfloor positioned three-way converter and closed-loop AFR control with oxygen sensor. For fuel feed both multi-point port injection as well as a few single-point, throttle-body type of systems were used. Even a couple of electronically controlled carburettors were encountered among the test vehicles.

The work has been covering an ambient temperature range that extended from the baseline testing at +22 °C down to ±0 °C and -7 °C, and with a small sub-fleet, even down to -20 °C. Both the US FTP75 and the European driving schedule has been used. The latter one was employed particularly in its revised form, which is to be mandated by the next step of the regulations coming into force by the year 2000. There the 40 second idle phase prior to the start-of-sampling will be omitted, giving much better representation of cold-start emissions.

The studies presented and discussed in this report have clearly pointed out, how the ambient temperature has a distinct influence upon exhaust emissions, especially carbon monoxide (CO) and unburnt hydrocarbons (HC), from petrol-fuelled passenger cars that are using three-way catalytic converters for exhaust emission control. Depending on the ambient temperature and vehicle design, this elevation can range from fivefold emissions up to even 10 times the amount measured in a similar test at normal temperature. Furthermore, the first, comparative study showed that cars with a TWC-system are even more susceptible to the effects of low ambient temperatures than regular, non-catalyst vehicles. However, one must here bear in mind that even at their worst, cars with a TWC system remain on par with their traditional, non-catalyst counterparts.

Already the early studies have shown that the core of the problem lies in the cold-start of a petrol-fueled SI engine. At low ambient temperatures, substantially increased fuel feel is necessary to compensate the poor evaporation of the fuel. This enrichment, which is to be further boosted when the ambient temperature falls into the sub-zero range, leads to an incomplete combustion forming CO and heavy condensation lossess along the intake manifold and combustion chamber walls and crevices, which are a source for unburnt hydrocarbons.

These effects are valid for both the non-catalyst cars and the current-technology vehicles with TWC emission control, because as long as the air-fuel ratio is off the prescribed range for efficient conversion, the so-called lambda window, no conversion will take place. This is true, even if the temperature of the catalytic converter would have reached light-off level, i.e. over 350 °C, because in traditional systems without any additional air supply, there is no free oxygen in those circumstances for the oxdizing reactions needed to balance the exhaust output.

The research has shown that only after the engine has been warmed-up sufficiently, the enrichment can be subsequently phased off, and effective three-way conversion is enabled. Depending on the start-up temperature and the engine design, this may take from 1 km to even more than 4 kilometers of driving, which is close to the average trip lenght in many countries and especially in urban environments. In practical terms this means that a major part of the driving would take place without the TWC system to work properly. However, it was found also, that after the enrichment has been phased off and effective conversion conditions has been reached, good system performance will be retained during normal driving even at low ambient temperatures.

Technologies do exist that address emissions associated with cold-start. To date the majority of them, however, is targeted towards meeting the Californian ULEV regulations by lowering the hydrocarbon emissions. Therefore, they are not particularly effective for operations at sub-zero temperatures. Some of the novel features like close-coupled or preheated converters may have a positive effect, but only, if they are accompanied with an auxiliary air supply system. Otherwise the advantage from the rapid rise in converter bed temperature is lost, if the exhaust composition is off-balanced due to the enrichment necessary to start and run the engine.

The outcome of the studies suggested that the most effective means of lowering the adverse effect of cold ambient temperature is lessening the need of enrichment via preheating the engine. This can be done, e.g. by using a relatively simple electrical block heater, but one is then restricted to those designated parking areas with suitable network outlets. More sophisticated, fuel-fired heaters are also available, which work independently without any external power, but with substantially added cost and complexity. The most elegant means of preheating is perhaps the device called “heat battery”, which retain some of the heat from the cooling system for a later re-start.

Furthermore, studies involving a fleet of in-use vehicles with varying mileages from 10,000 km up to 90,000 km have substantiated that the presumption of the fairly good overall durability of the current TWC systems, which was expected as a result from the limited field testing in Finnish driving conditions, was correct. When assessed at normal ambient temperature, the system performance and increase in emissions over the studied mileage range seemed to closely follow the expected deterioration expressed in the form of assigned deterioration factors (DF’s) included in the new vehicle certification regulations.

However, the dependence of cold-start emissions of total vehicle mileage was very weak at low ambient temperatures. This was taken as a definite sign that raw engine-out emissions, especially in terms of CO and HC, were overruling, and the functioning of the converter, which accroding to the normal-temperature testing seemed to be deteriorating over the use of the car, was in this case less important. Furthermore, this assumption lead to a suggestion that the actions targeted to the curbing of the cold-start emissions in low ambient temperature conditions should primarily be based on lessening the undue fuel feed by recalibration of the fuel enrichment function and better engine warm-up. This recommendation was further supported by fact that quite large differencies in emissions performance was found among the individual models in the tested car fleet. As no particular driveability problems were encountered simultaneously in any of the cars, the high-emitting vehicles were obviously subjected to an unduly heavy enrichment of the air-fuel mixture, subsequently causing excess emissions of CO and HC.

It has become also evident that not only the regulated emissions are affected by the low ambient temperature. To substantiate this allegation, many unregulated compounds, i.e. those not having any prescibed standard in the certification regulations, were determined. In this work both traditional sampling-based chemical analysis as well as the most novel, on-line operating FTIR analyser was employed. With this kind of system, it was possible to determine compounds like nitrous oxide (N_2O), ammonia (NH_3) and formaldehyde, all important and unwanted by-products of inefficient three-way catalyst operation. Furthermore, many speciated hydrocarbons, like benzene, toluene and xylenes, which along with 1,3 butadiene belong to the group of possible human carcinogens, were determined.

Of those compounds studied with FTIR, the emissions ammonia (NH_3) were found to increase, on average, when the ambient temperature was lowered. On the contrary, the emissions of nitrous oxide (N_2O), taken as a sub-fleet average, remained at about the same level in both of the temperatures. This, in spite of the fact that the responses of individual vehicles were deviating largely from one another and even contradicting each other in some of the cases. However, across the seven-car sub-fleet these variations largely compensated each other. Aside, a slight overall increase in the level of formaldehyde emission due to the low-temperature testing was spotted, but as these emissions remained at a very low level and close to the detection limit of the measurement system, this shift should be regarded as inconclusive.

Even if some suggestions were made here of the effect of ambient temperature, it must be strongly underlined that as the number of vehicles involved in testing for the unregulated emissions was very small. Therefore, decisive conclusions based on these results should be avoided, and all judgments should be taken as indicative only. Further work in this field is particularly needed to substantiate these early appraisals.

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Appendix 1

SUMMARY AND OUTLOOK TO THE EMISSIONS LEGISLATION

1 A BRIEF HISTORY OF EMISSION REGULATIONS AND EMISSION AFTERTREATMENT TECHNOLOGY

In mid-1950's, exhaust emissions from motor vehicles were identified as key contributors to the ambient air pollution problems encountered in many major cities and other densely-populated urban environments. This was true especially in the United States, where passenger cars constitute the overwhelming majority of the traffic volumes. The South Coast Air Basin in California, i.e. City of Los Angeles with its surroundings, was a prime example of this kind of urban settlement with major traffic-related air pollution problems, also known by the dreadful name of “smog”. Violations of the national ambient air quality standards (NAAQS), mostly for carbon monoxide, but increasingly also for ozone [1], were recorded almost constantly.

Subsequently, in 1964, State of California became the first area to issue regulations stating maximum allowable emission levels for 1966 and later model year[1] new cars [1]. A separate administrative office, Air Resources Board (CARB), was founded concurrently. Soon after that, in 1966, a very similar statute was made by the US Congress covering cars of model year 1968. Next major milestone was the passing of the Clean Air Act in 1970, which established the Environmental Protection Agency (EPA), and gave it the jurisdiction to control motor vehicle emissions[2].

Furthermore, parallel development took place in Europe, as in 1970 the European Economic Community (EEC) passed its first directive (70/220/ EEC) on the subject. Already preceding, the Inland Transport Committee (ITC) within United Nation’s Economic Commission for Europe (UN/ECE) had established an expert forum “Group of Rapporteurs on Pollution and Energy” (GRPE) to collaborate internationally and report of the matter to the Working Party No 29 (WP.29),

[1] In the usual wording of US emission regulations “model year” refers to the production period of motor vehicles, which usually starts in September, and not to any actual calendar year.

[2] The Californian Air Resources Board (CARB), however, retained its premium position and sole jurisdiction over the State of California, but the rest of the states were covered by the federal EPA regulations. Similar situation prevails even as of today.

which deals with the regulations related to the construction of motor vehicles.

With this development of legislative instruments and bodies, the way was then set and paved for ongoing development and emissions control soon became the major design objective of new motor vehicles. At first, only minimal engine modifications or schemes like exhaust gas recirculation (EGR) were sufficient to make cars to comply with the regulations. However, due to the increasing stringency of the legislation, especially in the US, engine technology development alone was apparently no more adequate to fulfill these requirements. Therefore, exhaust aftertreatment to remove and control the unwanted emissions of carbon monoxide (CO) and unburned hydrocarbons (HC) became necessary, and a device called "catalytic converter" was developed to rescue the automakers. It was a chemical reactor able to convert most of these harmful substances to harmless CO_2 and water by the aid of exhaust heat and the presence of some noble metals (platinum or palladium). These first generation, oxidizing-only catalytic converters appeared in model year 1975 vehicles aimed for the US market.

This positive development, along with the results of scientific research that linked both HC and oxides of nitrogen (NO_X)[3] as main precursors[4] in the atmospheric chemistry responsible for the production of smog and ozone (O_3), spurred the US Congress to pass amendments to the Clean Air Act in 1977. As a result, a revised set of requirements containing very low standards for HC and NO_X was promulgated by the EPA to cover 1981 and later model year cars. The industry's response to this move, apart from taking a heavily opposed position and challenging the US government deeply in a lengthy litigation process, was a second generation of catalytic converters, able to convert all three major pollutants (CO, HC, NO_X) into less harmful form. Subsequently, they were called "three-way converters" (TWC), although in Principe the reactions were either oxidizing (for HC and CO) or reducing (for NO_X).

Ever since TWC has become a household word among motorists, and practically all new petrol-fuelled passenger cars produced today are equipped with one. However, this well-matured and rather simple solution of one TWC converter and closed-loop controlled fuel metering apparently does not reach anymore below the most stringent limit values already in force in the United States, and soon to be equalled by the latest amendments of the EC directives.

[3] NO_X refers to the sum of nitrogen monoxide (NO) and nitrogen dioxide NO_2. It does not, however, contain nitrous oxide (N_2O), which can also be found among exhaust emissions.

[4] Strong UV-radiation is also an essential element in this very complex system.

2 PRESENT-DAY STATUS OF THE LEGISLATION

2.1 United States (Of America)

As it was stated in the main text, Californian Air Resources Board issued the first set of limit values for exhaust emissions. Following that tradition, by far the most stringent regulations at present are still those set by the CARB for the State of California. The values are expressed in their Low-emission Vehicle (LEV) Program, which is to be phased in during the present decade. Table 1 lists these standards, and shows that the program presents different limit value levels. It also gives an indicative share for each of these sets of the annual sales, compounded separately for each manufacturer marketing cars in State of California.

Table 1 Emission standards for the Californian Low Emission Vehicle. Program 1.

Regulated component	Standards [g/mile] FTP75 driving cycle, 50000 mile durability					
	< MY'94	Tier 1	'TLEV'	'LEV'	'ULEV'	'ZEV'
carbon monoxide (CO)	3.4	3.4	3.4	3.4	1.7	-
NMOG[1]	0.25	0.25	0.125	0.075	0.040	-
oxides of nitrogen (NO_X)	1	0.4	0.4	0.2	0.2	-
formaldehyde[2]	-	-	-	0.015	0.08	-
Model year	Suggested relative share of each set in annual sales					
1994	10%	80%	10%	-	-	-
1995		85%	15%	-	-	-
1996		80%	20%	-	-	-
1997		73%		25%	2%	-
1998		48%		48%	2%	(2%)[3]
1999		23%		73%	2%	(2%)[3]
2000				96%	2%	(2%)[3]
2001				90%	5%	(5%)[3]
2002				85%	10%	(5%)[3]
2003				75%	15%	10%

Remarks: [1] NMOG = 'Non-Methane Organic Gases', i.e. total hydrocarbons less CH_4; if the vehicle is fueled with alternative fuel (methanol or reformulated gasoline), the correction is made with applicable reactivity adjustment factor (RAF), which is based on the ozone forming potential of the individual species emitted.
[2] methanol-fueled vehicles only
[3] ZEV mandate was relaxed in 1996 and replaced with an introductory fleet evaluation program; annual ZEV sales share to be replaced with ULEV vehicle sales

Abbreviations: MY = model year (of the vehicle)
TLEV = Transitory Low Emission Vehicle LEV = Low Emission Vehicle
ULEV = Ultra-Low Emission Vehicle ZEV = Zero Emission Vehicle

The main objective for the Californian program has been the lowering of the ozone forming potential of the exhaust emissions, because ozone still remains as one of the main pollutants causing frequent violations of the National Ambient Air Quality Standards (NAAQS). This deliberation is reflected in the aggressive

lowering of the hydrocarbon standard coupled with more stringent NO_x control, as well. As seen in Table 1, standards for carbon monoxide (CO) remain at a rather relaxed level in all sets of numbers other than ULEV, where it will be lowered by 50 % from the present-day level.

The current US Federal requirements by the EPA (referred as Federal Tier I) are similar to the Californian numbers for model year 1994, and, therefore, not unduly challenging. Furthermore, the CAAA'90 has already mandated a further step, Federal Tier II, to be implemented by the EPA for model year 2003. However, because a strong political pressure was put on the EPA from several states with severe air pollution problems, which have formed an entity called the Ozone Transport Commission (OTC), the federal standards were revised. As a result of this work, the EPA announced an initiative called "National Low-Emission Vehicle Program" or NLEV in June 1997[5].

As Table 2 shows, this new initiative effectively copies the Californian programme with similar structure and equal limit values for the classes, but retains two important exemptions: there is no mandate for Zero-Emission Vehicles (ZEV) and the programme is not compulsory. The manufacturers or importers may rather make a voluntary choice, whether they want to join in or not. Once in, however, there are only a few strictly limited cases how they can withdraw themselves from the program.

Table 2 Exhaust emission standards for passenger cars according to the US EPA "National Low-Emission Vehicle Program" (NLEV)

Durability [miles]	Class	NMOG[1] [g/mile]	CO [g/mile]	NO_X [g/mile]	HCHO[2] [g/mile]	PM [g/mile]
50,000	TLEV	0.125	3.4	0.4	0.015	.....
	LEV	0.075	3.4	0.2	0.015	.....
	ULEV	0.040	1.7	0.2	0.008	.....
100,000	TLEV	0.156	4.2	0.6	0.018	0.08
	LEV	0.090	4.2	0.3	0.018	0.08
	ULEV	0.055	2.1	0.3	0.011	0.04

[1] NMOG = 'Non-Methane Organic Gases' [2] HCHO = formaldehyde

The response to the EPA's initiative has been quite positive, as right after the announcement of the NLEV, most of the manufacturers and major importers have opted to sign in to the programme, because there are clear advantages in doing so. The main one of them perhaps being that in the near-future, it would give them the possibility of covering the whole United States with one single model instead of separate Californian and Federal versions. This is an act that would much simplify the design and certification process and result in substantial cost-savings.

[5] 40 Code of Federal Register (CFR), Parts 85 and 86. Vol 62, No 109, pp. 31192 - 32170.

2.2 European Union

The current amendment (96/44/EEC) to the Directive of the European Union for passenger car exhaust emission control (70/220/EEC) does not entail any stricter requirements than those of the United States. Nevertheless, the recent progress in Europe has been very much parallel to the advances in the United States. Furthermore, almost concurrently with the announcement of US NLEV Programme in June 1997, a common position was reached between the Council and the Commission. This act, taken at the end of June, marked a further step in the European legislation, which shall become effective by the year 2000. These new limit values, which can be seen in Table 3, are about 40 to 50 % lower than present-day standards.

Apart from the amended numbers, added stringency comes also from the fact that the test procedure will be simultaneously revised to measure emissions more accurately after a cold-start[6]. The new numbers are, however, still under Parliament review and consideration, but no major alterations are expected. Final directive will be issued probably in the spring of 1998.

