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Evaluation of the environmental impact of modern passenger cars on petrol, diesel, automotive LPG, CNG

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Evaluation of the environmental impact of modern passenger cars on petrol, diesel, automotive LPG and CNG

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Summary

The project reported here concerns an investigation into the environmental performance of modern passenger cars on four different fuels: petrol, diesel, automotive LPG and CNG. The objectives of the project were twofold:

- To make a valid and useful comparison between modern vehicles fuelled by these four fuels, as a possible basis for governmental policy making.
- To establish characteristic up-to-date emission factors for modern passenger cars, fuelled by these four fuels, that can be used in a variety of inventories, calculations and forecasts by various (semi-)governmental agencies.

As such the project can be seen as an update of a similar project reported in 1993.

The project had both a Europe-wide and a Dutch national dimension. A basic test programme was carried out by four European test houses, financed by the European Autogas Industry. This test programme is named as the European Emission Test Programme (EETP). Additionally the programme carried out by TNO Automotive included some extra elements, on the request of the Dutch government, one of the sponsors of the Dutch test programme. The other sponsors of the Dutch test programme were the Dutch LPG association (VVG) and NGV-Holland (the Dutch association for natural gas fuelled vehicles).

In order to guarantee the best possible quality of the programme, and to obtain the best possible input from the relevant stakeholders, a Dutch steering committee was set up, containing representatives from the organisations that in the Netherlands are dealing with the various aspects that this programme addressed; these organisations represented the national authorities and their relevant agencies, the car industry and trade, the retail motor industry, the LPG and CNG equipment industry, and the fuel suppliers.

The test programme consisted of seven modern passenger cars for each of the fuels petrol, diesel and automotive LPG, and three modern passenger cars on CNG. With the exception of one vehicle on CNG, the vehicles were identical except for their fuel. Since the investigation needs to relate to the (near) future, the choice of vehicles was based on the most advanced (although developed) technology currently available for each of the fuels to be investigated:

- For petrol the aim was for technology as modern as possible. This meant 3-way catalyst, and Euro 3 or later (if available).
- For the diesels, only vehicles with direct injection engines were selected, all of them with electronic injection control. Five of these vehicles were fitted with common rail injection and the two others with a high pressure injection pump.
- For LPG and CNG the selection was aiming at the most modern systems available. It was decided to select **only OEM-equipped vehicle models** (OEM = Original Equipment Manufacturer, denoting a vehicle manufacturer).

Concerning the vehicle selection, the test programme contained the following additional elements:

- Inclusion of one passenger car with a DPF (diesel particulate filter) so as to obtain an impression of the possibilities for further emission reduction by means of such aftertreatment technologies for diesel vehicles.

- Inclusion of one van (on petrol, diesel and LPG), so as to obtain an impression to what extent the environmental performance of this class of vehicle might differ from that of passenger cars.

In order to evaluate the environmental performance of the vehicles, a number of potential human health and environmental effects are defined which are caused by various chemical components in the exhaust gas:

- Human health effects (including possibly carcinogenic substances);
- Ecological effects: ground level ozone formation, acidification and euthrophication;
- Climatic effects: global warming potential (GWP) and stratospheric ozone depletion.

There already existed a methodology that clearly identified this kind of (potential) effect [1], which was updated for this occasion with the latest insights, both with regard to the contributing components and with regard to their numerical contribution [2]. Since the effects considered are only *potential* effects, the resulting figures should be primarily regarded as environmental *indicators.*

For the determination of the human health and environmental effects caused by the direct tailpipe emissions, the following components are measured:

- The regulated components: CO, THC, NO_x and PM (the mass of particulates);
- Unregulated exhaust gas components (or component groups): CO_2, EC/OC, NO_2, N_2O, CH_4, C_2-C_5 (including 1,3-butadiene), C_6-C_{12} (including benzene, toluene and xylene - BTX), policyclic aromatic hydrocarbons (PAH), aldehydes, SO_2 and NH_3. Additionally the particle size distribution was determined by an ELPI analyser.

Of all cars the regulated emissions have been checked under type approval test conditions, so as to check whether they did comply with the limits. This was done in order to verify that they were in acceptable condition so far as emissions were concerned, and to avoid the risk of testing faulty cars. It begins to become generally accepted, however, that for modern cars the certification test cycle does give an insufficient representation of the actual emission performance on the road. For this reason the vehicles were additionally tested over a so-called ‘real-world’ test cycle in the interest of a correct interpretation of the emission behaviour in relation to the actual performance in the field. In the case of the present project for such real-world driving behaviour the Common Artemis Driving Cycle (CADC) was selected. At the moment it is the accepted real-world driving pattern, commonly used by the leading European research institutes for the generation of real-world emission data. The CADC consists of an urban part, a country road part and a motorway part.

The start with a cold engine is an important aspect of the driving cycle since in the case of catalyst equipped vehicles this contributes significantly to the total emissions. Since most of these cold starts can be assumed to take place in an urban environment, the resulting cold driving emissions can make an important contribution to the overall urban emissions. So as to determine the degree to which this cold start contributes to the total emissions under real-world circumstances, in the Dutch test programme the urban part of the CADC was driven twice: once starting with a cold engine, and once starting with a warmed-up engine. Additionally it was decided to perform the cold start of the CADC not at the ambient temperature window of the type approval test, but at the average annual ambient temperature in the Netherlands (9 ºC) since it is known that this can make a significant difference.

In the context of the Dutch test programme, for the evaluation of the real-world situation three different 'driver profiles' were defined:

- A business driver: characterised by overall traffic conditions and a warmed-up engine, representative for long duration trips (full CADC with warm start);
- A local driver: characterised by urban traffic and a representative cold start (urban part of the CADC, beginning with a cold start at 9 ºC);
- An average driver: characterised by overall traffic conditions, starting with a representative cold start (full CADC, extended with 2 urban parts of the CADC, and beginning with a representative cold start at 9 ºC).

The selection of fuels was based on the most modern technology currently on the market.

The relevance of the differences found in the human health and environmental effects between two fuels was checked by a statistical approach (paired-t-test), to see if the differences are statistically significant.

To obtain the full picture, additional to the direct tailpipe emissions, a literature study was performed into the indirect emissions from the energy chain. So, apart from the 'tank-to-wheel' (TTW) effects measured, the 'well-to-tank' (WTT) effects would be known. A check was made to see if this would seriously change the conclusions from the tailpipe measurement programme.

The programme led to the following main conclusions and recommendations:

CONCLUSIONS:

Regulated emission components:

The regulated emissions of most of the spark ignition (SI) engined vehicles, although certified as Euro 3 vehicles, are already below the Euro 4 limits. Such behaviour (actual emission values one step ahead of the legislation) is quite characteristic for 3-way catalyst equipped vehicles.

For diesel vehicles the emissions of CO and HC are not a problem; possible shortcomings may more readily be expected concerning NO_x and PM. The checks showed the HC + NO_x emissions to be closer to the Euro 3 limit than those of the SI engines; this was caused by the relatively high figures for NO_x, and not by the HC-emissions. Similar behaviour was observed for the PM-emissions. Such behaviour is characteristic for diesel vehicles.

Evaluation of the environmental performance (direct emissions)

The table below summarises the overall environmental performance of the four different fuels, with respect to the direct tailpipe emissions. In each cell of the table a rating is established by giving a score '--' to the case with the highest impact potential for the effect under consideration (i.e. to the 'case' where the emission or environmental indicator is highest). Subsequently the results for the other 'cases' are scored relatively to this case on a scale between '--' and '++'. A 'case' in this context means a combination of fuel and driver profile. This approach allows both the mutual comparison of the fuels and the comparison of the driver profiles, plus the combination of both.

In the table no further summary score has been indicated, since it is felt that it is a matter of policy which effect, in a given situation, has priority over another one, and to which extent. The four fuels simply have different impacts in different fields.

However, the following general conclusions can be made:

- Petrol shows lower impact potentials concerning health effects and/or ecological effects compared to diesel, however diesel shows a lower CO_2-emission and hence a lower direct GWP.
- The gaseous fuels LPG and CNG show the best overall results, especially CNG shows (very) low impact potentials on almost all effects in all driver situations.

Taking into account the statistical analysis to determine if the difference in environmental performance between two fuels is statistically significant, the following can be said:

- The overall score of the fuels, as stated above, is in most cases confirmed by the results of the paired-t-test.
- However, the advantage of CNG compared to LPG, concerning the human health and ecological effects, is in many cases not statistically significant. Beforehand it was recognised that the small sample size of the CNG vehicles (3 vehicles are measured) would result in a lower level of statistical confidence.