Table 3 The present-day and upcoming emission standards of European Union

Engine type / fuel (80,000 km durability	Standards in 96/44/EEC [g/km] driving cycle: ECE15+EUDC (=MVEG-2)				imple-mented
	CO	HC+NO_x	PM	e.HC_	
petrol	2.20	0.50	-	2 g	1996 (1
diesel, IDI	1.00	0.70	0.08	-	1997 (2
diesel, DI	1.00	0.90	0.1	-	
Driving cycle ECE15(-40s)+EUDC (=MVEG-3)					
comparative 96/44/EEC values	CO	HC	HC+NOx	NOx	PM	measured using new, revised test procedure
petrol	2.7	0.341	-	0.252	-	
diesel	1.06	-	0.71	0.566	0.08	
New standards tentatively set in the Common Position						
petrol	2.3	0.2	-	0.15	-	2000
diesel	0.64	-	0.50	0.37	0.05	
petrol	1.00	0.10	-	0.08	-	2005 (3
diesel	0.50	-	0.30	0.25	0.025	

1) new typest 2) all registrations 3) limit values to be re-evaluated before 30.6.1999

[6] The 40 s idle period now designated between engine start and sampling start shall be deleted.

Appendix 2

DETAILS OF THE TESTED VEHICLES

The following tables list the cars used in various sub-tasks discussed in this report with some basic details of their technology.

Table 1. BASIC STUDY

Make	Model	Vehicle Code	Displ. (dm^3)	Model Year	Test inertia (kg)	Odo-meter (km)	Fuel delivery system; emission control devices	Test type(s)
Nissan	Sunny	BS92A	1.4		960	35000	Carb	FTP75
SAAB	900i - 16V	BS92B	2.1		1360	≈8000	MPFI; TWC	FTP75
Volkswagen	Polo	BS92C	1.3		820		MPFI; TWC	FTP75
Toyota	Corolla XL	BS92D	1.6		1030	≈8000	MPFI; TWC	FTP&EC
Fuel system & emission control: MPFI=Multi-Point Fuel Inj. Carb=Carburettor TWC=three-way catalyst								

Table 2. CO-NORDIC STUDY

Make	Model	Vehicle Code	Displ. (dm^3)	Model Year	Test inertia (kg)	Odo-meter (km)	Fuel delivery system; emission control devices	Test type(s)
Fiat	Uno 1.1i	CN93A	1.1	1993	910	7254	SPFI; TWC	"EC2000"
Ford	Mondeo 1.8i CLX	CN93B	1.79	1993	1360	22045	MPFI; TWC	EC&FTP
Lancia	Dedra 1.8i	CN93C	1.8	1993	1360	9379	MPFI; TWC	"EC2000"
Opel	Astra 1.4i	CN93D	1.38	1993	1080	8818	MPFI; TWC	"EC2000"
Toyota	Carina Wagon	CN93E	1.59	1993	1300	7340	MPFI; TWC (LB)	"EC2000"
Vehicles tested at Motortestcenter / AB Svensk Bilprovning, Sweden								
Volvo	850	CN93F	2.5	1993		1780	MPFI; TWC	"EC2000"
Nissan	Primera	CN93G	2.0	1993		7820	SPFI, TWC; EGR	"EC2000"
Porsche	968	CN93H	3.0	1993		9290	MPFI; TWC (metal)	"EC2000"
Volkswagen	Golf 1.9 Ekodiesel	CN93K	1.9	1993			IDI (diesel); OC	"EC2000"
Mercedes-Benz	C 220 Diesel	CN93L	2.2	1994		≈1000	EC-IDI (diesel); OC	"EC2000"
Certified to EC1 = Swedish Env. Class 1 Vehicles tested at Motortestcenter / AB Svensk Bilprovning, Sweden								
Saab	900 T	CN93I	2.0	1993		8860	MPFI; TWC; EGR	"EC2000"
Honda	Civic	CN93J	1.5	1993		5950	MPFI; TWC; EGR	"EC2000"
Fuel system:	MPFI=Multi-Point Fuel Inj. SPFI=Single-Point Fuel Inj. Carb=Carburettor IDI = prechamber diesel, mechanical fuel pump EC-IDI = prechamber diesel, electronic fuel inj. Control							
Emission control:	TWC= Three-Way Catalyst OC=Oxidation catalyst EGR = exhaust gas recirculation (LB) = lean-burn combustion at part load							

Table 3. CATALYST STUDY

Make	Model	Vehicle Code	Displ. (dm^3)	Model Year	Test inertia (kg)	Odo-meter (km)	Fuel delivery system; emission control devices	Test type
Opel	Astra 1.6i GL	KK95A	1.59	1994	1010	44318	MPFI; TWC	EC&FTP
Volkswagen	Polo 1300	KK95B	1.29	1995	910	9473	MPFI; TWC	EC&FTP
Toyota	Corolla HB 1.6XLi	KK95C	1.58	1995	1060	12028	MPFI; TWC	EC&FTP
Fuel system & emission control: MPFI=Multi-Point Fuel Inj. TWC=three-way catalyst								

Table 4. TECHNOLOGY EVALUATION STUDY

Make	Model	Vehicle Code	Displ. (dm^3)	Model Year	Test inertia (kg)	Odo-meter (km)	Test type
Hyundai	Sonata	TM93A	n.a.	1993	1420	14291	FTP75:1
Saab	900 i	TM93B	1.99	1993	1360	4499	FTP75:1
Lancia	Dedra	TM93C	1.8	1993	1360	25445	FTP75:1
Nissan	Primera 2.0 SLX	TM93D	2.0	1993	1360	1306	FTP75:1
Peugeot	405 SRi	TM93E	1.99	1993	1300	6023	FTP75:1
Toyota	Carina E 2.0	TM93F	1.99	1993	1300	1194	FTP75:1
Mitsubishi	Galant 2.0 GLSi	TM93G	1.99	1993	1360	2257	FTP75:1
Opel	Vectra 2.0i GLS	TM93H	1.99	1993	1300	2081	FTP75:1
Audi	80 2.0 E	TM93I	1.98	1993	1360	1954	FTP75:1
Mazda	626 2.0i	TM93J	1.99	1993	1300	2824	FTP75:1
Alfa Romeo	155 Twin Spark 2.0	TM93K	1.99	1993	1360	18466	FTP75:1
Subaru	Legacy 2.0 GL	TM93L	1.99	1993	1300	553	FTP75:1
Honda	Accord	TM93M	1.99	1993	1360	2002	FTP75:1
Volvo	460 SE	TM93N	1.99	1993	1190	8751	FTP75:1
Volkswagen	Passat	TM93O	1.78	1993	1360	2278	FTP75:1
BMW	316i	TM93P	1.59	1993	1300	5488	FTP75:1
Seat	Toledo GLX	TM93Q	1.98	1993	1190	34526	FTP75:1
Renault	Twingo 1.2	TM94A	1.23	1994	850	6084	FTP75:1
Seat	Ibiza 1.6i CLX	TM94B	1.59	1994	1080	5357	FTP75:1
Peugeot	306 XR	TM94C	1.58	1994	1080	2120	FTP75:1
Citroen	Xantia 1.8i	TM94D	1.76	1994	1300	2431	FTP75:1
Saab	900S 2.3	TM94E	2.29	1994	1360	7971	FTP75:1
Ford	Mondeo 1.8i CLX	TM94F	1.79	1994	1300	3721	FTP75:1
Opel	Corsa 1.4i Swing	TM94G	1.38	1994	960	2274	FTP75:1
Honda	Accord 2.0i LS	TM94H	1.99	1994	1360	10162	FTP75:1
Mitsubishi	Galant 1.8 GLI	TM94I	1.83	1994	1300	8815	FTP75:1
Mercedes Benz	C 180	TM94J	1.79	1994	1360	5200	FTP75:1
Renault	19-1.8i RN	TM95A	1.79	1995	1080	4526	FTP75:1
Volvo	Sedan 460 1.8i	TM95B	1.79	1995	1080	14602	FTP75:1
Seat	Toledo 1.8i GL	TM95C	1.78	1995	1130	2281	FTP75:1
Opel	Astra 1.6i GLS	TM95D	1.59	1995	1130	4512	FTP75:1
Mazda	Familia 323-1.5i	TM95E	1.49	1995	1130	11709	FTP75:1
Hyundai	Accent 1.5i LS	TM95F	1.49	1995	1020	5314	FTP75:1
Ford	Escort 1.8 CLX	TM95G	1.79	1995	1190	3870	FTP75:1
Toyota	Corolla 1.6 GLi	TM95H	1.58	1995	1130	2537	FTP75:1
Volkswagen	Vento 1.8 GL	TM95I	1.78	1995	1190	2513	FTP75:1
Mitsubishi	Lancer 1.6 GLXi	TM95J	1.59	1995	1130	6599	FTP75:1
Nissan	Primera 1.6i Fantasy	TM95K	1.59	1995	1190	2262	FTP75:1
Fiat	Tempra 1.6S i.e.	TM95L	1.58	1995	1190	2908	FTP75:1
Peugeot	306 ST	TM95M	1.76	1995	1190	3272	FTP75:1
Honda	Civic DXi	TM95N	1.49	1995	1080	8275	FTP75:1
Citroen	Xantia 1.8i 16V	TM96A	1.76	1996	1360	4991	FTP75*
Hyundai	Elantra 1.8 GLS-16V	TM96B	1.8	1996	1300	15457	FTP75*
Opel	Vectra 1.8i-16V-GL	TM96C	1.79	1996	1360	3824	FTP75*
Ford	Mondeo 1.8i CLX	TM96D	1.79	1996	1360	3904	FTP75*
Renault	Laguna 2.0 RT	TM96E	1.99	1996	1420	8896	FTP75*
Mitsubishi	Carisma 1.8 GLX	TM96F	1.83	1996	1360	3925	FTP75*
Opel	Corsa 1.2 i ECO	TM97A	1.19	1997	1020	2097	FTP75*
Peugeot	106 1.1 l	TM97B	1.12	1997	960	2885	FTP75*
Ford	Fiesta 1.3	TM97C	1.29	1997	1080	3754	FTP75*
Volkswagen	Polo	TM97D	0.99	1997	1080	7639	FTP75*
Volvo	850	TM97E	2.43	1997	1530	6614	FTP75*
Fiat	Punto S	TM97F	n.a.	1997	1020	2294	FTP75*
Renault	Clio 1.4	TM97G	1.39	1997	1080	4253	FTP75*
Nissan	Micra 1.0	YM97H	0.99	1997	910	2624	FTP75*

FTP75:1 = Cold Transient Phase (Yct) of FTP75
FTP75* = 10 min pause shortened to 1 min

Table 5. IN-USE STUDY

Make	Model	Vehicle Code	Displ. (dm^3)	Model Year	Test inertia (kg)	Odo-meter (km)	Fuel delivery system; emission control devices	Test type
Toyota	Corolla XSi	ANH94Aa	1,29	1991	1130	76446	MPFI, TWC	FTP75
Toyota	Corolla XSi	ANH94Ab	1,29	1990	1130	60733		
Toyota	Corolla XLi	ANH94Ac	1,29	1990	1130	71876		
Ford	Escort STW 1.8	ANH94Ba	1,79	1992	1190	26391	MPFI, TWC, Pulse Air	FTP75
Ford	Escort STW 1.8	ANH94Bb	1,79	1992	1190	30434		
Ford	Escort 1.8 CL	ANH94Bc	1,79	1992	1190	81887		
Nissan	Sunny 1.6 SLX	ANH94Ca	1,59	1991	1190	46629	Carb, TWC	FTP75
Nissan	Sunny 1.6 LX	ANH94Cb	1,59	1991	1190	64010		
Nissan	Sunny 1.6 LX	ANH94Cc	1,59	1991	1190	48401		
Renault	R19 1.4 GTS	ANH94Da	1,39	1992	1080	42769	SPFI, TWC	FTP75
Renault	R19 1.4 RN	ANH94Db	1,39	1993	1080	39535		
Renault	R19 1.4 GTS	ANH94Dc	1,39	1991	1080	58602		
Mazda	323 1.3i	ANH94Ea	1,32	1991	1130	50834	MPFI, TWC	FTP75
Mazda	323 1.3i	ANH94Eb	1,32	1992	1130	74518		
Nissan	Primera 1.6XEi	ANH95Fa	1,59	1995	1360	27768	MPFI, TWC	FTP75
Nissan	Primera 1.6LXi	ANH95Fb	1,59	1995	1360	28975		
Nissan	Primera 1.6LXi	ANH95Fc	1,59	1995	1360	18509		
Volkswagen	Golf 1.8 CL	ANH95Ga	1,78	1993	1300	61755	MPFI, TWC	FTP75
Volkswagen	Golf 1.8 GL	ANH95Gb	1,78	1995	1300	37129		
Volkswagen	Golf 1.8 CL	ANH95Gc	1,78	1994	1300	68970		
Peugeot	306 XS	ANH95Ha	1,58	1995	1130	9368	MPFI, TWC	FTP75
Peugeot	306 XR	ANH95Hb	1,58	1995	1130	10210		
Peugeot	306 XR	ANH95Hc	1,58	1995	1130	16585		
Opel	Astra 1.6i GL	ANH95Ia	1,59	1994	1250	76760	MPFI, TWC	FTP75
Opel	Astra 1.6i GL	ANH95Ib	1,59	1994	1250	31068		
Opel	Astra 1.6i GL	ANH95Ic	1,59	1996	1250	10757		
Fiat	Tempra 1.6 i.e. SX	ANH95Ja	1,58	1995	1250	19460	MPFI, TWC	FTP75
Fiat	Tempra 1.6 i.e. SX	ANH95Jb	1,58	1995	1250	13441		
Fiat	Tempra 1.6 i.e. SX	ANH95Jc	1,58	1995	1250	14349		
Volvo	850 STW GL	ANH96Ka	2,43	1995	1530	62261	MPFI, TWC	FTP75
Volvo	850 Sedan GL	ANH96Kb	2,43	1994	1530	70080		
Volvo	850 STW GL	ANH96Kc	2,43	1994	1530	90131		
Lada	Samara 1500	ANH96La	1,49	1991	1080	60263	Carb, TWC	FTP75
Lada	Samara 1500	ANH96Lb	1,49	1994	1080	56777		
Lada	Samara 1500	ANH96Lc	1,49	1993	1080	77277		
Ford	Mondeo 1.8i GLX	ANH96Ma	1,79	1995	1460	66876	MPFI, TWC	FTP75
Ford	Mondeo 1.8i CLX	ANH96Mb	1,79	1993	1460	69562		
Ford	Mondeo 1.8i CLX	ANH96Mc	1,79	1993	1460	90454		
Citroén	Xantia 2.0i	ANH96Na	1,99	1993	1530	63763	MPFI, TWC	FTP75
Citroén	Xantia 2.0i	ANH96Nb	1,99	1994	1530	61211		
Citroén	Xantia 2.0i	ANH96Nc	1,99	1994	1530	74046		
Toyota	Carina E XLi	ANH96Oa	1,58	1995	1326	69376	MPFI, TWC	FTP75
Toyota	Carina E XLi	ANH96Ob	1,58	1996	1326	42256		
Toyota	Carina E XLi	ANH96Oc	1,58	1995	1326	64072		

Fuel system: MPFI=Multi-Point Fuel Inj. SPFI=Single-Point Fuel Inj. Carb=Carburettor
Emission control: TWC= Three-Way Catalyst Pulse Air=Auxiliary Air into Exhaust

Appendix 3

FUEL SPECIFICATIONS

This Appendix gives some examples of fuels and their specifications used in studies referred in this report. Table 1 identifies fuels per study.

Table 1. Examples of specifications for test fuels used in these studies.