Business driver

	Relevance	Petrol	Diesel	LPG	CNG
Health effects					
NO_2	high	++	--	++	++
Overall PM	high	+	-	+	++
Overall PAH	high	++	++	++	++
1,3-butadiene	high	++	++	++	++
Light aldehydes	high	++	++	++	++
BTX	medium	++	++	++	++
Smog potent. POCP	high	++	++	++	++
Smog potent. TOFP	high	++	-	++	++
Ecological effects					
Smog potent. TOFP	high	++	-	++	++
Acidification potent.	medium	+	-	+	++
Euthrophication potent.	high	+	-	+	++
Climatic effects					
Direct GWP	high	-	+	+	++
EC-OC (GWP)	uncertain	++	o	++	++

Local driver

	Relevance	Petrol	Diesel	LPG	CNG
Health effects					
NO_2	high	++	--	++	++
Overall PM	high	+	--	+	+
Overall PAH	high	--	o	+	++
1,3-butadiene	high	--	+	-	+
Light aldehydes	high	+	--	++	++
BTX	medium	--	++	-	+
Smog potent. POCP	high	--	++	-	o
Smog potent. TOFP	high	-	--	-	o
Ecological effects					
Smog potent. TOFP	high	-	--	-	o
Acidification potent.	medium	+	--	+	+
Euthrophication potent.	high	+	--	+	+
Climatic effects					
Direct GWP	high	--	+	o	+
EC-OC (GWP)	uncertain	+	--	++	++

Average driver

	Relevance	Petrol	Diesel	LPG	CNG
Health effects					
NO_2	high	++	--	++	++
Overall PM	high	+	-	+	++
Overall PAH	high	+	+	++	++
1,3-butadiene	high	+	++	+	++
Light aldehydes	high	++	+	++	++
BTX	medium	+	++	+	++
Smog potent. POCP	high	+	++	+	+
Smog potent. TOFP	high	+	-	+	+
Ecological effects					
Smog potent. TOFP	high	+	-	+	+
Acidification potent.	medium	+	-	+	+
Euthrophication potent.	high	+	-	+	+
Climatic effects					
Direct GWP	high	-	+	+	++
EC-OC (GWP)	uncertain	++	o	++	++

--	Very high impact potential	(highest impact potential of all cases for the effect under consideration; a 'case' means a combination of fuel and driver profile)
-	High impact potential	(relative to case with highest impact potential)
0	Average impact potential	(relative to case with highest impact potential)
+	Low impact potential	(relative to case with highest impact potential)
++	Very low impact potential	(relative to case with highest impact potential)

Additional technology assessments:

Concerning diesel particulate filter (DPF) technology:
The overall evaluation of the DPF technology indicates that this has a good potential to reduce the PM-emission (including the ELPI number emission), without noticeable adverse effects with regard to the NO_x- and CO_2-emission. It has to be stated that the results obtained only represent the operation between two regenerations. It is planned to measure the regulated and unregulated emissions during the regeneration phase in January 2004. The results will be described in a supplement that will become available at the beginning of 2004.

Concerning gaseous fuelled vehicles:
Evaluation of the gaseous fuelled vehicles (both automotive LPG and CNG) showed a number of remarkable aspects. Although they were not further investigated their most logical explanation would seem to be the regularly used strategy in bi-fuel vehicles to cold-start the vehicle on petrol. There are practical operational reasons for such strategies, but, as this investigation shows, the consequence is that exactly during the critical cold start and warming up phase the advantages of the gaseous fuel are not coming into play, since at that very time the vehicle is petrol fuelled.

Concerning small vans:
In general it should be said that a van is heavier than a comparable passenger car, usually without a comparable increase in engine power. This will mean that the van will need more engine power to drive the cycle, but that it will do so by using a higher relative share of the engine power installed.
The first observation is reflected in the significantly higher fuel consumption compared to passenger cars, and consequently the CO_2-emission is higher in proportion. Typical differences would need to be established on a bigger sample, but amounted in the measurements results to 30-70 % increase for spark ignition engines and 10-40 % for diesel engines, depending on driver profile.
The second observation will mean that vans equipped with a diesel engine may be expected to emit disproportionately more NO_x and possibly PM than a diesel passenger car. From the measurement results it can be concluded that the emissions of NO_x and PM of diesel vans tends to be significantly higher than that of passenger cars. Again typical differences would need to be established on a bigger sample. They amounted to 80 % higher for NO_x and to 2.5-4.5 times for PM, depending on driver profile. The NO_x increase would reflect in all environmental indicators that contain a NO_x-component.

Indirect emissions from the energy chain:

Indirect emissions, associated with the well-to-tank (WTT) energy chain of petrol, diesel, LPG and CNG vehicles have been assessed based on available data. Given the uncertainties related to the assessment of indirect emissions, the comparisons presented here should be considered as indicative. The comparisons are based on the average driver situation.

Emissions related to human health effects:
- The indirect emissions of CO, benzene and aldehydes are relatively small compared to the direct emissions for all fuels, with the exception of the CO-emission of diesel. For this fuel the direct and indirect CO-emissions are about equal, but both are relatively small. For these components the WTT-emissions therefore do not influence the outcome of the comparison between the different fuels.

- The indirect emissions of NO_x are comparable to the direct emissions in the case of petrol and LPG, but are much smaller than the direct emissions in the case of diesel and CNG. For this component the WTT-emissions therefore do somewhat influence the outcome of the comparison between petrol, LPG and CNG in the sense that they increase the advantage for CNG. The overall benefits of petrol, LPG and CNG relative to diesel, however, are not significantly affected by the WTT-emissions.
- If all indirect emissions are considered to contribute to the ozone formation potential, the resulting TOFP-value for the indirect emissions is found to be about half of the direct value for petrol and LPG. For diesel and CNG the indirect TOFP-values are a lower fraction of the direct TOFP-values. Including the full indirect TOFP-potential would therefore slightly reduce the advantage of petrol and LPG relative to diesel, and would give CNG a slight benefit compared to petrol and LPG. However, as ozone formation is a local phenomenon, strongly dependent on local meteorological, geographical and air quality characteristics, the contribution of the indirect emissions to ozone formation will in practice be much smaller than the upper limit estimated here.
- Both for primary PM and for secondary PM the emissions in the fuel chains of petrol and LPG are of the same order of magnitude as the direct emissions. For CNG the indirect emissions of primary and secondary PM are negligible. Including indirect emissions in the comparison increases the advantage of CNG compared to petrol and LPG. The comparison between these three fuels and diesel, with high direct emissions, is not significantly affected by the indirect emissions of primary and secondary PM.
- For petrol and diesel the indirect emissions of 1,3 butadiene are relatively high, both in absolute terms and compared to the direct emissions. For LPG and CNG the indirect emissions are much smaller and therefore insignificant compared to the direct emissions. Including the indirect emissions thus reduces the advantage of diesel compared to petrol and LPG, and increases the advantage of LPG and CNG relative to petrol and diesel.

Ecological effects:

- As for petrol, diesel and LPG the indirect emissions of both NO_x and SO_2 are relatively high, the estimated upper limit for the acidification potential resulting from the indirect emissions is of the same order of magnitude as the potential due to direct emissions. Including the total indirect acidification potential, the advantages of petrol, LPG and CNG relative to diesel would be significantly reduced. In the comparison between petrol, LPG and CNG, the indirect emissions increase the advantage of CNG.
- Consequently the score of CNG on acidification, as expressed in the table above on ecological effects for the average driver, would be positively affected by including the upper limit estimates for indirect emissions and acidification in the comparison and the resulting impact potentials. For smog (TOFP) the scores would remain unchanged.

Climatic effects:

- Based on the vehicle data measured in this project and the indirect emission data selected for this study, it can be concluded that the well-to-wheel (WTW) greenhouse gas emissions from diesel and LPG vehicles are both some 16% lower than the greenhouse gas emissions from comparable petrol vehicles. The WTW greenhouse gas emissions from CNG-vehicles, running on Dutch natural gas from the low pressure grid, are 25% lower than those of petrol. Compared to the evaluation of the direct emissions, including the indirect emissions thus increases the relative advantage of diesel and LPG compared to petrol, and even more strongly increases the relative advantage of CNG compared to petrol.

- Comparison with data on other natural gas mixes (e.g. EU-mix with significant share of imports from Russia or a future 100% import mix) shows that the WTW greenhouse gas emission benefit of CNG-vehicles would be reduced if, in the future, significant shares of Russian gas would be consumed. As this is largely a consequence of the technical state of the pipelines and other equipment used, appropriate "chain management" is considered of paramount importance if natural gas is to maintain its greenhouse gas emission benefits over the longer term. On the other hand, future filling stations connected to the high pressure grid could improve the WTW greenhouse gas emission benefit compared to the present situation due to the lower energy requirement for compression.
- Taking into account the above presented direct greenhouse warming potentials resulting from indirect emissions would not affect the score on climatic effects as displayed in the table above for the average driver.

Comparison with the 1993 project:

Comparing the results from the 2003 project with those of the 1993 project, the following aspects are the most obvious:

- The real-world emissions of SI engines do not seem to show any reduction for CO and THC, and only a modest reduction for NO_x. It should be noted, however, that the cold start of the 1993 project was made at about 22 ºC, and that of the 2003 project at 9 ºC. This is certain to have had a significant effect, but its magnitude is not really known. A rough estimate on the basis of other testdata would seem to indicate, however, that in reality the real-world emissions have decreased by about a third for CO and by about half for HC and NO_x.
- The real-world emission of diesel engines showed significant reductions for CO and THC (but in practice these components are not critical), a good reduction for PM, but no reduction for NO_x. This can be attributed to the general use of an oxidation catalysts and a shift in calibration that favours the reduction of PM at the expense of NO_x.
- Evaluation of the organic components showed a remarkable behaviour of PAH, which seems to constitute a bigger share of THC. This was noted for all four fuels, though in the case of the gaseous fuels that may have been caused by the cold start on petrol.

RECOMMENDATIONS:

The following recommendations can be made:

- It is felt that the manufacturers of LPG and CNG vehicles might do well to apply a different (cold) start strategy (starting on LPG/CNG instead of on petrol), since this would seem a relatively easy way to take much more advantage of the favourable characteristics of gaseous fuels for the local situation.
- It is recommended to further investigate the PAH situation, to find the likely cause of the remarkable behaviour.
- The total evaporative HC-emissions can be quite considerable compared to the HC emissions from the exhaust. Including the evaporative emissions in the comparison between the four fuels can significantly influence the outcome of the comparison, especially between diesel and the other three fuels. It is therefore recommended to further study the evaporative HC-emissions of the different vehicles types. The

study should not only quantify the evaporative HC-emissions of the different vehicle types but also examine the composition of these emissions (e.g. benzene content).

- It is recommended that the emission behaviour of SI engines is monitored for the coming model years, to check if the inclusion of the –7 ºC test in the type approval procedure does actually improve the emission performance under real-world driving circumstances at real-world ambient temperatures.

Contents

1 Introduction

BACKGROUND

With respect to exhaust gas quality there is a continuous debate as to the relative merits of various fuels. Especially the advantages and disadvantages of diesel fuel are subject to debate. On the one hand several parties do have clear doubts as to the desirability of a larger diesel share relative to petrol, because of the emissions of NO_x and particulate, whereas other parties point out that diesel engines do have a lower emission of CO_2 and it is alleged that modern diesels are, or have become, very clean. Still others point out that for the business traveller automotive LPG rather than petrol is the most relevant alternative to diesel, and that LPG does also give a CO_2 advantage, without the NO_x and particulate objections. These questions had begun to become relevant in the early nineties, and already at that time TNO had carried out an extensive comparison programme between vehicles fuelled by petrol, diesel, automotive LPG and CNG, which had been co-sponsored by the Dutch government, individual members of the Dutch LPG equipment industry and the then existing Dutch association of automotive LPG suppliers [1]. Apart from the regulated components this programme also measured a large range of unregulated components.

The present project came about through a combination of several simultaneous actions:

1. Given the significant developments in vehicle technology in the case of all these fuels, and given the fact that the relevance of the basic question had only increased, the Dutch LPG association VVG (an association of both the equipment industry, the fuel suppliers, that had been set up since the time of the previous project) pressed strongly for an extensive update of the comparison, and asked TNO for a proposal.
2. When this proposal was discussed with the Dutch Ministry of the Environment, they too expressed interest. Apart from the relative comparison of the environmental performance of the fuels concerned, the Ministry was for its policy making additionally interested, however, in the absolute (basic) emission factors that it needs for a range of inventories, calculations and forecasts that are regularly performed by various governmental and semi-governmental agencies. It is customary that TNO supplies such factors, which are determined on the basis of programmes financed by the Ministry. It was felt that in this context there was insufficient up-to-date information about the emission performance of modern LPG fuelled vehicles, as well as about a range of unregulated components from the other fuels.

On the basis of these common interests these three parties together developed a suitable measuring programme which included all three fuels currently available on the Dutch market: petrol, diesel and automotive LPG.

3. During this process it became known that the European Autogas Industry was considering a similar programme, to be carried out by a number of European test houses (named as the European Emission Test Programme – EETP). This resulted in mutual talks and a decision to harmonise the two programmes, meaning that:
   - the actual measurement programmes were harmonised as much as relevant;
   - the total sample of vehicles to be tested was divided over the participating test houses (IFP in France, Millbrook Proving Ground in the UK, RW-TÜV in Germany and TNO Automotive in the Netherlands);

  - it was decided that the parties involved could perform additional tests, but that steps were taken to avoid any unnecessary duplication.

   In practice it was only for the Dutch programme that it was decided to perform additional measurements. These concerned the following aspects:
   - It was decided to perform additional cold start tests at the actual average annual ambient temperature in the Netherlands (+ 9ºC).
   - It was decided to judge the environmental impact of the different fuels on the basis of a number of environmental criteria concerning human health, ecological effects and climatic effects. This decision resulted in the necessity to measure a specific range of unregulated components.
   - It was decided to perform a literature study into the well-to-wheel effects, so as to obtain a more complete picture for each fuel.
4. At a late stage in the process NGV-Holland (the Dutch association for natural gas fuelled vehicles) arranged additional funding for the inclusion of a limited number of CNG fuelled vehicles. These were included into the Dutch programme only. The funding was supplied by NGV-Holland, Municipality Haarlem and the Dutch Gasunie.

In order to guarantee the best possible quality of the programme, and to obtain the best possible input from the relevant stakeholders, a Dutch steering committee was set up, containing representatives from the organisations that in the Netherlands are dealing with the various aspects that this programme addressed; these organisations represented the national authorities and their relevant agencies, the car industry and trade, the retail motor industry, the LPG and CNG equipment industry, and the fuel suppliers:
- The sponsors of the project:
  - Ministry of Spatial Planning, Housing and the Environment (VROM);
  - Dutch LPG Association (VVG);
  - NGV-Holland;
- LPG/CNG equipment industry;
- Ministry of Transport, Public Works and Water Management (V&W);
- National Institute of Public Health and the Environment (RIVM);
- RDW Vehicle Technology and Information Centre;
- RAI association
- Dutch Retail Motor Industry Association (Bovag)
- Netherlands Petroleum Industry Association (VNPI)
- TNO Automotive.

In total 6 meetings were organised to discuss the design of the test programme, the progress of the project, the measurement results and the draft final report.

TEST PROGRAMME

TNO Automotive has set up a test programme that took into account the twofold purpose of the Dutch part of the project, and the approach of the 1993 project was updated for the present one [2]. This updating was done in advance of the start of the current project.
- For the 1993 project a methodology had been developed to present the environmental performance of a vehicle on the basis of a relatively limited number of environmental indicators concerning human health, local and regional ecological effects, and global (climatic) effects. These indicators are calculated from a number of emission components, so they determine which components need to be measured.
- The need for the establishment of emission factors also determined components that needed to be measured. These followed from the needs of the agencies that make use

of these emission factors for their calculations and inventories; they are directly linked to the environmental policy of the Dutch Ministry of the Environment. In so far as they had not already to be determined for the environmental indicators, they were added to the list.

SET-UP OF THE REPORT

The set-up of the main body of the report is as follows:

- Chapter 2 gives a description of the project.
- Chapter 3 gives an overview of the sampling and analysis methods used, especially of the unregulated components.
- Chapter 4 refers to the direct measurement results, although the detailed results are given separately in Annex B. This chapter also refers to some problems that occurred during the measurements and the way in which they were dealt with.
- Chapter 5 shows the results of the calculation of the environmental indicators, and an evaluation of the overall environmental performance of the four fuels used in the investigation. These calculations are based on the measured tailpipe emissions (tank-to-wheel) only.
- Chapter 6 presents a few further environmental aspects of different technologies
- Chapter 7 presents the indirect (well-to-tank) emissions connected with the four fuels, on the basis of a literature survey, and discusses their influence on the overall evaluation of the environmental performance of the four fuels.
- Chapter 8 gives an account of the statistical methods used in the judgement of the pure measurement results.
- Chapter 9 makes a comparison between the results of the current investigation with those of the previous (1993) project.
- Chapter 10 contains the overall conclusions and recommendations.

2 Measuring programme

2.1 Objective

The objective of the project was to evaluate the exhaust gas qualities of the fuels petrol, diesel, Automotive LPG (Liquefied Petroleum Gas, further referred to as LPG) and CNG (Compressed Natural Gas), so as to allow a meaningful comparison between them, and in a way that would make the results of the project applicable in a broad context.

From a previous, similar, project [1, 1993] it was known that such a measuring programme will inevitably result in very large numbers of data (some 10,000 individual data in that case), which will render it extremely difficult, if not impossible, to draw simple straightforward conclusions. Hence the exhaust gas quality is not defined as a simple addition of a large number of individual components, but mainly as a series of environmental effects. The effects of the current project have been modified slightly from those of the previous project, however. They are now defined under the following headings:

- Human health effects (including possibly carcinogenic substances);
- Ecological effects: acidification, euthrophication, ground level ozone formation;
- Climatic effects: green house potential, stratospheric ozone depletion.