Study	Ref.	Type	RON	Page
Co-Nordic In-Use '94	RF-08-A-85, ML 406/93	Unleaded petrol, complying with reference grade specification	95	2
In-Use '95	RF-08-A-85, ML 479/94, Batch 94/276	Unleaded petrol, complying with reference grade specification	95	3
In-Use '96 Catalyst	RF-08-A-85, ML 149/96, Batch 96/127	Unleaded petrol, complying with reference grade specification	95	4
Basic Co-Nordic TM '93 TM '94 TM '95	Citybensiini 95EC (oxygenated) (example of market fuel for Finland between 1992-1995)	Unleaded petrol, commercial	95	5
TM '96 TM '97	Citybensiini 95ECR (reformulated) (example of market fuel for Finland since spring 1996)	Unleaded petrol, commercial	95	6-7

NESTE OY
Oil

Engine Laboratory/Jussi Kokko

ANALYSIS OF REFERENCE GASOLINE ECE-RF-08-A-85/B4

Code or name		CEC-RF-08-A-85/B4	*CEC-RF-08-A-85*	
Sample number		ML406/93		
Date of analysis		2.6.1993		
			Min	*Max*
Density, 15 C	kg/m3	758.2	***748***	***762***
Vapour Pressure, Reid	mbar	590	***560***	***640***
Copper Corrosion		1a		***1***
Existent Gum				
Unwashed	mg/100 ml	12.6		
Washed	mg/100 ml	1.0		***4***
Oxidation Stability	min	>1500	***480***	
Sulphur Content	mg/kg	295		***400***
Benzene Content	%-weight	3.5		***5***
Lead Content	mg/kg	0		***5***
Phosporous Content	mg/kg	<0.5		***1.3***
FIA				
Olefins	%-vol	6.6		***20***
Aromatics	%-vol	36.6		***45***
Saturates	%-vol	56.8		
OCTANE NUMBERS				
RON		95.5	***95.0***	
MON		86.2	***85.0***	
DISTILLATION, ASTM D86				
	IBP	33		
	5	46	***24***	***40***
	10	55		
	20	70		
	30	84		
	40	96		
	50	107		
	60	118		
	70	129		
	80	144		
	90	162		
	95	174		
	FBP	201		***215***
Recovery, %-vol	%-vol	97.0		
Residue	%-vol	1.0		***2.0***
Loss	%-vol	2.0		

C:\QPW\JMK\REFERENS.WB1;07-Jun-93

NESTE

TUTKIMUSTODISTUS

Päivämäärä	Numero	Sivu(ja)
12.6.1995	ÖTT 300/95	1(1)

Tutkimuksen aihe

CEC RF-08-A-85 -polttoaineen analyysi

Käsittelijä: Armi Ruotsalainen

Hyväksyjä: Kari Seppälä

Tutkimusseloste

Tutkimuksen aihe: Analysoitiin (20.10.1994) CEC RF-08-A-85 -referenssipolttoaine (ML 479/94; erānumero 94/276).

Tulokset: Tulokset on esitetty seuraavassa taulukossa.

Analyysi	Menetelmä	Tulos	Laatuvaatimus min.	max.
Tiheys 15 °C kg/l	D 4052	759.7	748	762
Höyrynpaine, Reid, Kpa	NM 103	58	56	64
Kuparikorroosio	D 130	1a		1
Hartsipitoisuus Kok/tod, mg/100ml	D 381	 1.2/0.0		 4
Hapetusaika, min	D 525	>1500	480	
Rikkipitoisuus, mg/kg	D 3120	13		400
Bentseenipitoisuus, p-%	GC	1.5		5
Lyijypitoisuus, mg/kg	NM 101	4		5
Fosforipitoisuus, mg/kg		<0.2		1.3
FIA Olefiinit, til-% Aromaatit, til-% Parafiinit + nafteenit, til-%	D 1319	 7.3 37.0 55.7		 20 45
Oktaaniluku, RON	D 2699	96.1	95.0	
Oktaaniluku, MON	D 2700	85.9	85.0	
Tislaus, °C / til-% TA 10 50 90 TL Saanto/jäännös/häviö, til-%	D 86	 33 50 105 157 188 95.0/1.0/4.0	 24 42 90 155	 40 58 110 180 215 -/2.0/-

Armi Ruotsalainen

JAKELU: PO, KSE, ARJ, JUHK, JMK, JJKI

☐ Laskutetaan ☐ Ei laskuteta

NESTE

TUTKIMUSTODISTUS

Päivämäärä	Numero	Sivu (yht.)
11. 6. 1996	ÖTT 245/96	1(1)

Tutkimuksen aihe

RF-08-A-85 -polttoaineen analyysi

Käsittelijä	Hyväksyjä
Marja-Liisa Tyyskä	Pirjo Saikkonen

Tutkimusseloste

Tutkimuksen aihe: Analysoitiin valmistettu RF-08-A-85 -referenssipolttoaine (ML 149/96; eränumero 96/127)

Tulokset: Tulokset on esitetty seuraavassa taulukossa.

Analyysi	Menetelmä	Tulos	Laatuvaatimus min.	max.
Tiheys 15 °C kg/l	D4052	0.758	0.748	0.762
Höyrynpaine, Reid, kPa	NM103	61	56	64
Tislaus, til%/°C	D86			
TA		32.0	24	40
10		52.1	42	58
50		105.2	90	110
90		157.0	155	180
TL		192.8	190	215
Saanto/jäännös/häviö, til-%		96.6/1.2/2.2	-/2.0/-	
Rikkipitoisuus, mg/kg	D3120	140		400
Hapetusaika, min.	D525	>1500	480	
Kuparikorroosio, 50 °C	D130	1a		1
Bentseenipitoisuus, p-%	GC	2.3		5
Hartsipitoisuus, Kok/tod, mg/100ml	D381	2.6/0.9		4
Lyijypitoisuus, mg/l	NM101	1		5
Fosforipitoisuus, g/l	D3231	<0.0002		0.0013
Oktaaniluku, RON	D2699	96	95	
Oktaaniluku, MON	D2700	86	85	
FIA	D1319			
Olefiinit, til-%		5.5		20
Aromaatit, til-%		35.5		45
Parafiinit + nafteenit, til-%		59.2		
C/H - suhde		6.8	Ilmoitettava	

Näyte ei sisällä oksygenaatteja

Marja-Liisa Tyyskä

Marja-Liisa Tyyskä

JAKELU ARJ, JMK, PRS, ARU, JUHK

☐ Laskutetaan ☐ Ei laskuteta

NESTE
Öljy

TUOTETIEDOTE
LAATUOMINAISUUDET

CITYBENSIINI 95EC, LYIJYTÖN
OKTAANILUKU 95
Lyhenne BE95EC

1.1.1993

	Yksikkö	Laaturaja	Tyypillinen arvo	Määritys-menetelmä
Oktaaniluvut				
RON		≥ 95,0	96	ISO 5164
MON		≥ 85,0	85	ISO 5163
Lyijy	g/l	≤ 0,003	< 0,003	ASTM D 3237
Tislaus				ASTM D 86
Haihtunut 70°C:ssa (E70)(kesä)	til.-%	20 ... 40	30	
" (E70)(kevät)	til.-%	23 ... 43	32	
" (E70)(talvi)	til.-%	25 ... 45	34	
" 100°C:ssa (E100)(kesä)	til.-%	43 ... 63	50	
" 100°C:ssa (E100)(kevät)	til.-%	45 ... 66	52	
" 100°C:ssa (E100)(talvi)	til.-%	48 ... 70	56	
" 180°C:ssa (E180)	til.-%	≥ 91	98	
Tislauksen loppupiste	°C	≤ 210	188	
Tislausjäännös	til.-%	≤ 2	< 2	
Höyrynpaine Reid				ASTM D 4953, EN 12
- kesä	kPa	60 ... 70	68	
- kevät	kPa	70 ... 80	78	
- talvi	kPa	80 ... 90	88	
VLI (höyrylukkoindeksi)				
- talvi		≤ 1200	1150	
Tiheys, 15°C	kg/m³	725 ... 770	745	ASTM D 4052
Rikki	p-%	≤ 0,04	0,02	ASTM D 4294
Kuparikorroosio		1	1	ISO 2160
Hartsi	mg/100 ml	≤ 5	< 1	EN 5
Hapetusaika	min	≥ 530	> 700	ASTM D 525
Bentseeni	til.-%	≤ 3	2	ASTM D 4053, EN 238
Happi	til.-%	2 ... 2,7	2,1	DIN 51413/5, DIN 51413/7, NM 246
Väri ja ulkonäkö	kirkas, ei kiinteitä epäpuhtauksia			ASTM D 4176

Tuote täyttää polttoaineverosta annetussa laissa 948/82 ja sen 2 § koskevassa muutoksessa (joulukuu 1992) esitetyt reformuloidulle bensiinille asetetut vaatimukset.

Tuotteet ovat jakelussa: kesä 1.4.- 30.9., kevät 15.2.- 30.4., talvi 1.9.-15.3.
Markkinointiyhtiöt vastaavat bensiinin lisäaineistuksesta, joka puhdistaa moottorin imujärjestelmää, suojaa korroosiolta ja estää kaasuttimen jäätymistä.
NM-numero viittaa Neste-menetelmään.
Spesifikaatiorajoihin liityvät kiistatapaukset ratkaistaan ISO 4259:n mukaan.

TIEDUSTELUT
Neste Öljy
Öljytuoteneuvonta
PL 310
06101 PORVOO

Neste Öljy
Tekninen palvelu
PL 20
02151 ESPOO

NESTE

9.2.1996

TUOTETIEDOTE	PRODUKTDATA	PRODUCT DATA SHEET
REFORMULOITU BENSIINI 95ER	REFORMULERAD BENSIN 95ER	REFORMULATED GASOLINE 95ER
LYIJYTÖN	BLYFRI	UNLEADED
OKTAANILUKU 95	OKTANTAL 95	OCTANE NUMBER 95
LYHENNE BE95ER	FÖRKORTNING BE95ER	ABBREVIATION BE95ER

	Yksikkö Enhet Unit	Laaturaja Kvalitetskrav Specification	Tyypillinen arvo Typvärde Typical analysis	Määritysmenetelmä Testmetod Test method
Oktaaniluku Oktantal Octane number	RON MON	≥ 95,0 ≥ 85,0	95,2 85,1	ISO 5164 ISO 5163
Lyijy Blyhalt Lead content	g/l	≤ 0,003	< 0,003	ASTM D 3237, EN 237
Tislaus, Destillation, Distillation Haihtunut, Förångat, Evaporated: 70 °C:ssa, vid 70 °C, at 70 °C				ASTM D 86, ISO 3405
E70 (kesä, sommar, summer)	til.-%	20 ... 40	25	
E70 (kevät, vår, spring)	vol.-%	23 ... 43	30	
E70 (talvi, vinter, winter)	% v/v	25 ... 45	32	
100 °C:ssa, vid 100 °C, at 100 °C				
E100 (kesä, sommar, summer)	til.-%	43 ... 63	55	
E100 (kevät, vår, spring)	vol.-%	45 ... 66	57	
E100 (talvi, vinter, winter)	% v/v	48 ... 70	60	
180 °C:ssa vid 180 °C at 180 °C	til.-% vol.-% % v/v	≥ 91	> 96	
Tislauksen loppupiste Slutkokpunkt Final boiling point	°C	≤ 210	190	
Tislausjäännös Destillationsrest Distillation residue	til.-% vol.-% % v/v	≤ 2	< 2	
Tiheys, 15 °C Densitet vid15 °C Density at 15 °C	kg/m^3	725 ... 770	745	ASTM D 4052
Höynpaine Reid Ångtryck Reid Reid vapour pressure				
– kesä, sommar, summer	kPa	60 ... 70	68	EN 12
– kevät, vår, spring	kPa	70 ... 80	78	
– talvi, vinter, winter	kPa	80 ... 90	88	
VLI (höyrylukkoindeksi) VLI (total flyktighet) VLI (vapour lock index)				
– kesä, sommar, summer		≤ 1000	900	EN 228
– kevät, vår, spring		≤ 1100	1000	
– talvi, vinter, winter		≤ 1200	1100	

Käänna Vänd See overleaf

BE95ER	Yksikkö Enhet Unit	Laaturaja Kvalitetskrav Specification	Tyypillinen arvo Typvärde Typical analysis	Määritysmenetelmä Testmetod Test method
Rikki Svavelhalt Sulphur content	p-% mass-% % m/m	≤ 0,01	< 0,01	ASTM D 4294
Kuparikorroosio Kopparkorrosion Copper strip corrosion		1	1	ASTM D 130, ISO 2160
Hartsi Hartstal Existent gum content	mg/100 ml	≤ 4	< 1	EN 5
Hapetusaika Oxidationsstabilitet Oxidation stability	min	≥ 530	> 700	ASTM D 525
Bentseeni Bensenhalt Benzene content	til.-% vol.-% % v/v	≤ 1,0	< 1,0	ASTM D 4053
Happipitoisuus Syre Oxygen	p-% mass-% % m/m	2,0 ... 2,7	2,1	DIN 51413/5 DIN 51413/7, NM 246
Väri ja ulkonäkö Färg och utseende Appearance		kirkas, ei kiinteitä epäpuhtauksia klar clear and bright		ASTM D 4176

Tuote täyttää nestemäisten polttoaineiden valmisteverosta annetun lain 1472/94 2 §:ssä esitetyt reformuloidulle bensiinille asetetut vaatimukset.	Produkten uppfyller kraven för reformulerad bensin som fastställts i lag om accis på flytande bränslen 1472/94.	The product meets the requirements for reformulated gasoline set by Finnish authorities.
Tuote täyttää SFS-EN 228 vaatimukset.	Produkten uppfyller SFS-EN 228.	The product meets SFS-EN 228.
Tuotteet ovat jakelussa: kesä 1.4.-30.9., kevät 15.2.-30.4., talvi 1.9.-15.3.	Produkten distribueras: sommar 1.4-30.9, vår 15.2-30.4, vinter 1.9-15.3.	The products will be delivered: summer 1.4.-30.9., spring 15.2.-30.4., winter 1.9.-15.3.
Markkinointiyhtiöt vastaavat bensiinin lisäaineistuksesta.	Marknadsförningsbolagen ansvarar för de tillsatsmedlen.	The Oil Marketing Companies are responsible for the additives.
Määritysmenetelmien epätarkkuuteen liittyvät kysymykset ratkaistaan ISO 4259:n mukaan.	Konflikter beträffande testmetodernas inexakthet avgörs enligt ISO 4259.	In case of dispute on the precision of test methods, the procedures described in ISO 4259 shall be used.
Käyttöturvallisuuden osalta viittaamme Neste Oy:n julkaisemiin käyttöturvallisuustiedotteisiin sekä tuotteiden käyttöä koskeviin oppaisiin.	Angående skyddsinformation hänvisar vi till skyddsinformationsblad publicerade av Neste Oy samt till produkternas bruksanvisningar.	Concerning safe use of the products, we refer to the Safety Data Sheets and User's Guides published by Neste Oy.
TIEDUSTELUT NESTE OY, ÖLJYNJALOSTUS Kotimaan jalostamomyynti PL 20 02151 ESPOO	FÖRFRÅGNINGAR NESTE OY, OLJERAFFINERING Försäljning, Finland PB 20 FIN-02151 ESBO, Finland	INQUIRIES NESTE OY, OIL REFINING Sales, Finland P.O. Box 20 FIN-02151 ESPOO, Finland
Puhelin (90) 450 4006	Telefon (90) 450 4006 eller +358 0 450 4006	Phone +358 0 450 4006

Käänna Vänd See overleaf

Appendix 4

CALCULATION PROCEDURES FOR EMISSIONS

1. Regulated components from bag samples

The rules and regulations that stipulate limit values for the emissions designate also procedures how the emissions should be measured and calculated. The following is an outline of these procedures that were adopted for the calculation of the regulated components from bag samples. The method used was chosen according to the driving schedule used, i.e. US method was used in connection to the US FTP75 cycle, and vice versa, European method for tests with EC cycles, althoug no major difference in these procedures exists. The main difference is in calculating the total test value, which is a weighted average for the FTP75 and a normal, unweighted aggregate in the EC procedure.

1.1 Total test average

$$\Sigma M_{ECE} = \frac{m_1 \times d_1 + m_2 \times d_2 + m_3 \times d_3}{d_1 + d_2 + d_3} \qquad (1)$$

$$\Sigma M_{FTP} = 0.43 \times \frac{m_1 \times d_1 + m_2 \times d_2}{d_1 + d_2} + 0.57 \times \frac{m_2 \times d_2 + m_3 \times d_3}{d_2 + d_3} \qquad (2)$$

where

ΣM_{ECE}	is	total test result for EC test, in [g/km]
ΣM_{FTP}		total test result for FTP test, in [g/km]
m_n		emission for bag $_n$ n = 1,2,3 in [g]
d_n		driven distance during bag $_n$ collection, n = 1,2,3, in [km]

1.2 Gaseous emissions, bag sample

$$m = \frac{V_{mix} \times \rho \times kH \times C \times 10^{-3}}{d} \qquad (3)$$

where

m	is	emission in bag sample, in [g/km]
V_{mix}		diluted exhaust volme (from CVS); corrected to NTP, in [m^3]
ρ		density for the given component, in [g/dm^3], *see list below*
kH		humidity correction factor, only for NO_X, *see* (6)
C		corrected concentration of the component, in [ppm], *see* (4)
d		distance driven during bag sampling, in [km]

The following density values were used for calculation of the regulated emissions:

CO	1.25 g/l	
HC	1.857 g/l	[= 3 x 0.619 g/l, FID calibrated with C_3 (propane)]
NO_X	2.05 g/l	[= NO_2]

1.3 Corrected concentrations

$$C = C_e - C_d \times (1 - 1/Df) \qquad (4)$$

where

C	is	corrected concentration, in [ppm] or [%]
C_e		concentration of the component in exhaust sample, in [ppm] or [%]
C_d		concentration of the component in dilution air sample, in [ppm] or [%]
df		dilution factor, *see* (5)

1.4 Dilution factor

$$df = 13.4 / C_{CO2} + (C_{CO} + C_{HC}) \times 10^{-4} \quad (5)$$

where

C_{CO2} is concentration of CO_2 in exhaust sample, in [%]
C_{CO} concentration of CO in exhaust sample, in [%]
C_{HC} concentration of HC in exhaust sample, in [ppm]

Note: this formula is applicable to petrol fuel only; other fuels use different coefficient

1.5 Humidity correction factor for NO_X

$$kH = \frac{1}{1 - (0.0329 \times (H - 10.71))} \quad (6)$$

where

H is absolute humidity in test cell, in [$gH_2O/kg_{dry\ air}$], *see* (7)

1.6 Absolute humidity

$$H = \frac{6.211 \times R_a \times P_d}{P_a + P_d \times R_a \times 10^{-2}} \quad (7)$$

where

R_a is relative humidity in test cell, in [%]
P_d saturated water vapor pressure in test cell temperature, in [kPa], *see* (8)
P_a barometric pressure, in [kPa]

1.7 Water vapor pressure

$$P_d = 0.1 \times e^{(Y)} \times 10^3 \quad (8)$$

and $Y = 11.78 \times (T - 99.64) / (T + 230)$

where

T is temperature in test cell, in [°C]

2. Unregulated compounds from bag samples

A number of unregulated compounds, mainly speciated hydrocarbons, were determined from the bag samples. The following procedures were adopted for this calculation.

$$m_{HC} = C_{SHC} \times V_{mix} \times M_{SHC} / 22.4 / d \quad (9)$$

where

m_{HC} is emission of the given hydrocarbon species, in [g/km]
C_{SHC} is corrected concentration of the HC species, in [ppm], *see* (10)
M_{SHC} molecular weight of the HC species, *see list below*
V_{mix} diluted exhaust volume (from CVS); corrected to NTP, in [m^3]
d distance driven during bag sampling, in [km]

$$C_{SHC} = C_{SHCe} - C_{SHCd} \times (1 - 1/df) \quad (10)$$

where

C_{SHC} is corrected concentration for HC species, in [ppm]
C_{SHCe} concentration of the HC species in exhaust sample, in [ppm]
C_{SHCd} concentration of the HC species in dilution air sample, in [ppm]
df dilution factor, *see* (5)

Concentrations C_{SHCe} and C_{SHCd} were determined by the GC/ChemStation software.

The following molecular weights were used for speciated hydrocarbons:

name of the species	chemical formula	molecular weight
methane	CH_4	16
ethane	C_2H_6	30
ethene	C_2H_4	28
propene	C_3H_6	42
iso-butene	C_4H_8	56
iso-pentane	C_5H_{12}	72
1,3-butadiene	C_4H_6	54
benzene	C_6H_6	78
toluene	C_7H_8	92
ethylbenzene	C_8H_{10}	106
m-,p-xylene	C_8H_{10}	106
o-xylene	C_8H_{10}	106

3. Continuous analysis and instantaneous values

Additionally, instantaneous emission output was calculated for a number of constituents, bith regulated and unregulated. The basic structure of the formulae to calculate instantaneous emissions was:

$$m_{poll} = C_{poll} \times 10^6 \times \rho_{poll} \times V_{exh} \quad (11)$$

where

m_{poll} is mass emission of the pollutant, in [g/s]
C_{poll} concentration of the pollutant, in [ppm]
ρ_{poll} density of the pollutant, in [g/dm^3]
V_{exh} volume flow of exhaust, in [dm^3/s] (*see* (12))

The list of densities (ρ_{poll}) used for different compounds has been listed in previous chapters 1. and 2.

Furthermore, instantaneous exhaust flow in CVS was determined from the average flow in CVS and instantaneous dilution ratio, determined by instantaneous CO_2 concentrations in raw exhaust, diluted sample and background. The formulaes used was as follows:

$$V_{exh} = V_{exh,\,CVS} \times (CO_{2,T} - CO_{2,B}) / CO_{2,\,Exh} \times 10^3 \quad (12)$$

and

$$V_{exh,\ CVS} = V_{exh,\ dill} / t_{bag} \quad (13)$$

where

$CO_{2,T}$	is	instantaneous CO_2 concentration in diluted sample, in [vol-%]
$CO_{2,B}$		background CO_2 concentration in dilution air sample, in [vol-%]
$CO_{2,\ Exh}$		instantaneous CO_2 concentration in raw exhaust, in [vol-%]
$V_{exh,\ CVS}$		average sample flow in CVS, in [dm^3/s]
$V_{exh,\ dill}$		sample amount per bag, in [m^3], corrected to NTP by the system
t_{bag}		sampling time per bag, in [s]

Appendix 5

STATISTICAL VARIATIONS IN THE MEASUREMENT RESULTS

This Appendix gives information about the statistical variations encountered within the measurement results at the laboratory of VTT Energy, where all the work discussed in this report has been accomplished. It shall also give an estimate, what would be the margin of error in the measurements of the regulated emission components. This is essential for the evaluation of the results in this study, in which, because of limited resources, basicly no duplicate or repeated tests has been run, which would have given basis for a direct statistical evaluation. Instead, the estimated margin of error must be used.

Table 1 list some of the characteristics of the data, which has been used to estimate the statistical variations and subsequent margin of error.

Table 1. Specifications for the data used in statistical analysis.

Engine Type	Fuel type	Cars	Tests per Car	Test Cycle	Temperature [°C]	Year
SI	CEC RF-08A-85	14	3	FTP75	+22	1994
SI	Various experim. fuels (4)	5	4	FTP75	+22	1995
SI	CEC RF-08A-85	15	3	FTP75	+22	1995
SI	CEC RF-08A-85	15	3	FTP75	+22	1996
CI	Various experim. fuels (4)	4	2	FTP75	+22 (-7)*	1995
CI	Experimental Fuel	2	2	FTP75	+22 (-7)*	1996
Total of Case Entries for FTP75		81				
SI	Commercial & CEC RF	3	2	NEDC	-15, -7, 0, 15, 22	1993
CI	Various experim. fuels (14)	3	2 (7)**	NEDC	+22	1995
CI	Experimental Fuel	2	2	NEDC	+22, -7	1996
Total of Case Entries for NEDC		41				

* only a subset of fleet ** one vehicle only

For the test data described in Table 1, a statistical analysis has been made employing the functions @AVERAGE and @STDEVP provided in Microsoft® Excel®. The attached sheets contain the data and its analysis along with graphical representation. Table 2 summarises the outcome of the analysis for both of the main test types (i.e. driving cycles).

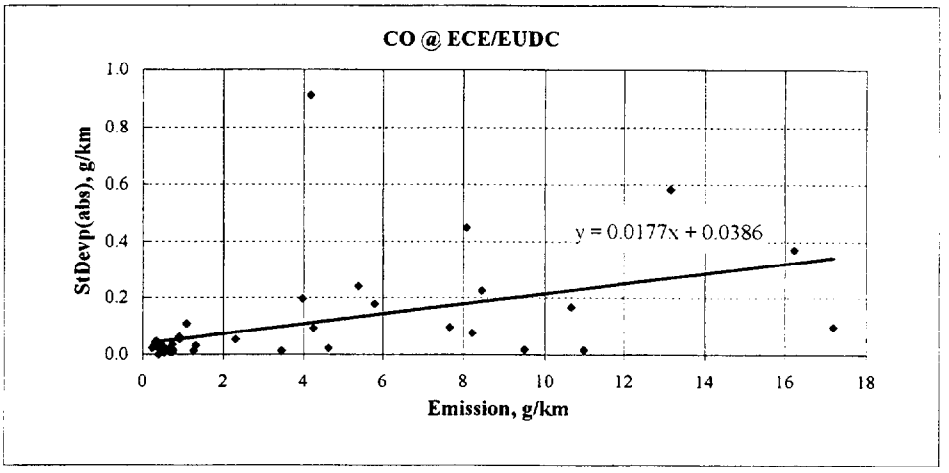
Table 2. Summary of the statistical analysis for main test types.

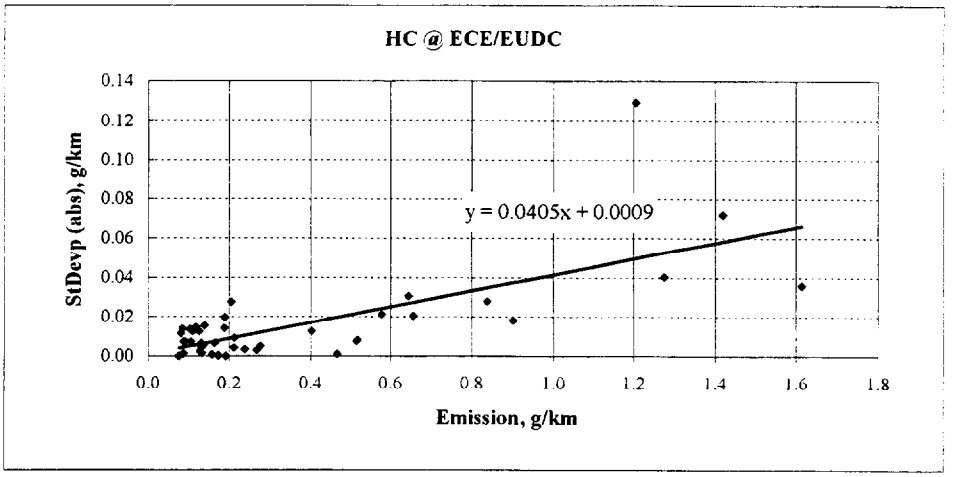
Component / Test Case	Average Margin of Error (=StDEVp [%])			
	CO	HC	NOx	PM
FTP75	6.6	6.4	5.7	3.4
NEDC	4.1	5.3	3.9	3.9

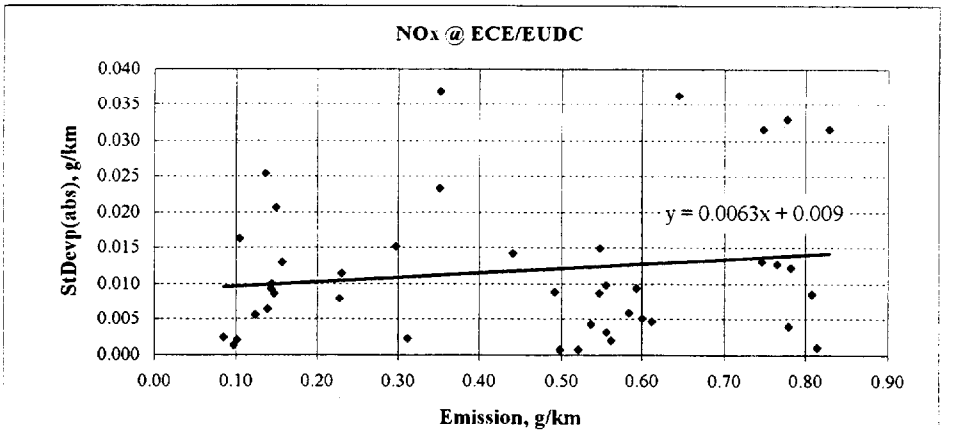
A general estimate was made, based on the values presented in Table 2, that for the results achieved in FTP75 type of test, the average margin of error for the gaseous emissions would be in the order of ± 6 % of the nominal value. Furthermore, for results in the ECE/NEDC type of tests the average margin of error could be set to a slightly lower level, ± 4 % for CO and NO_x and ± 5 % for HC. However, as the number of test cases for NEDC test is only half of the number associated with FTP75, and as the tests are using the same equipment and should follow similar procedures, there should be no major differences between them. Therefore, a uniform figure of ± 6 % is used also for the estimate of the margin of error even in the case of NEDC tests.