The need to determine these environmental effects determined the regulated and unregulated emission components that had to be measured.

The actual activities necessary to obtain the objectives are described in detail in the following paragraphs. For the final report TNO has also made use of the measurement results of the other test houses. For that reason the complete European Emission Test Programme (EETP) is described; the measurements that were carried out by TNO are indicated in Paragraph 2.7.

2.2 The environmental effects

In order to evaluate the environmental performance of petrol, diesel, LPG and CNG fuelled passenger cars, a number of potential environmental effects are defined which are caused by various chemical components in the exhaust gases. There already existed a methodology that clearly identified this kind of (potential) effect [1], which was updated for this occasion with the latest insights, both with regard to the contributing components and with regard to their numerical contribution [2]. Also the actual potential effects to be considered were slightly updated. According to this methodology for each effect the components were selected that contribute to it. Where necessary these components were added together after weighing them for their contribution to the effect considered. Since the effects considered are only *potential* effects, the resulting figures should be primarily regarded as environmental *indicators.* Where relevant, their evaluation also takes into account whether the order of magnitude of the contribution by traffic sources to the overall effect, or potential effect, is sufficiently significant to attach any significance to the differences measured. The (potential) effects defined for the current investigation are outlined in more detail in the preceding study mentioned [2].

Human health effects
For this category the following indicators are used:

- Carbon monoxide (CO)
- Nitrogen dioxide (NO_2)
- Primary particulate matter (PM):
  - Particle mass
  - Particle size distribution
- Secondary PM formation potential (see below):
  this effect is caused by the reactivity of NO_x, SO_2 and NH_3
- Sulphur dioxide (SO_2)
- Sulphate (SO_4^{--}) ought to be included here as well, but see Chapter 4
- Polycyclic Aromatic Hydrocarbons (PAH, selection of 8 compounds, see below)
- Light aldehydes (LA: formaldehyde, acetaldehyde, acrolein)
- 1,3-Butadiene
- Benzene, Toluene and Xylene (BTX)
- Ground-level ozone formation or 'smog potential', expressed both as POCP index and as TOFP index: this effect is caused by the reactivity of NMVOC, CO and CH_4, plus NO_x in the case of TOFP. See below for further clarification.

Ecological effects
For this category the following indicators are used:

- Ground-level ozone formation or 'smog potential' (expressed as TOFP index):
  this effect is caused by the reactivity of NO_x, NMVOC, CO and CH_4
- Acidification potential (expressed as eq. H^+):
  this effect is caused by the components NO_x, NH_3 and SO_2.
- Euthrophication potential (expressed as eq. NO_3^-):
  this effect is related to the emission of NO_x and NH_3.

Climatic effects:
For this category the following indicators are used:

- The direct Global Warming Potential (expressed as equivalent GWP):
  this effect is caused by CO_2, CH_4 and N_2O.
- The indirect global warming potential (expressed as mg/km):
  this effect is caused by elemental carbon and organic carbon (EC/OC, see below).
- Ozone depletion:
  this effect is caused by the N_2O-emission (expressed in mg/km).

To this list the following further remarks may be added:

Primary PM is the particulate matter directly emitted, whereas secondary PM is the PM formed in the atmosphere from the precursor components NO_x, SO_2 and NH_3.

The PAH analysis is based on the selection by the IARC group (International Agency for Research on Cancer) [5]. This selection is divided into a class 2A ('probably carcinogenic', 3 components), a class 2B ('possibly carcinogenic', 4 components) and a class 3 ('not classifiable', 14 components). This lists includes the range of 16 components recommended by the EPA, albeit that 3 of those 16 are labelled as 'not evaluated' by the IARPC group. For the current evaluation the classes 2A and 2B have been selected. Class 3 PAHs have been measured, but have not been incorporated in the evaluation. The components classified 2A (‘*probably* carcinogenic’) are:

- benzo-a-pyrene,
- benzo-a-antracene
- dibenzo-a,h-antracene

and the components classified 2B (‘*possibly* carcinogenic’) are:

- benzo-b-fluoranthene
- benzo-k-fluoranthene
- indeno-1,2,3-cd-pyrene
- dibenzo-a,l-pyrene

Additionally benzo-a-pyrene (class 2A) is reported separately, since it is designated as a ‘priority substance’ by the Dutch government. It is listed under the human health effects. Particle-bound as well as (semi-)volatile PAH are measured.

Ground-level ozone formation potential has been calculated according to the POCP (photochemical ozone creation potential) and the TOFP (tropospheric ozone formation potential) approaches. The POCP approach is based on the reactivities of the various VOC emissions and the CO emission, and does not take into account the source’s own NO_x emission. It is based on the consideration that the reaction rates are dependant on the actual background NO_x concentration, which may be strongly determined by other NO_x-sources than the one considered (in this case traffic), meaning that in practice the reaction rates may actually be influenced both in a positive way or even in a negative way by the vehicle’s own contribution to that background. It is assumed to be relevant for local conditions, where in practice the actual background concentration can be measured and taken into account. The TOFP approach is taking into account the source’s *own* NO_x emission. It is assumed to be relevant for regional conditions that are much less dependant on dominant local sources. In the results it is very apparent that the exclusion or inclusion of NO_x can create a very significant change in evaluation. For the category ‘ecological effects’ only the TOFP has been considered.

The long-term indirect greenhouse effect potential of compounds containing elementary carbon (EC) and organic carbon (OC) is still very much under discussion. It is clear, however, that if it is found to be significant the effects on the current comparison will be large. For that reason it has been determined and reported separately, so that, if it *is* found to be relevant indeed, its contribution may be judged too from this investigation.

2.3 The direct emissions measured

In view of the necessities following from Paragraph 2.2, for the determination of the environmental effects caused by the direct emissions, the following components are measured:

- The regulated components: CO, THC, NO_x and PM (the mass of particulates);
- Unregulated exhaust gas components (or component groups): CO_2, EC/OC, NO_2, N_2O, CH_4, C_2-C_5 (including 1,3-butadiene), C_6-C_{12} (including BTX), PAH, light aldehydes, SO_2 and NH_3. Additionally the particle size distribution was determined by an ELPI analyser.

Because of the necessity to determine the background concentrations of the (unregulated) components measured, a number of so-called blank measurement were made.

2.4 Indirect emissions and evaporative emissions

Since the level of direct emissions (‘tank to wheel’) is continuously decreasing, through the application of modern technology, the indirect emissions and evaporative emissions might well be playing a relatively increasing part with respect to the contribution to the environmental effects. Indirect emissions are *all* emissions (evaporative effects included) that originate in the total route from the production of crude oil to the filling of the fuel tank at the filling station (‘well to tank’). Evaporative emissions here mean those emissions occurring once the fuel has been stored in the fuel tank of the vehicle. For the indirect and evaporative emissions it is true that the values are subject to change, not in the least since ever increasing legal limits are coming into force. One may think of vapour recovery systems on fuel stations and the use of carbon canisters and venting systems in cars, special filling connectors for LPG systems, etc..

In the interest of a picture, as complete as possible, of the contribution of each individual fuel category to the environmental effects defined in Paragraph 2.2, the indirect and evaporative emissions need to be included in the investigation. So as to be able to determine these indirect and evaporative emissions the available literature and research reports in this field were used.

2.5 Driving cycles

General approach
Of all cars the regulated emissions have been checked under type approval test conditions, so as to check whether they did comply with the limits. This was done in order to verify that they were in acceptable conditions so far as emissions were concerned, and to avoid the risk of testing faulty cars. Furthermore these tests allow to compare the test results with research done elsewhere. It begins to become generally accepted, however, that for modern cars the certification test cycle does give an insufficient representation of the actual emission performance on the road. For this reason the vehicles were additionally tested over a so-called ‘real-world’ test cycle, partly in combination with ‘real-world’ testing circumstances, in the interest of a correct interpretation of the emission behaviour in relation to the actual performance in the field.

The standard European (type approval) test cycle
The standard European driving cycle (EDC) is a ‘synthetic’ driving pattern, consisting of an urban part (UDC = urban driving cycle) plus an extra-urban part (EUDC = extra-urban driving cycle) that combines country road and motorway circumstances. Because of its synthetic character both parts are characterised by low dynamic driving behaviour.

The real-world test cycle
Recent research programmes into real-world emission behaviour have shown that in the standard certification test the emission results of modern cars are often underestimated, since the driving pattern does no longer represent real-world driving behaviour. For that reason it begins to become common practice to establish actual emission behaviour on the basis of driving patterns that better simulate actual driving. In the case of the present project for such ‘real-world’ driving behaviour the CADC cycle was selected. This

driving cycle is based on an extensive European database, commissioned by the European Commission in the research projects DRIVE and HYZEM that were intended to generate real-world driving data of conventional and electrically propelled vehicles respectively. These projects were carried out in Great Britain, France, Germany and Greece by leading research institutes in each of these countries. The database is managed by the French research institute INRETS, one of the original participants. It has been analysed extensively by one of INRETS' researchers [3]. In the context of the European 5th Framework Project ARTEMIS, carried out by a consortium of leading European research institutes working in the field of emission research (including TNO-Automotive), a 'standard' real-world driving pattern was formulated from these data, based on commonly agreed evaluation criteria [4, 5]. This driving pattern is characterised by a significantly higher degree of dynamics than the legal certification test, and may hence be regarded as resulting in much more representative figures for normal emission behaviour in the field. It was designated the 'Common Artemis Driving Cycle' (CADC). At the moment it is the accepted real-world driving pattern, commonly used by those leading European research institutes for the generation of real-world emission data. The CADC consists of an urban part, a country road part and a motorway part.

In *Figure 1* and *Figure 2* the driving patterns used are shown graphically. *Table 1* shows some important characteristics of the cycles.

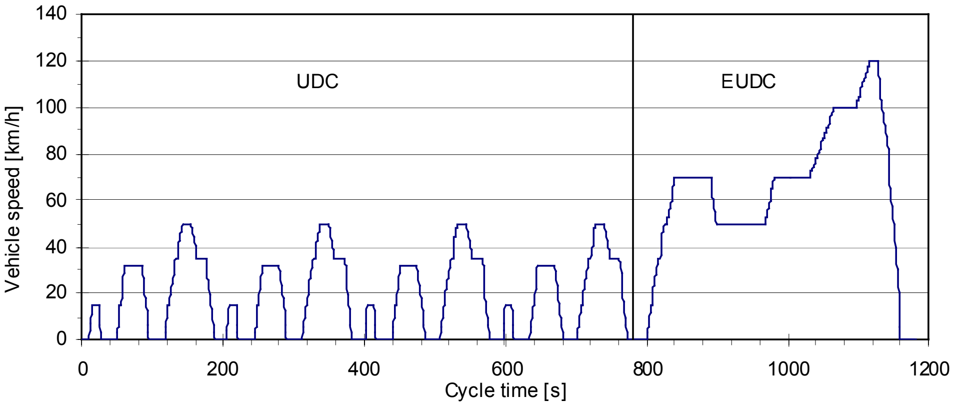


Figure 1: European Driving Cycle EDC, also known as MVEG cycle

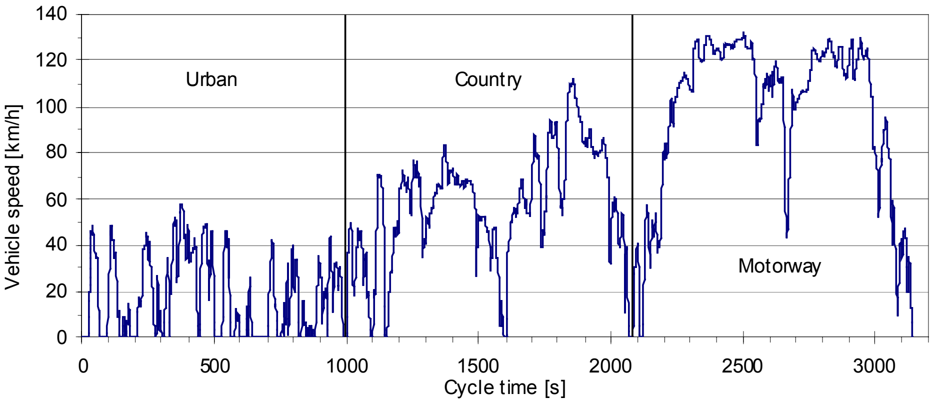


Figure 2: CADC (Common Artemis Driving Cycle)

Table 1: Some characteristics of the EDC and CADC

	EDC		CADC		
Sub cycle	UDC	EUDC	Urban	Country	Motorway
Average speed [km/h]	18.7	62.6	17.5	60.5	116.4
RPA* [m/s^2] (driving dynamics)	0.14	0.09	0.30	0.16	0.10

** Relative Positive Acceleration: a measure for driving dynamics*

2.6 The laboratory programme

European Emission Test Programme (EETP):

The European type approval test procedure is a complete procedure containing test circumstances in addition to the driving pattern. The urban part is started with a cold engine, and the combined country/motorway part is driven immediately following, and hence with a warm engine. The legally prescribed ambient temperature window for the cold start is 20-30 ºC. In the present programme for the Eurotest the ambient temperature window was set at the narrower interval of 20-25 ºC. For the EETP it was decided to add an additional EDC starting with a warm engine to the test programme. During the Eurotest in principle only the regulated emission components were measured. For comparison of the different test houses benzene was measured in a few cases, however, (3 vehicles only) as a representative unregulated component (only during the Eurotest starting with a cold engine).

Since the CADC is a cycle and not a procedure, it is up to the test house to decide if it is started with a cold or with a warm engine. The European Autogas Industry had decided to include the CADC driving cycle in the EETP, starting with a warm engine.

Additional elements in the Dutch test programme:

The start with a cold engine is an important aspect of the driving cycle, however, since in the case of catalyst equipped vehicles this contributes significantly to the total emissions. Since most of these cold starts can be assumed to take place in an urban environment the resulting cold driving emissions can make an important contribution to the overall urban emissions. So as to determine the degree to which this cold start contributes to the total emissions under real-world circumstances, in the Dutch programme the urban part of the CADC was driven twice: once starting with a cold engine, and once starting with a warmed-up engine. The difference between both trips is the emission caused by the cold start (for urban conditions). This made it also possible to calculate the emission of the complete CADC when starting with a cold engine, since the emissions may be assumed to have stabilised after the urban part. Additionally it was decided to perform the cold start of the CADC not at the ambient temperature window of the type approval test but at the average annual ambient temperature in the Netherlands, since it was known that this can make a significant difference. The cold starting at 9 ºC was done by using a separate cooling cell in which the vehicles were conditioned before the test to somewhat below that temperature. The vehicles were subsequently moved to the test room and tested in an ambient surrounding of 20-25 °C.

Long-time experience at TNO has shown that, at the temperature level concerned, such an approach renders sufficiently accurate emission figures for the ambient temperature thus simulated.

In the context of the Dutch project for the evaluation of the real-world situation three different ‘driver profiles’ were defined:
- A business driver: characterised by overall traffic conditions and a warmed-up engine (representative for long duration trips);
- A local driver: characterised by urban traffic, a representative cold start;
- An average driver: characterised by overall traffic conditions, starting with a representative cold start.

These three ‘driver profiles’ were then filled in as follows:
- Business driver: full CADC with warm start;
- Local driver: urban part of the CADC, beginning with a cold start at 9 ºC;
- Average driver: full CADC, extended with 2 urban parts of the CADC, and beginning with a cold start at 9 ºC.

For the average driver the full CADC was extended with 2 times the urban part of the CADC in order to have the urban/road/motorway share in the complete driving cycle comparable with the average driving situation in the Netherlands [8].
The effects of the cold start on the average driver profile were taken into account as follows. The additional cold start emission effect was calculated by subtracting the hot start emissions for the urban part of the CADC from the cold start emissions over the same cycle part. Simply adding these cold start ‘surplus’ emissions to the hot start CADC would underrate their effect, however, since they would then be ‘shared out’ over the complete length of the CADC, which is about 3 times that of the average Dutch trip length. On the other hand in real-world situations not all starts are cold: about one out of every three starts may be assumed to be hot [8]. It was therefore decided to upscale the cold start surplus emissions to the actual trip length of the CADC. An upscale factor of 2.2 was used for the cold start surplus emissions.

Over the CADC both the regulated and unregulated components, as specified in Paragraph 2.3, were measured.

In summary, the following tests were performed in the Dutch programme:
- Complete Eurotest (UDC and an EUDC), from <u>cold</u>.
  - Ambient temperature during preconditioning and test between 20 and 25 °C.
  - Regulated components plus CO_2, determined for both parts of the cycle and added for the complete Eurotest.
  - Benzene measured over the complete driving cycle (3 vehicles only).
- Complete Eurotest (UDC and an EUDC), <u>warm</u>.
  - Ambient temperature during test between 20 and 25 °C.
  - Regulated components plus CO_2, determined for both parts of the cycle and added for the complete Eurotest.
- Common ARTEMIS Driving Cycle (CADC), <u>warm</u>.
  - Ambient temperature during test between 20 and 25 °C.
  - Regulated components plus CO_2, determined for both parts of the cycle and added for the complete Eurotest.
  - Unregulated components, determined for the whole cycle.
- The urban part of the CADC, starting from <u>cold</u>.

  - Ambient temperature during preconditioning approximately 9 °C.
  - Ambient temperature during test between 20 and 25 °C.
  - Regulated components and unregulated components determined for this part.
- The urban part of the CADC, warm.
  - Ambient temperature during test between 20 and 25 °C.
  - Regulated components and unregulated components determined for this part.