ECE/EUDC = NEDC

							Averages				Sidevp, abs				Sidevp, %			
tests	type	make/ID#	fuel	source	°C test	year	COg/km	HCg/km	NOxg/km	PMg/km	COg/km	HCg/km	NOxg/km	PMg/km	CO	HC	NOx	PM
2	PETROL	NISSAN	95E (European export)	TNO93	-15	1993	9.520	1.616	0.352		0.818	0.036	0.037		8.2	2.2	10.5	
2	PETROL	RENAULT	95E (European export)	TNO93	-15	1993	16.241	1.419	0.136		0.372	0.072	0.025		2.3	5.1	18.7	
2	PETROL	VOLKSWAGEN	95E (European export)	TNO93	-15	1993	17.199	1.276	0.101		0.099	0.041	0.002		0.6	3.2	2.0	
2	PETROL	FIAT	BE95	TNO93	-7	1993	8.233	0.840	0.228		0.077	0.028	0.008		0.9	3.3	3.5	
2	PETROL	NISSAN	95E (European export)	TNO93	-7	1993	8.090	1.207	0.441		0.448	0.129	0.014		5.5	10.7	3.2	
2	PETROL	RENAULT	95E (European export)	TNO93	-7	1993	13.167	0.902	0.142		0.585	0.018	0.009		4.4	2.0	6.5	
2	PETROL	VOLKSWAGEN	95E (European export)	TNO93	-7	1993	10.665	0.579	0.104		0.168	0.021	0.016		1.6	3.7	15.6	
2	PETROL	NISSAN	95E (European export)	TNO93	0	1993	5.708	0.644	0.312		0.180	0.031	0.002		3.1	4.8	0.7	
2	PETROL	RENAULT	95E (European export)	TNO93	0	1993	10.980	0.656	0.085		0.016	0.021	0.002		0.1	3.1	2.8	
2	PETROL	VOLKSWAGEN	95E (European export)	TNO93	0	1993	8.465	0.402	0.097		0.227	0.013	0.001		2.7	3.2	1.4	
2	PETROL	FIAT	BE95	TNO93	7	1993	5.388	0.516	0.231		0.241	0.008	0.011		4.5	1.5	4.9	
2	PETROL	NISSAN	CEC-RF-08-A-85	TNO93	7	1993	3.976	0.518	0.351		0.197	0.008	0.023		5.0	1.6	6.6	
2	PETROL	RENAULT	CEC-RF-08-A-85	TNO93	7	1993	7.670	0.468	0.149		0.096	0.001	0.021		1.3	0.3	13.9	
2	PETROL	VOLKSWAGEN	CEC-RF-08-A-85	TNO93	7	1993	4.246	0.212	0.138		0.092	0.009	0.006		2.1	4.3	4.6	
2	PETROL	NISSAN	CEC-RF-08-A-85	TNO93	15	1993	1.325	0.211	0.297		0.031	0.004	0.015		2.4	2.0	5.1	
2	PETROL	RENAULT	CEC-RF-08-A-85	TNO93	15	1993	4.636	0.276	0.123		0.022	0.005	0.006		0.5	1.8	4.5	
2	PETROL	VOLKSWAGEN	CEC-RF-08-A-85	TNO93	15	1993	3.447	0.173	0.156		0.012	0.000	0.013		0.4	0.1	8.3	
2	PETROL	RENAULT	CEC-RF-08-A-85	TNO93	22	1993	4.175	0.238	0.146		0.910	0.003	0.009		21.8	1.4	5.9	
2	PETROL	VOLKSWAGEN	CEC-RF-08-A-85	TNO93	22	1993	2.306	0.137	0.144		0.053	0.006	0.010		2.3	4.1	6.9	
2	DIESEL	V4	DIK 93/222	107Y-8	22 °C	1994	0.701	0.188	0.556	0.110	0.015	0.020	0.010	0.012	2.1	10.6	1.8	11.1
2	DIESEL	V5	DIK 93/222	107Y-8	22 °C	1994	0.415	0.104	0.645	0.094	0.019	0.014	0.036	0.006	4.6	13.3	5.6	6.7
2	DIESEL	V4	DIKC 94/237	107Y-8	22 °C	1994	0.543	0.128	0.547	0.079	0.014	0.003	0.009	0.006	2.6	2.0	1.6	7.6
2	DIESEL	V5	DIKC 94/237	107Y-8	22 °C	1994	0.301	0.081	0.584	0.065	0.036	0.012	0.006	0.002	11.8	14.3	1.0	2.4
2	DIESEL	V4	DITC 94/149	107Y-8	22 °C	1994	0.577	0.118	0.536	0.067	0.012	0.015	0.004	0.002	2.1	12.6	0.8	2.8
2	DIESEL	V5	DITC 94/149	107Y-8	22 °C	1994	0.401	0.092	0.612	0.074	0.000	0.007	0.005	0.004	0.1	8.1	0.8	4.7
2	DIESEL	V4	DITC+sk	107Y-8	22 °C	1994	0.551	0.139	0.521	0.066	0.022	0.016	0.001	0.001	4.0	11.2	0.1	1.3
2	DIESEL	V5	DITC+sk	107Y-8	22 °C	1994	0.343	0.085	0.601	0.073	0.048	0.014	0.005	0.000	14.1	16.7	0.8	0.3
2	DIESEL	V4	MK1 94/138	107Y-8	22 °C	1994	0.532	0.110	0.491	0.059	0.026	0.013	0.009	0.008	4.9	11.6	1.8	12.7
2	DIESEL	V5	MK1 94/138	107Y-8	22 °C	1994	0.359	0.088	0.562	0.070	0.031	0.001	0.002	0.005	8.7	1.4	0.3	6.9
2	DIESEL	TOYOTA		NEDI96	22 °C	1996	0.343	0.075	0.498	0.066	0.005	0.000	0.001	0.000	0.9	0.2	0.1	0.5
2	DIESEL	TOYOTA		NEDI96	-7 °C	1996	0.681	0.106	0.547	0.076	0.018	0.007	0.015	0.002	2.7	7.0	2.7	2.4
2	DIESEL	SEAT		NEDI96	22 °C	1996	0.440	0.088	0.556	0.042	0.036	0.007	0.003	0.000	8.1	8.4	0.6	0.9
2	DIESEL	SEAT		NEDI96	-7 °C	1996	0.736	0.164	0.593	0.050	0.034	0.007	0.009	0.001	4.6	4.1	1.6	2.6
7	DIESEL	Transit	REFLS	JOU2-0098	22 °C	1994	0.926	0.187	0.778	0.101	0.053	0.014	0.033	0.011	5.7	7.6	4.2	10.7
2	DIESEL	Transit	J11	JOU2-0098	22 °C	1994	0.682	0.126	0.749	0.109	0.008	0.013	0.032	0.003	1.2	10.1	4.2	2.9
2	DIESEL	Transit	J12	JOU2-0098	22 °C	1994	1.104	0.204	0.765	0.097	0.109	0.028	0.013	0.000	9.9	13.6	1.7	0.3
2	DIESEL	Transit	J3	JOU2-0098	22 °C	1994	0.233	0.192	0.783	0.087	0.022	0.000	0.012	0.006	9.6	0.0	1.6	7.4
2	DIESEL	Transit	J4	JOU2-0098	22 °C	1994	1.275	0.267	0.808	0.109	0.013	0.003	0.009	0.001	1.0	1.1	1.1	0.5
2	DIESEL	Transit	J5	JOU2-0098	22 °C	1994	0.724	0.131	0.814	0.114	0.009	0.004	0.001	0.003	1.3	3.3	0.1	2.2
2	DIESEL	Transit	J13	JOU2-0098	22 °C	1994	0.911	0.157	0.747	0.093	0.062	0.001	0.013	0.002	6.8	0.6	1.8	2.1
2	DIESEL	Transit	J14	JOU2-0098	22 °C	1994	0.550	0.132	0.829	0.096	0.008	0.002	0.032	0.000	1.4	1.3	3.8	0.1
2	DIESEL	Transit	J17	JOU2-0098	22 °C	1994	0.766	0.131	0.780	0.082	0.015	0.006	0.004	0.001	2.0	5.0	0.5	1.4
DATA ANALYSIS		Max.					17.199	1.616	0.829	0.114	0.910	0.129	0.037	0.012	21.8	16.7	18.7	12.7
		@AVG					3.810	0.366	0.444	0.082	0.106	0.016	0.012	0.003	4.1	5.3	3.9	3.9
CONST.OF INACCURACY		a									0.0177	0.0405	0.0063	0.0539	-0.2673	-0.0174	-0.0321	0.0006
		b									0.0386	0.0009	0.0090	-0.0011	4.9015	0.4582	0.5693	0.0795
		min					0	0	0	0	0	0	0	0				
		max					17.199	1.616	0.829	0.114	0.343854	0.066384	0.014194	0.005038				
INACCURACY OF EQUIPMENT		a									0.11484	0.116045	0.159329	0.053445				
		b									0.016586	0.010162	-0.0497	0.000115				
		min					0	0	0	0	0	0	0	0				
		max					17.199	1.616	0.829	0.114	1.991748	0.197652	0.082397	0.006205				
TOTAL ERROR		min					0	0	0	0	0	0	0	0				
		max					17.199	1.616	0.829	0.114	2.335602	0.264036	0.096591	0.011243				


CO @ ECE/EUDC
StDevp(abs), g/km
Emission, g/km
y = 0.0177x + 0.0386
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10
12
14
16
18


HC @ ECE/EUDC
StDevp (abs), g/km
Emission, g/km
y = 0.0405x + 0.0009
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8


NOx @ ECE/EUDC
StDevp(abs), g/km
Emission, g/km
y = 0.0063x + 0.009
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90

FTP75

							Averages				Stdevp, abs				Stdevp, %			
tests	type	make/ID#	fuel	source	°C test	year	COg/km	HCg/km	NOxg/km	PMg/km	COg/km	HCg/km	NOxg/km	PMg/km	CO	HC	NOx	PM
4	PETROL	BMW	EURO	105Y-4	22 °C	1995	0.733	0.124	0.118		0.056	0.012	0.006		7.7	9.5	5.2	
4	PETROL	BMW	REFO	105Y-4	22 °C	1995	0.532	0.101	0.145		0.079	0.002	0.004		14.8	2.1	3.1	
4	PETROL	BMW	REFO2	105Y-4	22 °C	1995	0.676	0.111	0.120		0.048	0.005	0.010		7.1	4.6	8.2	
4	PETROL	BMW	CARB	105Y-4	22 °C	1995	0.718	0.105	0.143		0.088	0.010	0.009		12.2	9.7	6.2	
4	PETROL	CHRYSLER	EURO	105Y-4	22 °C	1995	0.912	0.108	0.114		0.089	0.006	0.014		9.7	5.6	12.6	
4	PETROL	CHRYSLER	REFO	105Y-4	22 °C	1995	0.473	0.079	0.108		0.057	0.011	0.006		12.0	14.2	5.2	
4	PETROL	CHRYSLER	REFO2	105Y-4	22 °C	1995	0.474	0.080	0.112		0.045	0.007	0.011		9.5	8.4	9.6	
4	PETROL	CHRYSLER	CARB	105Y-4	22 °C	1995	0.505	0.089	0.096		0.067	0.003	0.006		13.2	3.9	6.6	
4	PETROL	HONDA	EURO	105Y-4	22 °C	1995	0.989	0.128	0.119		0.059	0.010	0.008		6.0	7.9	6.6	
4	PETROL	HONDA	REFO	105Y-4	22 °C	1995	0.625	0.087	0.105		0.042	0.007	0.006		6.6	8.3	5.9	
4	PETROL	HONDA	REFO2	105Y-4	22 °C	1995	0.746	0.085	0.088		0.073	0.011	0.006		9.7	13.3	7.2	
4	PETROL	HONDA	CARB	105Y-4	22 °C	1995	0.658	0.069	0.087		0.013	0.005	0.006		2.0	6.6	6.7	
4	PETROL	VOLVO	EURO	105Y-4	22 °C	1995	0.672	0.102	0.067		0.057	0.001	0.012		8.4	1.4	18.3	
4	PETROL	VOLVO	REFO	105Y-4	22 °C	1995	0.528	0.086	0.104		0.031	0.009	0.014		5.8	10.9	13.3	
4	PETROL	VOLVO	REFO2	105Y-4	22 °C	1995	0.648	0.091	0.063		0.049	0.005	0.007		7.6	6.0	11.8	
4	PETROL	VOLVO	CARB	105Y-4	22 °C	1995	0.699	0.104	0.083		0.025	0.008	0.007		3.6	7.3	8.2	
3	PETROL	UGH-243	CEC RF-08-A-85	ANH95	22 °C	1995	0.631	0.044	0.311		0.081	0.004	0.012		12.8	9.4	4.0	
3	PETROL	GBJ-310	CEC RF-08-A-85	ANH95	22 °C	1995	1.267	0.080	0.200		0.111	0.002	0.022		8.8	2.0	10.9	
3	PETROL	NAX-112	CEC RF-08-A-85	ANH95	22 °C	1995	1.636	0.093	0.211		0.218	0.006	0.009		13.3	6.0	4.1	
3	PETROL	BGL-416	CEC RF-08-A-85	ANH95	22 °C	1995	0.691	0.121	0.196		0.117	0.022	0.004		17.0	18.5	1.8	
3	PETROL	BGR-556	CEC RF-08-A-85	ANH95	22 °C	1995	0.649	0.105	0.235		0.035	0.004	0.015		5.3	3.8	6.5	
3	PETROL	ZGE-481	CEC RF-08-A-85	ANH95	22 °C	1995	0.742	0.118	0.194		0.050	0.005	0.011		6.8	4.6	5.9	
3	PETROL	VGI-335	CEC RF-08-A-85	ANH95	22 °C	1995	0.994	0.084	0.123		0.016	0.005	0.012		1.6	5.5	9.5	
3	PETROL	TGM-377	CEC RF-08-A-85	ANH95	22 °C	1995	1.054	0.085	0.164		0.078	0.006	0.007		7.4	7.5	4.3	
3	PETROL	VGH-944	CEC RF-08-A-85	ANH95	22 °C	1995	1.050	0.081	0.120		0.088	0.003	0.012		8.4	3.3	10.1	
3	PETROL	RGB-498	CEC RF-08-A-85	ANH95	22 °C	1995	0.332	0.048	0.113		0.015	0.002	0.003		4.5	4.4	2.8	
3	PETROL	LGR-941	CEC RF-08-A-85	ANH95	22 °C	1995	0.216	0.041	0.072		0.024	0.006	0.005		11.3	14.4	7.3	
3	PETROL	ZFS-533	CEC RF-08-A-85	ANH95	22 °C	1995	0.551	0.055	0.184		0.005	0.006	0.004		0.9	10.3	2.4	
3	PETROL	FBU-785	CEC RF-08-A-85	ANH95	22 °C	1995	1.277	0.134	0.040		0.063	0.014	0.003		4.9	10.3	6.7	
3	PETROL	AGN-169	CEC RF-08-A-85	ANH95	22 °C	1995	0.574	0.090	0.081		0.004	0.003	0.003		0.6	2.8	3.6	
3	PETROL	BGP-920	CEC RF-08-A-85	ANH95	22 °C	1995	0.647	0.086	0.046		0.032	0.001	0.003		4.9	0.6	6.7	
4	PETROL	FORD	EURO	105Y-4	22 °C	1995	16.507	2.220	1.473		0.711	0.021	0.069		4.3	0.9	4.7	
4	PETROL	FORD	REFO	105Y-4	22 °C	1995	12.030	2.092	1.511		0.098	0.073	0.028		0.8	3.5	1.8	
4	PETROL	FORD	REFO2	105Y-4	22 °C	1995	13.097	2.144	1.571		1.349	0.077	0.068		10.3	3.6	4.3	
4	PETROL	FORD	CARB	105Y-4	22 °C	1995	14.885	2.203	1.435		0.431	0.063	0.051		2.9	2.8	3.6	
3	PETROL	AGC-718	CEC RF-08-A-85	ANH94	22 °C	1994	1.038	0.108	0.132		0.110	0.007	0.024		10.6	6.5	17.9	
3	PETROL	LFX-459	CEC RF-08-A-85	ANH94	22 °C	1994	1.781	0.224	0.215		0.110	0.017	0.014		6.2	7.6	6.7	
3	PETROL	TFS-422	CEC RF-08-A-85	ANH94	22 °C	1994	1.253	0.115	0.212		0.152	0.009	0.015		12.1	8.0	7.3	
3	PETROL	KFU-947	CEC RF-08-A-85	ANH94	22 °C	1994	1.016	0.112	0.198		0.019	0.012	0.003		1.9	10.8	1.4	
3	PETROL	KFU-960	CEC RF-08-A-85	ANH94	22 °C	1994	1.158	0.132	0.218		0.040	0.009	0.026		3.4	7.2	11.7	
3	PETROL	FAT-103	CEC RF-08-A-85	ANH94	22 °C	1994	2.177	0.150	0.550		0.095	0.006	0.021		4.4	4.1	3.8	
3	PETROL	OFR-981	CEC RF-08-A-85	ANH94	22 °C	1994	1.936	0.147	0.580		0.122	0.002	0.039		6.3	1.3	6.7	
3	PETROL	TFN-594	CEC RF-08-A-85	ANH94	22 °C	1994	3.419	0.242	0.453		1.570	0.067	0.082		45.9	27.5	18.1	
3	PETROL	KFY-320	CEC RF-08-A-85	ANH94	22 °C	1994	1.722	0.128	0.275		0.219	0.011	0.022		12.7	8.2	8.0	
4	PETROL	SFR-410	CEC RF-08-A-85	ANH94	22 °C	1994	3.008	0.159	0.256		0.158	0.009	0.013		5.3	5.5	5.0	
3	PETROL	TFL 954	CEC RF-08-A-85	ANH94	22 °C	1994	1.677	0.142	0.163		0.353	0.024	0.020		21.0	17.0	12.1	
3	PETROL	MKB-375	CEC RF-08-A-85	ANH94	22 °C	1994	0.914	0.147	0.090		0.048	0.004	0.003		5.3	2.6	3.4	
3	PETROL	SJM-746	CEC RF-08-A-85	ANH94	22 °C	1994	1.371	0.168	0.144		0.073	0.001	0.008		5.4	0.8	5.6	
4	PETROL	YAG-746	CEC RF-08-A-85	ANH94	22 °C	1994	0.751	0.164	0.142		0.030	0.004	0.005		4.0	2.3	3.6	
3	PETROL	CBC-523	CEC RF-08-A-85	ANH96	22 °C	1996	1.762	0.091	0.278		0.068	0.001	0.029		3.9	1.5	10.5	
3	PETROL	GBJ-680	CEC RF-08-A-85	ANH96	22 °C	1996	1.468	0.082	0.334		0.059	0.003	0.014		4.0	3.9	4.1	