Additionally a preconditioning sequence was incorporated within the test programme. This preconditioning sequence consisted of:

- 20 minutes of driving at 140km/h on the chassis dynamometer the day before the actual tests took place. This conditioning drive was carried out in order to enable the engine management system to 'adapt' to the test fuel. Furthermore, a preconditioning drive at high speed is recommended for diesel vehicles equipped with an oxidation catalyst, because particles accumulated in the catalytic converter are removed in this way. At the beginning of the actual test sequence, all the catalysts will then be at the same low level of particle accumulation.
- driving the UDC part of the Eurotest before every hot started driving cycle, followed by a soak period of 10 minutes between the end of the preconditioning cycle and the actual test cycle. This enables the engine to heat up before the test and the engine management system to 'adapt', if necessary, to a normal driving style and to normal ambient circumstances.

2.7 Vehicle selection

Since the investigation needs to relate to the (near) future, the choice of vehicles was based on the most advanced (although developed) technology currently available for each of the fuels to be investigated. This determined the choice of the vehicles to be tested. So as to make a valid comparison between the vehicles, which are petrol, diesel, LPG, and CNG fuelled, an evaluation was made of sales, state of the art in technology, and some important vehicle specifications such as weight and maximum engine power. As regards the criteria for selection:

- For petrol the aim was for technology as modern as possible. This meant 3-way catalyst, and Euro 3 or later (if available). DI technology was not selected, however since this is still in a development stage.
- For the diesels, only vehicles with direct injection engines were selected, all of them with electronic injection control. Five of these vehicles were fitted with common rail injection and the two others with a high pressure injection pump. They were all fitted with an oxidation catalyst. One extra diesel vehicle was selected with an additional aftertreatment system (a Peugeot 307 with a particulate filter).
- For LPG the selection was aiming at the most modern systems available. It was decided to select **only OEM-equipped vehicle models** (OEM = Original Equipment Manufacturer, denoting a vehicle manufacturer); in the 1993 programme the LPG and CNG fuelled vehicles all were retrofitted vehicles. Most systems were of the fourth generation (sequential injection), although some non-sequential systems had to be included when the OEM concerned did not supply a sequential one. The decision to include only OEM-equipped vehicles limited the available choice of models, since not many OEM-equipped LPG vehicles are already available on the market.

- The petrol, diesel and LPG fuelled vehicles were all of the same types, so as to maximise the validity of the comparisons. In 3 cases the petrol and LPG fuelled vehicles were actually the same (bifuel) vehicle (2 passenger cars and 1 van), whereas in the other cases different vehicles of the same type were selected. Where bifuel vehicles were selected for the petrol measurements it was checked with the manufacturer if the hardware controlling the fuelling was identical with that of the monofuel petrol version and if for the petrol fuelling the same software was used as well. In the 3 cases mentioned the answer was that although hard- and software were not actually identical, the differences could be expected to have no actual influence on the test results.
- For CNG likewise OEM-equipped vehicles models were selected. Unfortunately, only two models could be included that had also been selected for the other fuels; the third one (a Fiat Multipla) had to be of a different type. For budgetary reasons it was not possible to include more vehicles, so only 3 models were finally included into the programme. Since in the end the statistical significance of the differences in measurement results was judged on the basis of ‘paired t-tests’ the Fiat was compared with the average results for the other fuels (see further Chapter 8).

For the test programme 7 passenger car series were selected for each fuel category. In the majority of cases medium class passenger cars were selected, since in the choice between petrol, LPG or diesel especially this category of vehicles plays an important role. The vehicles selected for the programme had been operated between 5.000 and 25.000 km.

Additionally a small van was selected to see if this category of vehicle does show a significantly different behaviour. Since only one vehicle of this category was tested for the Dutch programme, the conclusions are only presented in a qualitative way. This is done in Chapter 6.

Similarly a single additional vehicle diesel passenger car with particulate filter was selected, so as to judge the general way in which the conclusions from the programme might shift if such technology becomes state of the art in the near future. Again the conclusions are only presented in a qualitative way, in Chapter 6.

In *Table 2* the selection of the passenger cars for the EETP and Dutch test programme is shown. The Ford Focus was included in the Dutch test programme only. The Peugeot 307 was only tested with a diesel engine; it was selected because of the additional aftertreatment system.

Table 2: Selection of passenger cars for the test programme

Petrol	**Diesel**	**LPG**	**CNG**
Opel Vectra 1.8 16V Bi-fuel	Opel Vectra 2.0 DTi 16v	Opel Vectra 1.8 16V Bi-fuel	
Opel Astra 1.6 16V Bi-fuel	Opel Astra 1.7 DTi	Opel Astra 1.6 16V Bi-fuel	Opel Astra 1.6 16V*
Peugeot 406 1.8 16V	Peugeot 406 2.0 HDi	Peugeot 406 1.8 16V Bi-fuel	
Renault Scenic 1.6 16V	Renault Scenic 1.9 DCi	Renault Scenic 1.6 16V Bi-fuel	
Volvo V40 1.8 16V	Volvo V40 1.9 D	Volvo V40 1.8 16V Bi-fuel	
Volvo V70 2.4	Volvo V70 D5	Volvo V70 2.4 Bi-fuel	Volvo V70 2.4 Bi-fuel
Ford Focus 1.8 16V *	Ford Focus 1.8 TDCi *	Ford Focus 1.8 16V Bi-fuel *	
Ford Transit Bi-fuel	Ford Transit TDCi	Ford Transit Bi-fuel	
			Fiat Multipla Bi-power*
	Peugeot 307 2.0 HDI (with particulate filter)		

** in the Dutch programme only*

The Opels Vectra and Astra, and the Ford Transit bi-fuel vehicles were tested on both petrol and LPG. The other vehicles marked bi-fuel in the LPG column were only tested on LPG: the corresponding vehicles in the petrol column were different vehicles of the same type.

Three vehicles (Opel Astra diesel and LPG, and Volvo V 70 LPG) have been subjected to a round robin test over the four participating laboratories. The results of this round robin series showed that the measurements in the four laboratories are comparable to the degree that is customary for such correlation exercises.

Table 3 shows the tests (combination of vehicle and driving cycle) that are carried out by each of the participating test houses and that are used in this report.

Annex A gives more details concerning the vehicles selected.

Table 3: Division of tests by each of the test houses

Vehicles	Petrol	Diesel	LPG	CNG	Eurotest cold start	Eurotest warm start	CADC warm start	CADC urban cold start	CADC urban warm start
Peugeot 406	1,**3**	1,**3**	1,**3**		**3**	1	1	**3**	**3**
Renault Scenic	1,**3**	1,**3**	1,**3**		**3**	1	1	**3**	**3**
Ford Transit	2,**3**	2,**3**	2,**3**		**3**	2	2	**3**	**3**
Opel Vectra	2,**3**	2,**3**	2,**3**		**3**	2	2	**3**	**3**
Opel Astra	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**
Ford Focus	**3**	**3**	**3**		**3**	**3**	**3**	**3**	**3**
Volvo V40	**3**	**3**	**3**		**3**	**3**	**3**	**3**	**3**
Volvo V70	**3**	**3**	**3**	**3**,4	**3**	**3**, 4(CNG)	**3**, 4(CNG)	**3**	**3**
Fiat Multipla				**3**	**3**	**3**	**3**	**3**	**3**
Peugeot 307		**3**			**3**	**3**	**3**	**3**	**3**

Code: 1 = IFP (France) 2 = Millbrook (UK) **3** = TNO (Netherlands) 4 = TÜV (Germany)

2.8 Fuels

The selection of fuels was based on the most modern technology currently on the market. It appeared not possible to already specify the fuel composition for the year 2005 (Euro 5). The selected fuels complied with the current EU specifications for commercial fuels:

- EN 228: petrol
- EN 590: diesel
- EN 589: automotive LPG

The diesel fuel had a sulphur content below 50 ppm, the petrol had a sulphur content below 100 ppm. For the LPG vehicles a propane/butane ratio of around 60/40 was chosen, and the sulphur content was below 25 ppm. Each of the fuels was obtained from one single source in order to eliminate spread in the results due to variations of the fuel compositions. The fuels were analysed before the start of the project and the main characteristics are shown in *Table 4.*

Table 4: Fuel analyses

	Petrol	Diesel	Automotive LPG	CNG
Customary name	Reference fuel RF-02-99	Low sulphur diesel	60/40	H-gas (comparable to G20)
Density	0.751 [kg/l]	0.842 [kg/l]	0,538 [kg/l]	0.734 [kg/m^3] *
Sulphur content [ppm]	64	35	15	<10
Aromatics [%-vol]	32.6	29.60	n.a.	n.a.
Oxygenates	6.1	n.a.	n.a.	n.a.
Benzene [%-vol]	0.5	n.a.	n.a.	n.a.
Fuel specific data				
RON [-]	96.8			
MON [-]	86		92.6	
Cetane number [-]		54.8		
propane/butane			60/40	
Wobbe index [kWh/m^3]				14.928
CO_2 content [mol-%]				0.0278
N_2 content [mol-%]				0.154

*[1013.25mbar, 288.15K]

The LPG specification allows for a larger difference of composition (and thus density) than petrol and diesel. So as to guarantee the continuous acceptability of the emission performance, the fuelling systems are made ‘self-adaptive’, meaning that the fuel supply to the engine is automatically adjusted to the fuel characteristics in order to maintain the stoichiometric air/fuel ratio. When the homologation of gaseous fuelled vehicles was introduced into the European legislation, provisions were made to check this self-adaptive behaviour by measuring these emissions on two different fuels that span the range in the field. For LPG (and light duty vehicles) these are fuels with a C3/C4 (propane/butane) ratio of 85/15 and 70/30. For the Dutch market a ratio of 60/40 is common, however, and it is used nationally for homologation concerning a national tax incentive scheme; this composition does in fact make even somewhat higher demands on the self-adaptive qualities of the system, but in practice the systems can cope with that.

In the case of natural gas the situation is more complicated. Where LPG could be blended to a specification, natural gas is primarily a product that can only be modified to a very limited extent. In practice such modification is only performed in order to keep the so-called Wobbe Index constant. Natural gas as available from European sources comes in two different basic ranges: high calorific gas (H-gas) and low calorific gas (L-gas). Each of these varieties span a range that in the emission legislation is covered by two reference gases: G20 and G23 for the H-range (high calorific) and G23 and G25 for the L-range (low calorific). It was decided, however, that light duty vehicles must be capable to perform acceptably on all qualities available across Europe, since they cannot be trusted to be used only locally. For that reason they can only receive a European homologation on G20 and G25 for the complete range. Since the L-range is almost exclusively relevant for the Netherlands it was decided to run the CNG vehicles on a G20 quality. The difference with the reference gas G20 is that the test gas was slightly contaminated with light hydrocarbons, N_2 and CO_2.

Generally speaking lower calorific gases contain inert components such as N_2 or CO_2. Dutch natural gas contains typically 15 mol% N_2 and 1 mol% CO_2. This means that the volumetric or gravimetric fuel consumption will be higher, although the emissions need not be different if the adaptation function is performing well. The CO_2 content of the fuel will mean, however, that the gross CO_2 content of the exhaust gases will be up to 1 % higher in the case of typical Dutch natural gas. This is a fuel effect and not a technology effect; it is further evaluated in Chapter 7 (Indirect emissions).

3 Sampling and analysis

The experimental set-up that is used to sample the regulated and unregulated exhaust gas components consists of the basic measurement equipment for vehicle exhaust gas sampling, in accordance with the Directives of the European Union (96/69/EC), and dedicated equipment that is used for sampling the unregulated components. This is described in the first paragraph. In the second paragraph is presented how the samples are analysed. The last paragraph describes the special effort that has been taken to improve the accuracy of the measurement and calculation.

3.1 Sampling of the exhaust gas components

The method that is used for sampling exhaust gas components can be divided into regulated components and CO_2, and the unregulated components. The first is in conformance with the Directives of the European Union (96/69/EC), and briefly described in the first paragraph. The additions that were made to sample the unregulated components are described in the second paragraph.

3.1.1 Sampling of regulated exhaust gas components and CO_2

Figure 3 presents a schematic drawing of the equipment that is used for sampling the exhaust gas components. The basic equipment for regulated exhaust gases is indicated in black. The additions that are made for sampling unregulated exhaust gas components are indicated in blue.

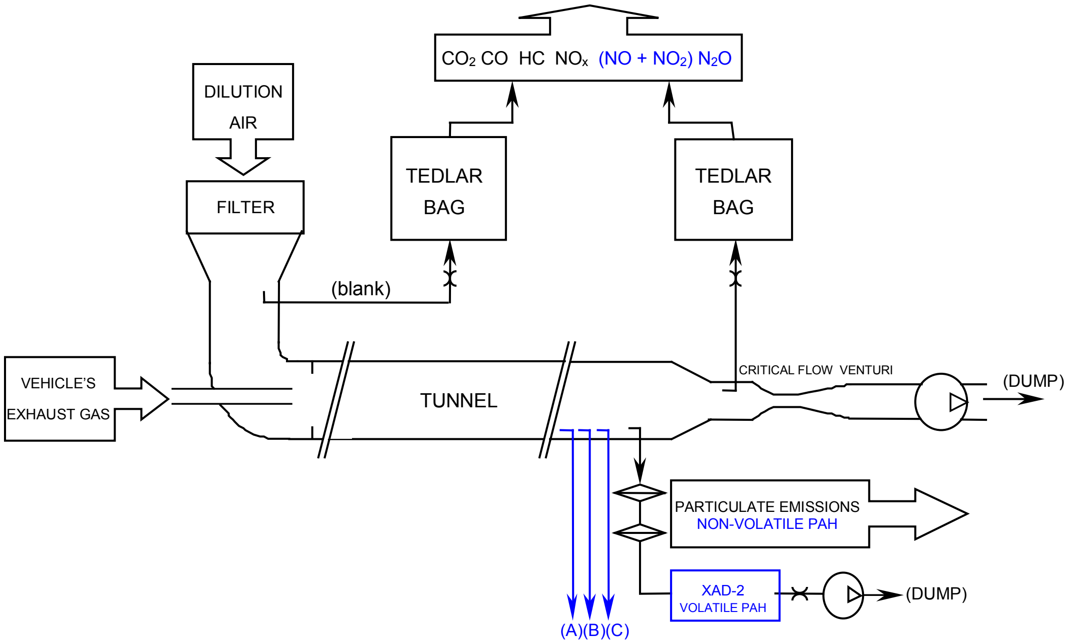


Figure 3: Measurement set-up for regulated and unregulated exhaust gas emission components

The vehicle's exhaust gases are diluted with filtered air, to prevent condensation or reactions between the different exhaust gas components. The dilution takes place in a long tube, referred to as the dilution tunnel or CVS (Constant Volume Sampler). The system maintains a constant volumetric flow, determined by the dimensions of a critical flow venturi and a pump located at the end of the tunnel. For a specific venturi, the dilution ratio (which is the ratio of the dilution air and the exhaust gas flow) depends on the exhaust gas flow of the vehicle.

During the emission test, a sample of the diluted exhaust gas flow is drawn from this tunnel, and collected in a pair of sampling bags, fabricated of Tedlar®. Of each pair, one bag is used for the diluted exhaust gas, and the other for the dilution air. The latter is used for correction, because the dilution air may also contains small fractions of CO_2, CO, HC and NO_x.

After the test, the content of the Tedlar® bags is analysed. Gas analysers for CO, CO_2, HC and for NO_x are used to determine the concentrations of these components. Multiplication of the concentrations and the tunnel flow yields the emissions in gram per kilometre. The calculation procedure is extensively described in the European Directives.

For diesel vehicles, Particulate Matter (PM) is collected separately from the other emission components, by drawing diluted exhaust gas from the tunnel through a pair of Pallflex® filters. The filters are weighed before and after the test, and their weight increase is indicative for the particle concentration of the diluted exhaust gas. Again by multiplication with the flow though the tunnel the total particulate emission may be calculated. The second filter serves to detect, and if necessary to correct for any breakthrough of the first filter.

Although there are no limit values defined for CO_2, the CO_2 concentration is also determined, because it is used in the calculation procedure. The CO_2-emission value is furthermore used to calculate the fuel consumption F (in l/100km) using the carbon balance method.

3.1.2 *Sampling of unregulated exhaust gas components*

The additions indicated in blue in *Figure 3* represent the sampling set-up for the unregulated emission components. The additions comprise:

- The determination of the composition of NO_x (into NO and NO_2), as well as the concentration of N_2O is made from the standard Tedlar bags for the regulated components.
- Polycyclic aromatic hydrocarbons (PAH) are sampled in a two-stage set-up. Particle-bound PAH are caught on the filters that are used to sample the particulate emission. After weighing, the filters are analysed to determine the non-volatile PAH content. After passing the filters, the sample flow is led through a glass tube, packed with an Amberlite XAD-2. By this absorbent, the remaining (semi-)volatile PAH is caught.

Three extra sampling probes are inserted into the tunnel, for reasons of clarity they are represented by separate figures (see below).

- The sample flow that is drawn by branch A (see *Figure 4*) is diluted with filtered and dried compressed air, with an approximate dilution factor of 8.5. The diluted sample flow is split into two.