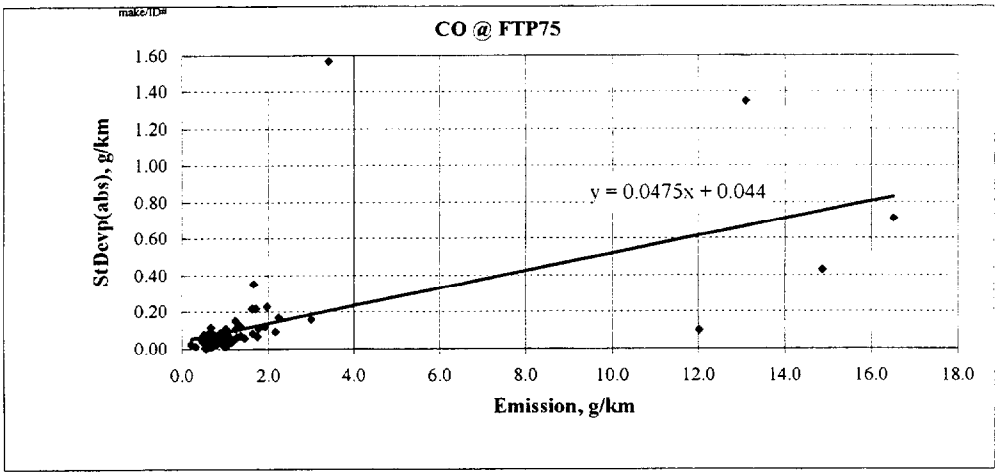
FTP75

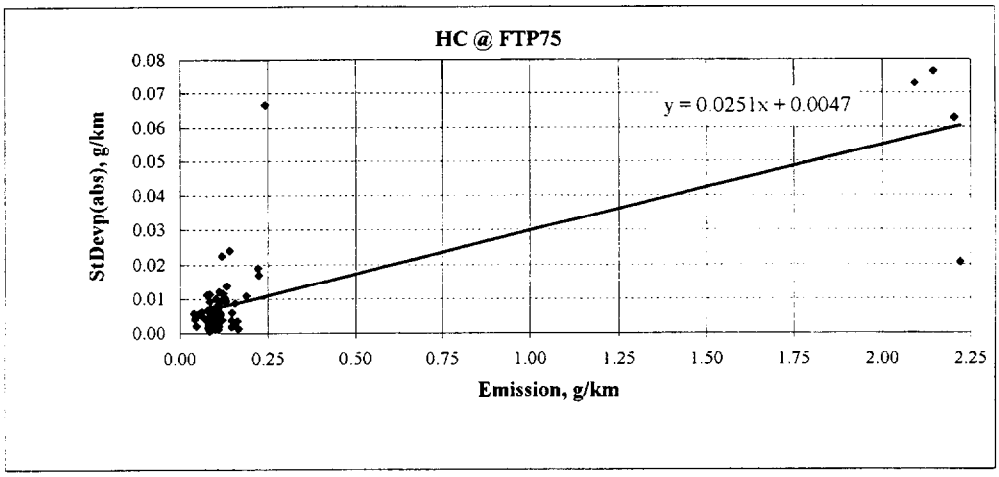
							Averages				Stdevp, abs				Stdevp, %			
tests	type	make/ID#	fuel	source	°C test	year	COg/km	HCg/km	NOxg/km	PMg/km	COg/km	HCg/km	NOxg/km	PMg/km	CO	HC	NOx	PM
3	PETROL	HGM-821	CEC RF-08-A-85	ANH96	22 °C	1996	1.359	0.091	0.179		0.135	0.002	0.025		9.2	2.7	14.1	
3	PETROL	EGH-177	CEC RF-08-A-85	ANH96	22 °C	1996	1.120	0.088	0.161		0.062	0.003	0.013		5.5	2.9	7.9	
3	PETROL	FBE-436	CEC RF-08-A-85	ANH96	22 °C	1996	1.179	0.111	0.168		0.039	0.001	0.014		3.3	1.1	8.5	
3	PETROL	LGL-642	CEC RF-08-A-85	ANH96	22 °C	1996	1.043	0.113	0.149		0.031	0.002	0.016		3.0	1.9	10.4	
3	PETROL	BGI-468	CEC RF-08-A-85	ANH96	22 °C	1996	1.644	0.190	0.231		0.086	0.011	0.006		5.2	5.8	2.6	
3	PETROL	GAT-672	CEC RF-08-A-85	ANH96	22 °C	1996	2.246	0.221	0.285		0.169	0.019	0.018		7.5	8.6	6.4	
3	PETROL	MFX-112	CEC RF-08-A-85	ANH96	22 °C	1996	1.985	0.158	0.331		0.229	0.003	0.011		11.5	1.9	3.5	
3	PETROL	YBA-731	CEC RF-08-A-85	ANH96	22 °C	1996	0.824	0.088	0.278		0.024	0.005	0.010		2.9	5.5	3.5	
3	PETROL	YBA-758	CEC RF-08-A-85	ANH96	22 °C	1996	1.049	0.114	0.250		0.017	0.003	0.006		1.6	3.1	2.6	
3	PETROL	ZGJ-887	CEC RF-08-A-85	ANH96	22 °C	1996	0.653	0.063	0.104		0.073	0.006	0.004		11.2	9.9	4.3	
3	PETROL	CBM-956	CEC RF-08-A-85	ANH96	22 °C	1996	0.710	0.122	0.443		0.011	0.004	0.007		1.5	3.2	1.5	
3	PETROL	FBK-230	CEC RF-08-A-85	ANH96	22 °C	1996	0.631	0.090	0.209		0.011	0.001	0.011		1.7	1.0	5.5	
3	PETROL	UGF-296	CEC RF-08-A-85	ANH96	22 °C	1996	0.829	0.116	0.131		0.069	0.006	0.007		8.3	5.3	5.5	
2	DIESEL	V1	DIKR 95/289	107Y-8	22 °C	1995	0.218	0.026	0.471	0.094	0.017	0.008	0.008	0.005	8.0	30.5	1.6	4.9
2	DIESEL	V1	DIK 93/222	107Y-8	22 °C	1995	0.241	0.030	0.494	0.118	0.007	0.007	0.008	0.006	2.9	21.9	1.6	5.2
2	DIESEL	V1	DITC 95/235	107Y-8	22 °C	1995	0.194	0.039	0.483	0.078	0.000	0.001	0.012	0.004	0.2	2.8	2.4	4.6
2	DIESEL	V1	DIKC 95/290	107Y-8	22 °C	1995	0.209	0.029	0.490	0.090	0.021	0.002	0.008	0.002	9.9	5.9	1.7	1.7
2	DIESEL	V1	DIK 93/222	107Y-8	-7 °C	1995	0.483	0.073	0.503	0.139	0.016	0.003	0.012	0.006	3.2	4.0	2.4	4.3
2	DIESEL	V1	DIKC 95/290	107Y-8	-7 °C	1995	0.375	0.047	0.491	0.096	0.005	0.007	0.001	0.002	1.3	15.0	0.2	1.7
2	DIESEL	V3	DIK 93/222	107Y-8	22 °C	1995	0.793	0.124	0.556	0.130	0.026	0.006	0.030	0.004	3.3	4.6	5.3	2.8
2	DIESEL	V3	DIKC 95/290	107Y-8	22 °C	1995	0.674	0.115	0.542	0.099	0.008	0.000	0.010	0.006	1.2	0.2	1.8	5.6
2	DIESEL	V3	DIK 93/222	107Y-8	-7 °C	1995	0.849	0.127	0.559	0.166	0.000	0.000	0.000	0.000	0.0	0.0	0.0	0.0
2	DIESEL	V3	DIKC 95/290	107Y-8	-7 °C	1995	0.827	0.114	0.531	0.119	0.002	0.000	0.031	0.002	0.2	0.2	5.9	2.1
2	DIESEL	TOYOTA		NEDI96	+22	1996	0.704	0.114	0.514	0.071	0.016	0.002	0.010	0.001	2.2	1.8	1.9	1.5
2	DIESEL	TOYOTA		NEDI96	-7	1996	0.787	0.123	0.514	0.079	0.017	0.001	0.001	0.000	2.1	0.7	0.3	0.4
2	DIESEL	SEAT		NEDI96	+22	1996	0.101	0.047	0.583	0.049	0.006	0.002	0.013	0.002	5.8	4.2	2.2	3.2
2	DIESEL	SEAT		NEDI96	-7	1996	0.197	0.098	0.574	0.045	0.006	0.000	0.013	0.001	3.2	0.3	2.3	2.0
2	DIESEL	V2	DIKR 95/289	107Y-8	22 °C	1995	0.749	0.144	1.171	0.121	0.015	0.014	0.016	0.004	2.0	9.5	1.3	3.3
2	DIESEL	V2	DIK 93/222	107Y-8	22 °C	1995	0.781	0.151	1.146	0.127	0.021	0.008	0.010	0.002	2.7	5.0	0.8	1.9
2	DIESEL	V2	DITC 95/235	107Y-8	22 °C	1995	0.694	0.185	1.160	0.093	0.018	0.019	0.002	0.010	2.6	10.2	0.2	10.3
6	DIESEL	V2	DIKC 95/290	107Y-8	22 °C	1995	0.727	0.138	1.146	0.121	0.016	0.004	0.017	0.007	2.2	3.2	1.5	5.4

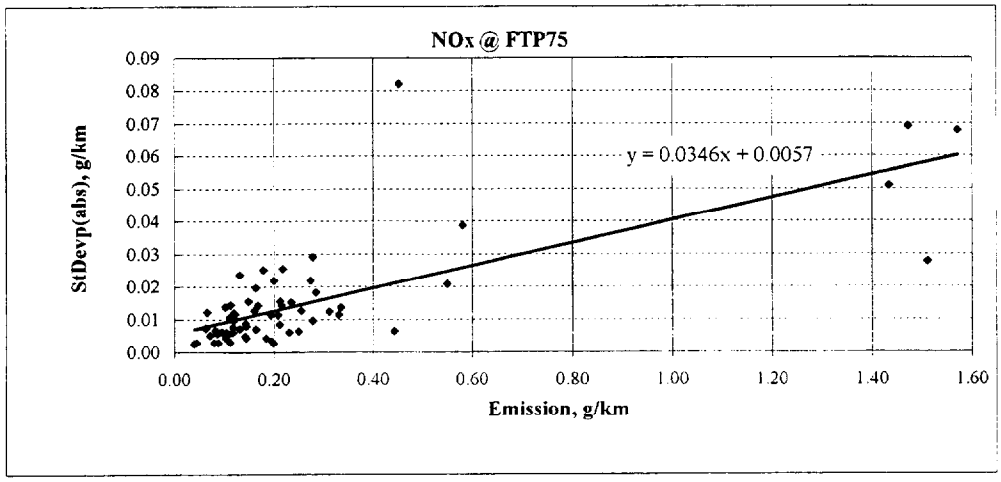
DATA ANALYSIS	Max.	16.507	2.220	1.571	0.166
	@AVG	1.594	0.208	0.354	0.102
CONST.OF INACCURACY	a				
	b				
	min	0	0	0	0
	max	16.507	2.220	1.571	0.166
INACCURACY OF EQUIPMENT	a				
	b				
	min	0	0	0	0
	max	16.507	2.220	1.571	0.166
TOTAL ERROR	min	0	0	0	0
	max	16.507	2.220	1.571	0.166

DATA ANALYSIS	Max.	1.570	0.077	0.082	0.010
	@AVG	0.107	0.009	0.014	0.003
CONST.OF INACCURACY	a	0.0490	0.0254	0.0215	0.0185
	b	0.0291	0.0041	0.0065	0.0015
	min	0	0	0	0
	max	0.838007	0.0605	0.040331	0.004613
INACCURACY OF EQUIPMENT	a	0.119393	0.121812	0.146388	0.056486
	b	0.01845	0.009945	-0.029454	0.00018
	min	0	0	0	0
	max	1.989248	0.280406	0.200559	0.009568
TOTAL ERROR	min	0	0	0	0
	max	2.827315	0.340906	0.24089	0.01418

DATA ANALYSIS	Max.	48.9	30.5	18.3	10.3
	@AVG	6.6	6.4	5.7	3.4
CONST.OF INACCURACY	a	0.0054	-0.0119	-0.0366	-0.0005
	b	1.5587	0.2839	0.5645	0.1037
	min				
	max				
INACCURACY OF EQUIPMENT	a				
	b				
	min				
	max				
TOTAL ERROR	min				
	max				


make/ID=
CO @ FTP75
StDevp(abs), g/km
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
y = 0.0475x + 0.044
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
Emission, g/km


HC @ FTP75
StDevp(abs), g/km
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
y = 0.0251x + 0.0047
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
Emission, g/km


NOx @ FTP75
StDevp(abs), g/km
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
y = 0.0346x + 0.0057
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
Emission, g/km

Appendix 6

INSTANTANEOUS CONCENTRATIONS AND EMISSION RATES

The continuous measurement of exhaust composition performed during the tests in the Co-Nordic study gave a possibility to study the differencies between cars during warm-up and to form an average for this sub-fleet at different ambient temperatures. Cars that were randomly picked to this sub-fleet were CN93B, CN93C, CN93D and CN93E, i.e. those that were tested even at -20 °C ambient. Because previous studies had quite solidly manifested that ambient temperature affets mainly on CO and HC emissions, this examination was limited to these pollutants only.

The outcome of this analysis of continuously measured data is presented here in several figures. As a general pattern, one figure displaying concentration and another one illustrating instantaneous emission output rate are given for both of the pollutants considered (CO and HC) as well as for each of the three test temperatures (+22, -7 and -20 °C).

As a rule these figures give traces individually for each of the four tested cars in this sub-fleet as well as an average calculated as an unweighted value from the instantaneous values of each individual car. The traces for individual cars are here merely representing the disperse of the performance. Therefore, the choise was made not to mark individual cars into the figures in an attempt to emphasize the average nature of the value and generalize this approach rather than pointing out the behaviour of any type of car in particular.

The final outcome of the analysis is presented in figures combining the average values from each of the temperatures. In these figures (Figures 7 and 8 for CO, Figures 15 and 16 for HC), 2nd order polynomials are fitted to the data to form a kind of simple mathemathical model of the situation.

If one would consider the differencies between individual cars, which is possible by viewing the detailed numbers in Appendix 2, one would see that they were rather sizeable even among this small four-car sub-fleet. For example, the best car was superior, i.e. emitting less CO, even at -20 °C than the poor-preforming ones at -7 °C. The probable cause for such a heavy enrichment that was seen in some of the cars was that the manufacturers had probably chosen such a fueling strategy in view of ensuring the driveability and avoid hesitation during warm-up running. Yet, no reports of any problems with driveability was recorded for any of the vehicles, not even for the one having very mild enrichment. This suggests that at least for some desings and manifold configurations it is possible to tune the engine to run with less enricment than currently employed in most of the cases.

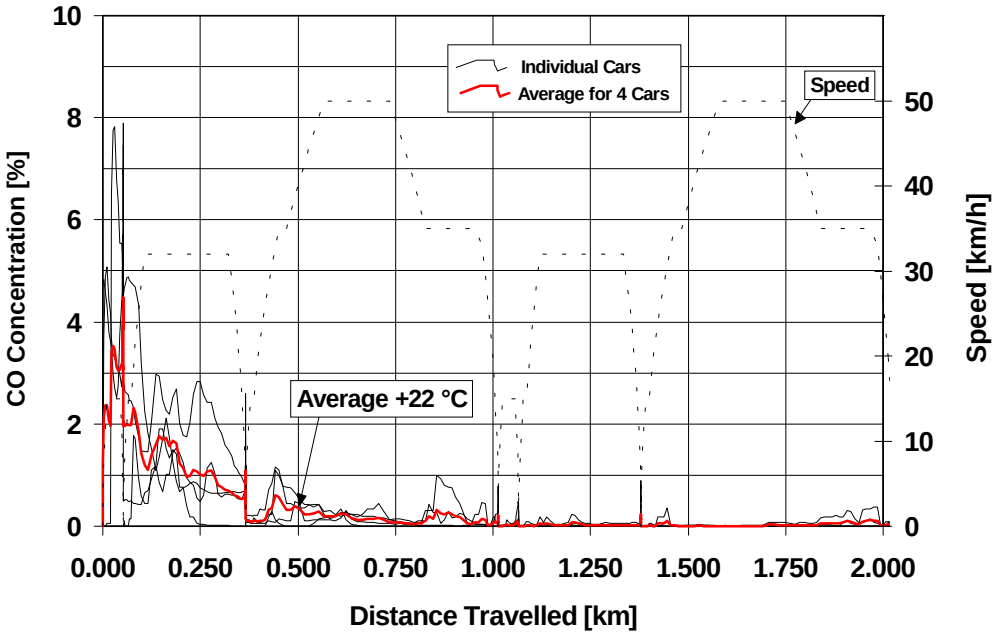


Figure 1 Concentration of CO as a function of distance travelled in ECE15 driving cycle (start-up modified, no 40 s idle) at +20 °C ambient temperature for individual cars as an average for this four car sub-fleet in the Co-Nordic study.

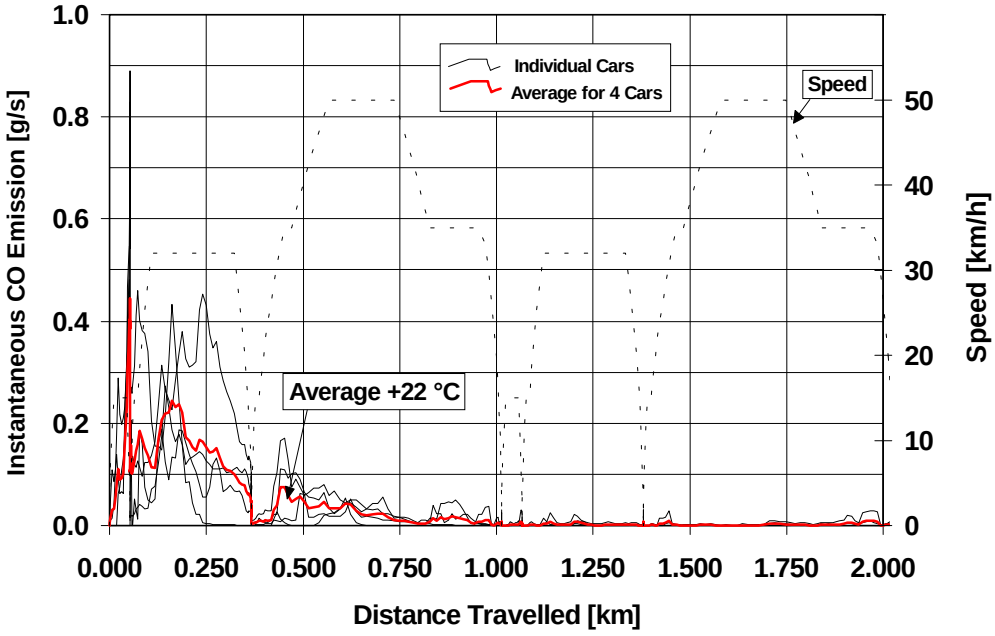


Figure 2 Instantaneous CO emission rate as a function of distance travelled in ECE15 driving cycle (start-up modified, no 40 s idle) at +20 °C ambient temperature for individual cars as an average for this four car sub-fleet in the Co-Nordic study.

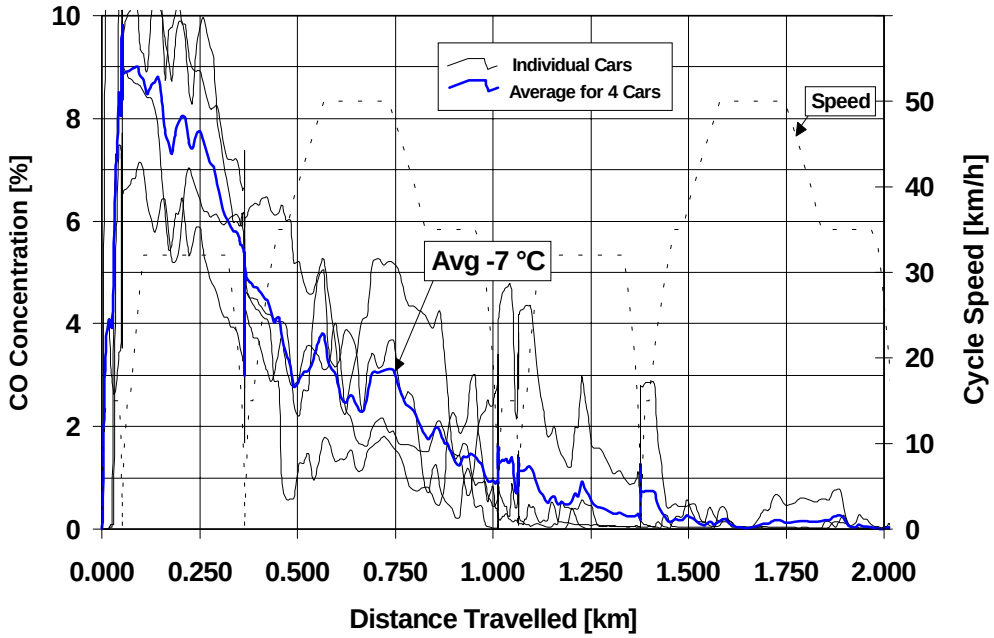


Figure 3 CO consentration as a function of distance travelled in ECE15 driving cycle (start-up modified, no 40 s idle) at -7 °C ambient temperature for individual cars as an average for this four car sub-fleet in the Co-Nordic study.

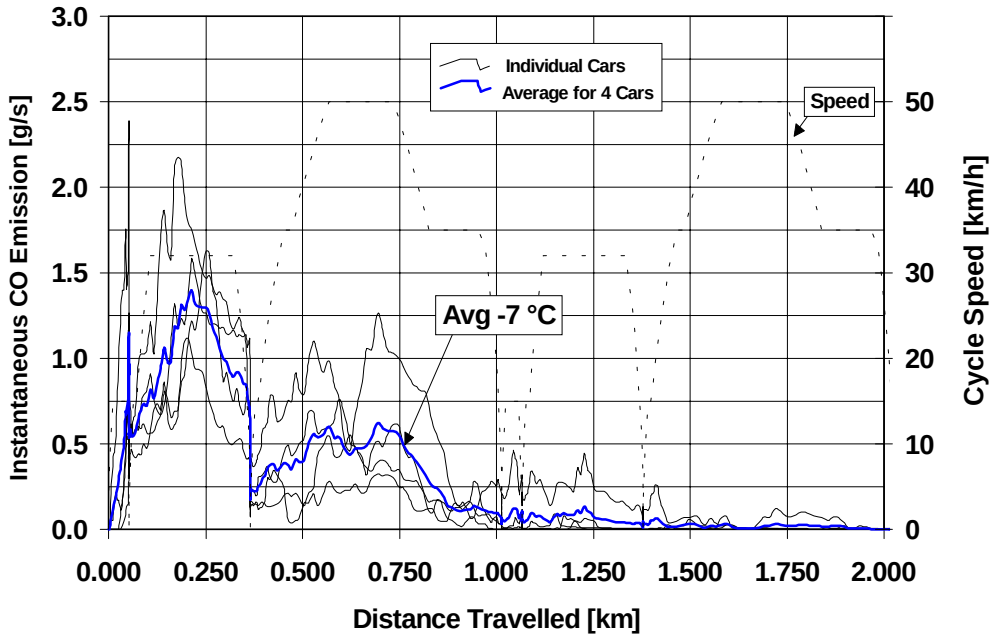


Figure 4 Instantaneous CO emission rate as a function of distance travelled in ECE15 driving cycle (start-up modified, no 40 s idle) at +20 °C ambient temperature for individual cars as an average for this four car sub-fleet in the Co-Nordic study.

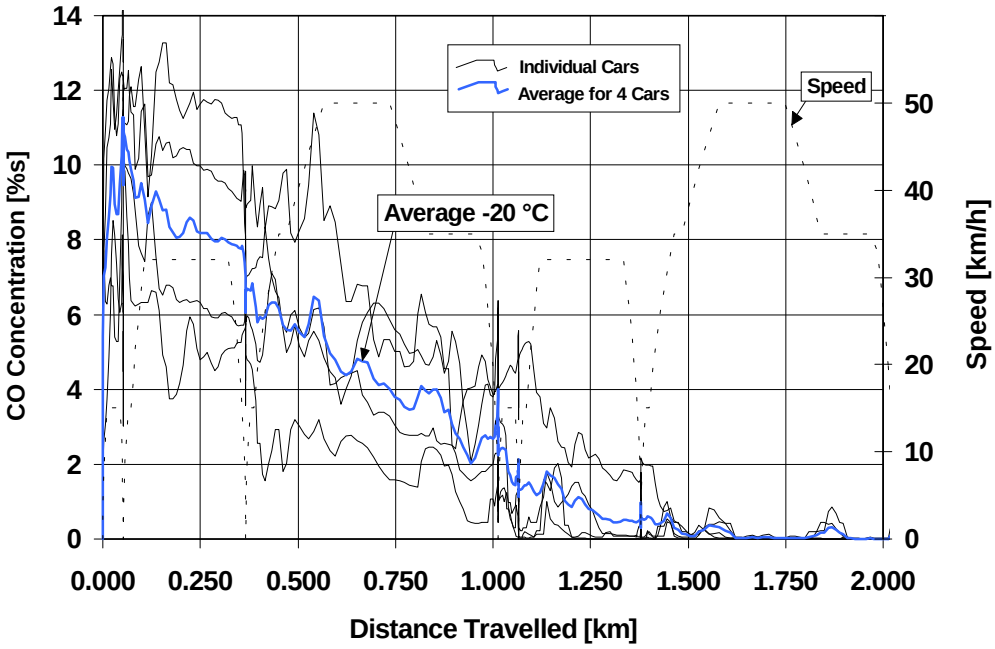


Figure 5 Concentration of CO as a function of distance travelled in ECE15 driving cycle (start-up modified, no 40 s idle) at -20 °C ambient temperature for individual cars as an average for this four car sub-fleet in the Co-Nordic study.

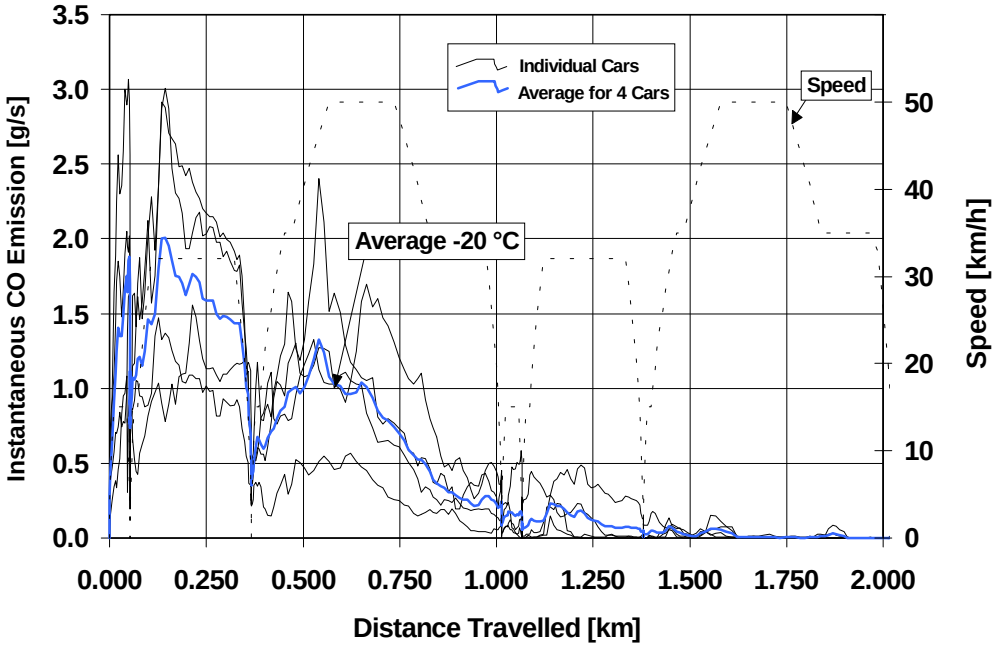


Figure 6 Instantaneous CO emission rate as a function of distance travelled in ECE15 driving cycle (start-up modified, no 40 s idle) at -20 °C ambient temperature for individual cars as an average for this four car sub-fleet in the Co-Nordic study.

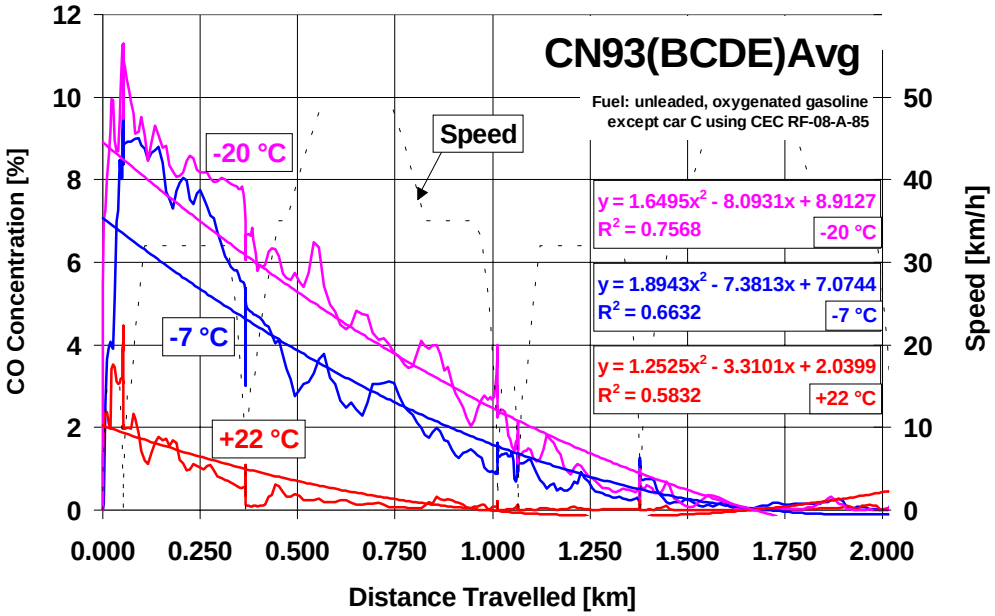


Figure 7 Concentration of CO as a function of distance travelled in ECE15 driving cycle (start-up modified, no 40 s idle) at +22, -7 and -20 °C ambient temperatures as an average for this four car sub-fleet in the Co-Nordic study and 2nd order polynomials fitted to the data.

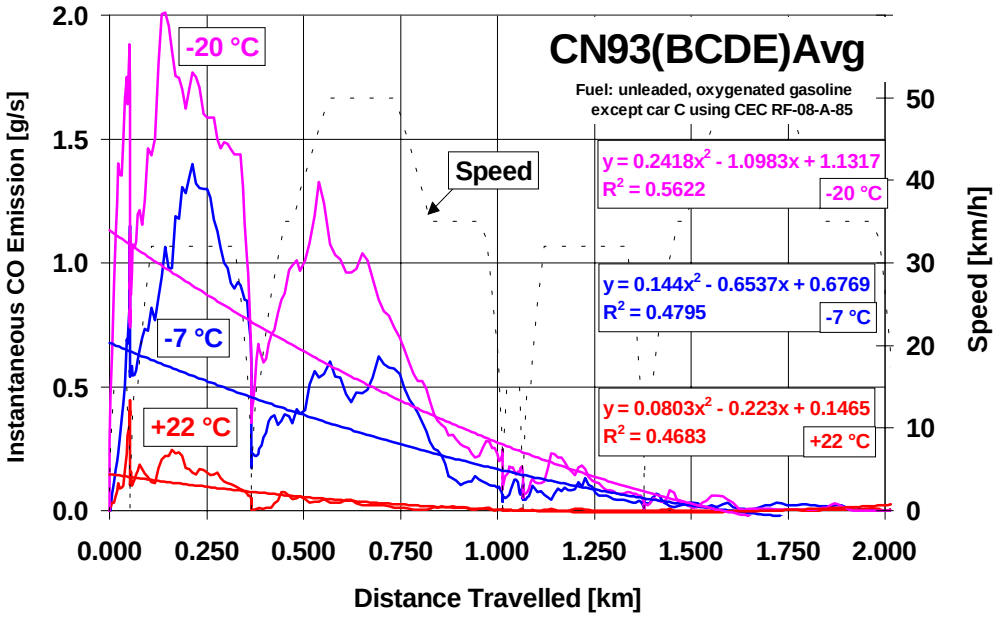


Figure 8 Instantaneus CO emission rate as a function of distance travelled in ECE15 driving cycle (start-up modified, no 40 s idle) at +22, -7, and -20 °C ambient temperature for individual cars as an average for this four car sub-fleet in the Co-Nordic study and 2nd order polynomial fitted to the data..

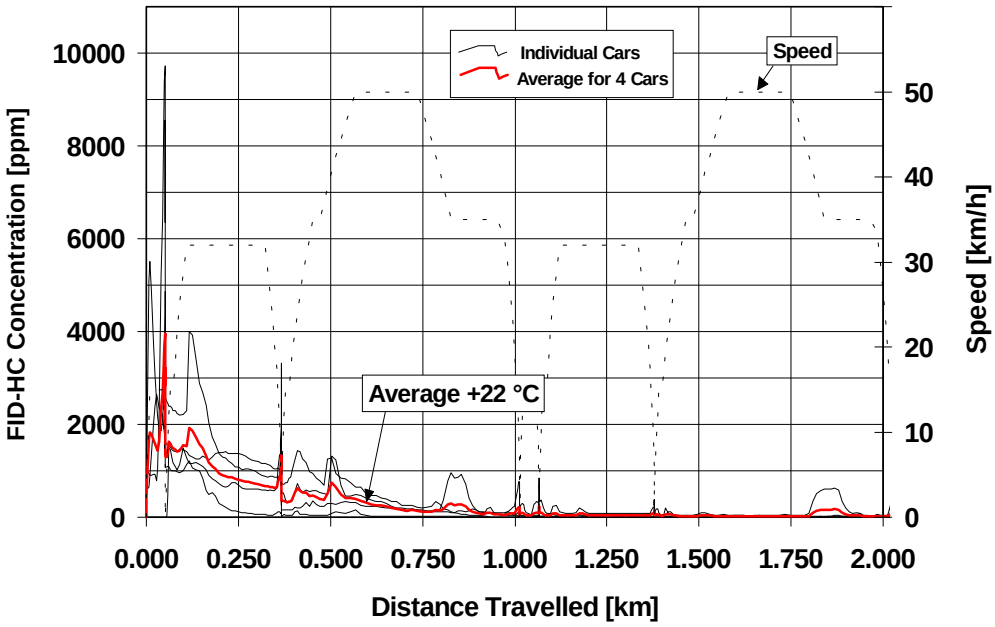


Figure 9 Concentration of HC (FID) as a function of distance travelled in ECE15 driving cycle (start-up modified, no 40 s idle) at +22 °C ambient temperature for individual cars and as an average for this four car sub-fleet in the Co-Nordic study.

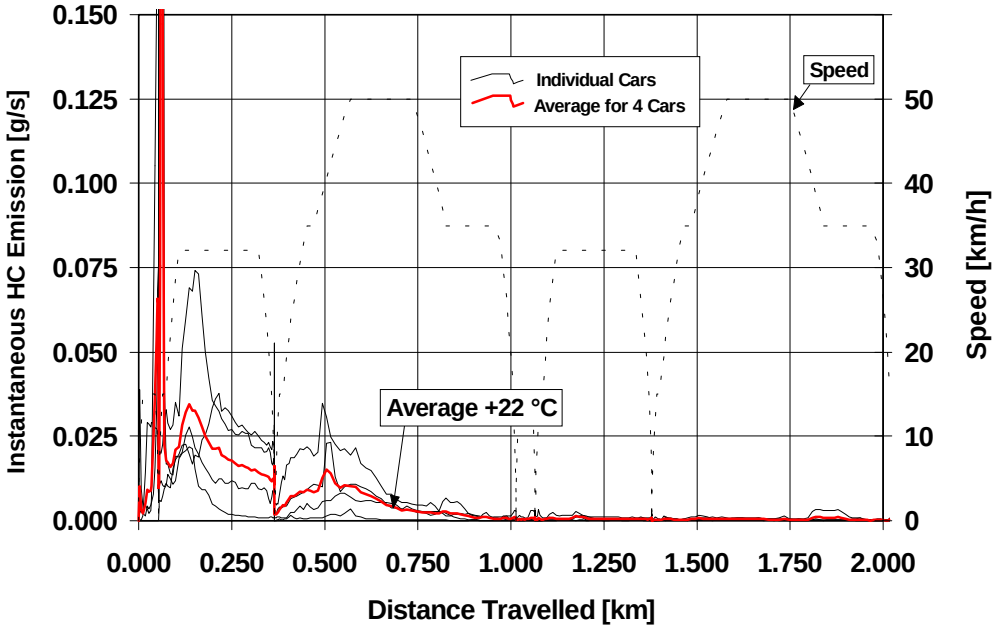


Figure 10 Instantaneous of HC emission rate as a function of distance travelled in ECE15 driving cycle (start-up modified, no 40 s idle) at +22 °C ambient temperature for individual cars and as an average for this four car sub-fleet in the Co-Nordic study.

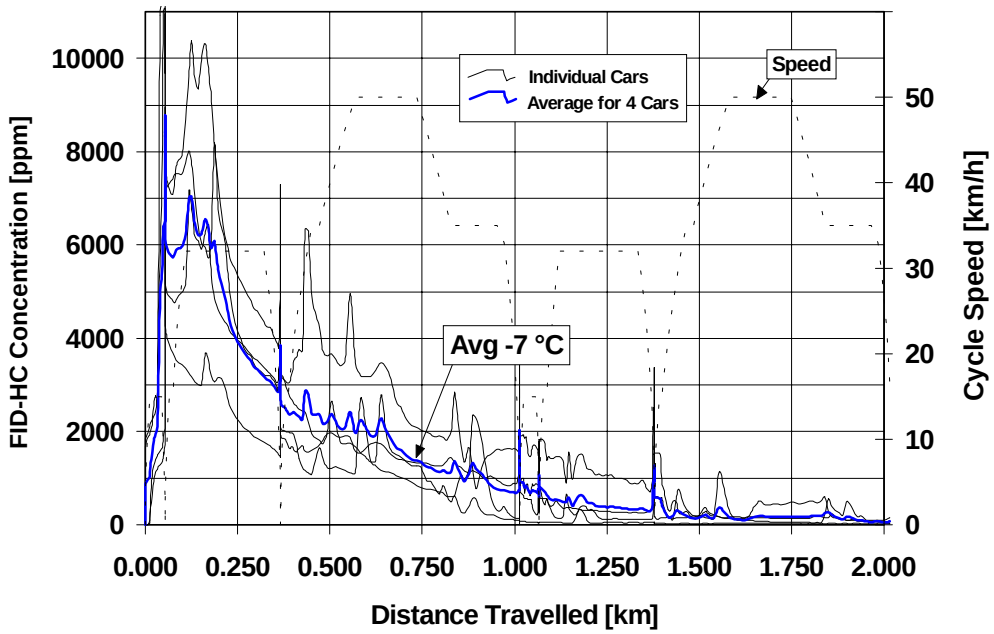


Figure 11 Concentration of HC (FID) as a function of distance travelled in ECE15 driving cycle (start-up modified, no 40 s idle) at -7 °C ambient temperature for individual cars and as an average for this four car sub-fleet in the Co-Nordic study.

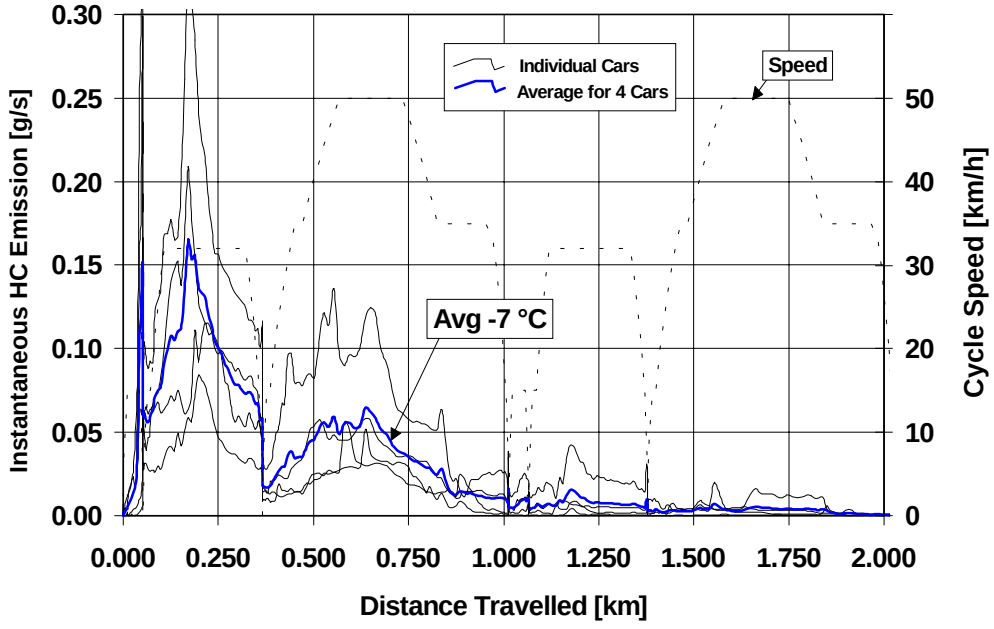


Figure 12 Concentration of HC emission rate as a function of distance travelled in ECE15 driving cycle (start-up modified, no 40 s idle) at -7 °C ambient temperature for individual cars and as an average for this four car sub-fleet in the Co-Nordic study.

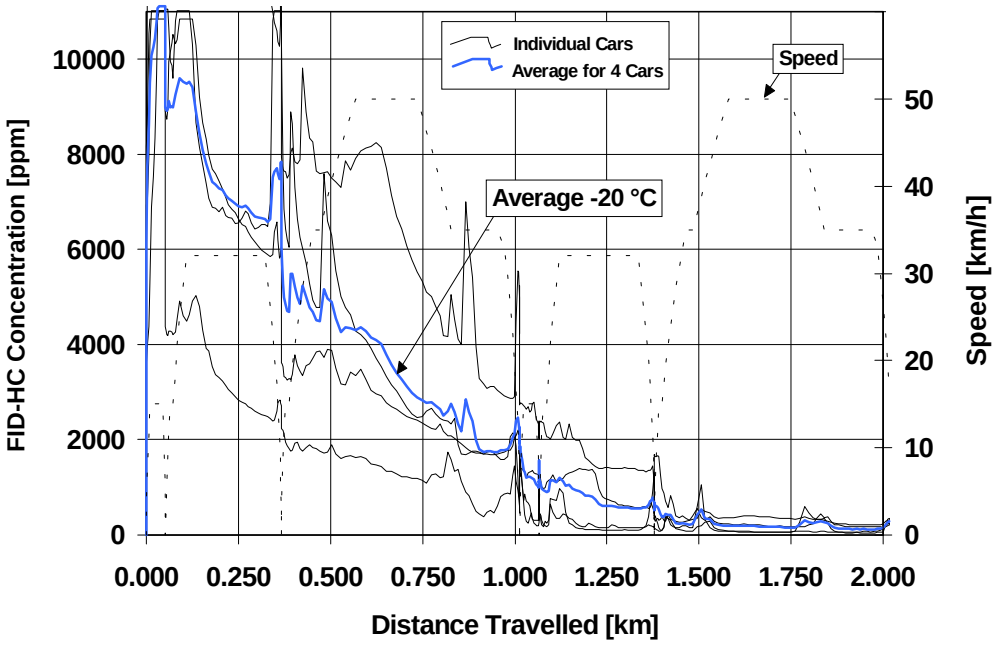


Figure 13 Concentration of HC (FID) as a function of distance travelled in ECE15 driving cycle (start-up modified, no 40 s idle) at -20 °C ambient temperature for individual cars and as an average for this four car sub-fleet in the Co-Nordic study.

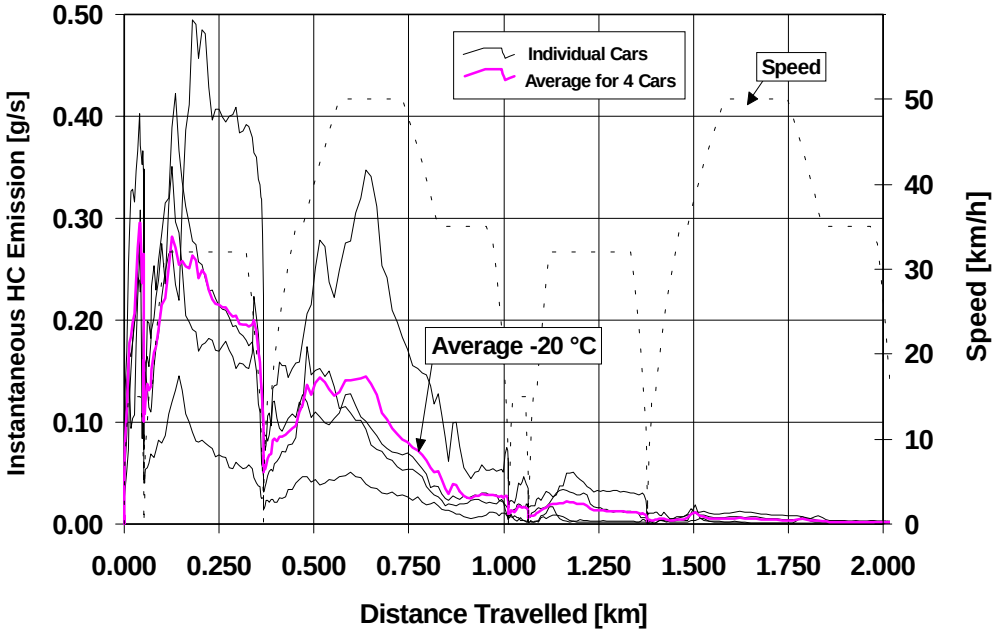


Figure 14 Instantaneous HC emission rate as a function of distance travelled in ECE15 driving cycle (start-up modified, no 40 s idle) at -20 °C ambient temperature for individual cars and as an average for this four car sub-fleet in the Co-Nordic study.

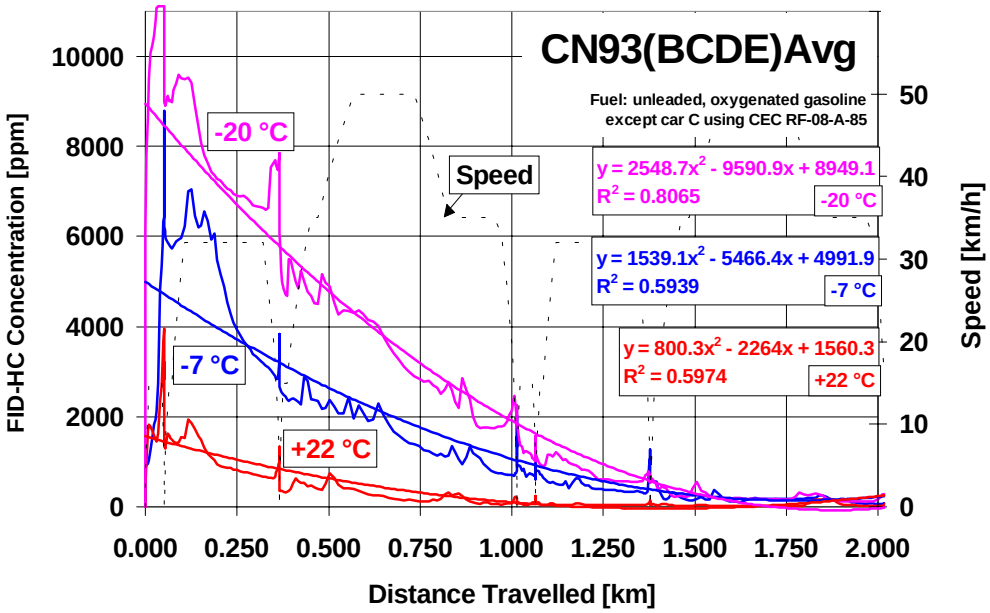


Figure 15 Concentration of HC (FID) as a function of distance travelled in ECE15 driving cycle (start-up modified, no 40 s idle) at +22, -7 and -20 °C ambient temperature as an avergage for this four car sub-fleet in the Co-Nordic study and 2nd order polynomials fitted to the data..

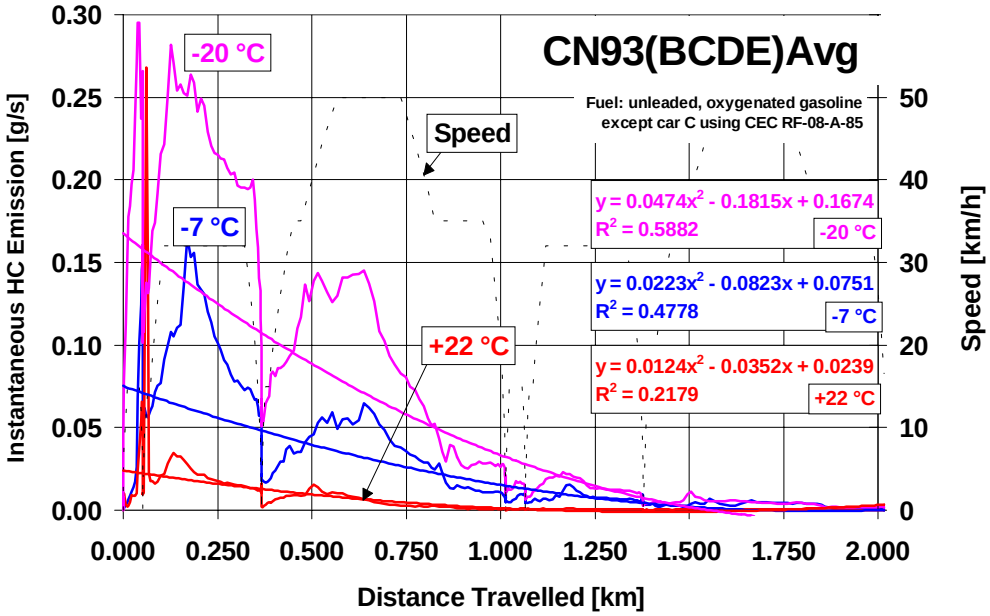


Figure 16 Instantaneous HC emission rate as a function of distance travelled in ECE15 driving cycle (start-up modified, no 40 s idle) at +22, -7 and -20 °C ambient temperature as an avergage for this four car sub-fleet in the Co-Nordic study and 2nd order polynomials fitted to the data..