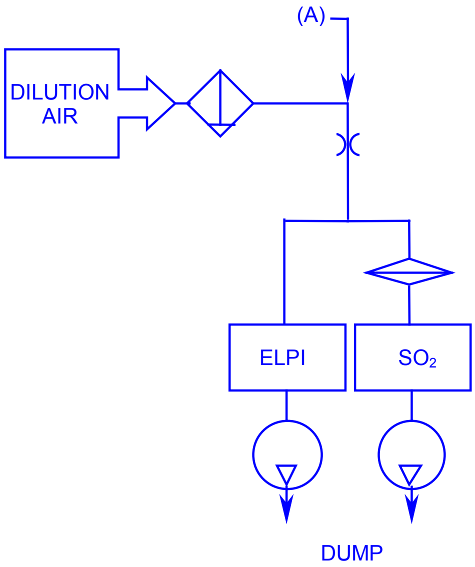


Figure 4: Branch A for sampling SO2 and for the particle size distribution.

One part is led to an SO_2 analyser, after passing a filter. The output signal of the SO_2 analyser is connected to a data acquisition system, where the momentary SO_2 concentration is stored with a 1 Hz frequency.
The second branch is led to an Electronic Low Pressure Impactor (ELPI), where different particle sizes are separated based on their aerodynamic diameter, yielding a particle size distribution. A personal computer is linked to the ELPI, to control and adjust the ELPI settings, and for data acquisition. Momentary particle numbers are stored with a sample frequency of 1 Hz. To prevent particle loss or coagulation particles, the sample line to the ELPI is kept as short as possible.

- Branch B (see *Figure 5*) consists of a filter holder, featuring a quarts filter for sampling Elementary and Organic Carbon (EC/OC). A pump is used to draw the sample flow from the dilution tunnel through the filter. The pump is automatically switched at the start and end of the test. The filter holder is followed by a calibrated flow restrictor. The flow together with the sample time yields the amount of diluted exhaust gas that is drawn through the filter.

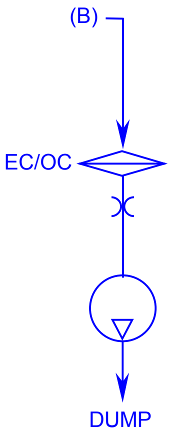


Figure 5: Branch B for sampling EC/OC.

- Branch C (see *Figure 6*) is a short heated sample line, connected to a glass manifold. From this manifold, light hydrocarbons (C_1-C_5), heavier hydrocarbons (C_6-C_{12}), ammonia (NH_3) and aldehydes are sampled.

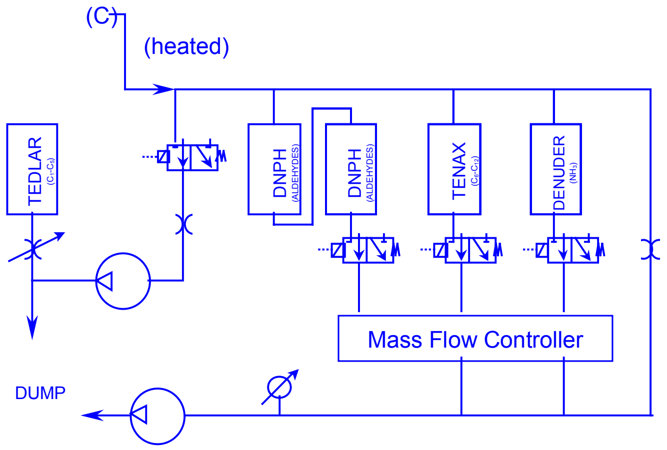


Figure 6: Branch C for sampling C_1-C_5, C_6-C_{12}, NH_3 and aldehydes.

C_1-C_5 is collected in an aluminium coated Tedlar® bag. An individual pump is used, and a manually adjustable Brooks flow restrictor, to ensure that sufficient sample is drawn for the analysis.

For the heavier hydrocarbons (C_6-C_{12}), sample flow is drawn through a metal tube containing Tenax (Tenax GR, Chrompack®). Tenax is an absorbent consisting of small extremely porous plastic globules.

Ammonia is sampled by drawing diluted exhaust gas through a denuder, containing oxalic acid.

Aldehydes are sampled by drawing diluted exhaust gas through a filter cartridge, containing 2,4 dinitrophenylhydrazine (DNPH). The aldehydes are trapped on the filter, because the DNPH reacts with them. After the test the filter is extracted with an acetonitrile solution. It was experienced that the DNPH reagens is washed off under high concentrations of NO_x. Therefore, for vehicles that are expected to emit a high level of NO_x, a second filter is placed sequentially to the first. This ensures that any breakthrough of aldehydes is trapped on the second filter. Analysis of the extract of both filters yields the total aldehydes concentration.

Each sampling unit mounted on the manifold features an individual solenoid valve, that is simultaneously switched at the start and the end of the test. The switch is manually operated at the beginning and the end of sampling. It also operates the pump on branch B. For the components C_6-C_{12}, NH_3 and for the aldehydes, the flow is regulated by an adjustable mass flow controller unit.
To ensure a stable flow during switching at the beginning and end of sampling, the pump operates continuously. While not sampling, ambient air is drawn through the valves. At the start of sampling the valves are repositioned to draw diluted exhaust gas though the sampling units.

3.2 Analysis of the exhaust gas components

3.2.1 *Analysis of the regulated exhaust gas components and CO_2*

The analysis of the regulated exhaust gases and CO_2 is quite straightforward, and is extensively described in the Directives of the European Union (96/69/EC). Dedicated analysers for CO, NO_x ,HC and CO_2 are used to analyse the diluted exhaust gas from the Tedlar bags.
The CO and CO_2 analysers operate by non-dispersive infrared (NDIR). The HC analyser operates by flame ionisation detection (FID) and the NO_x-analyser by chemoluminescence (CL).

3.2.2 *Analysis of the unregulated exhaust gas components*

NO and NO_2
The CL-analyser features two operating modes, measuring NO or NO+NO_2 (NO_x). The concentration of NO_2 is obtained by subtracting the NO from the NO_x concentration. A calculated emission of NO_x is in NO_2 equivalent, therefore the sum of NO and NO_2 emissions do not equal the NO_x emission, due to the difference in specific weight of NO and NO_2.

N_2O
For the N_2O measurements a Thermo Environmental Instruments Model 46C N_2O analyser was used. The measuring principle of this instrument is based on infrared absorption. In order to be able to measure the small quantities of N_2O in the emission matrix of combustion engines, the most sensitive type of instrument was used, being GFC (Gas Filter Correlation).

SO_2
The SO_2 analyser principle is based on pulsed UV Fluorescence. SO_2 molecules absorb ultraviolet (UV) light, become excited at one wavelength, then decay to a lower energy

state emitting UV light at a different wavelength. The UV light is proportional to the total sulphur concentration in the sample.

ELPI

The ELPI consists basically of a low pressure cascade impactor and a charger. Before entering the low pressure impactor unit (see *Figure 7*), the particles receive a unit charge, applied by a corona discharger. Once entered the impactor unit, the flow makes a sharp bend in the first stage. The biggest particles cannot follow the flow and collide on the first impactor plate. In the next stage of the impactor the flow increases because of a narrower cross section. Smaller particles will therefore impact on the next plate. This process is repeated until the flow has passed all 12 stages. At each stage particles within a certain range are trapped. The impactor plates are connected to electrometers, and a particle impacting on the plate will loose its current. The current is indicative for the number of particles, belonging to the size range of that plate.

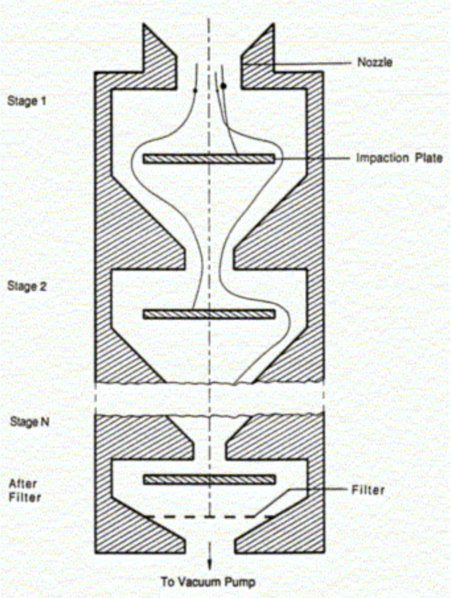


Figure 7: Principle of a cascade low pressure impactor.

For the ELPI an additional stage may be added to measure the number of particles in the range below 30 nm. Particles up to a size of 40 to 50 nm are referred to as nucleation mode particles. They are composed mostly of volatile condensates (hydrocarbons, sulphuric acid) and contain little solid material. In the current research, the additional stage for particles below 30 nm was not used. Uncertainties still exist in the reliability of the measurement of nucleation mode particles.

Particle size distribution measurements in general, and especially the nucleation mode, are prone to sampling artefacts due to the sensitivity of the aerosol to sampling conditions. The dilution ratio, the tunnel temperature, the residence time, the humidity and the content of sulphur and volatile materials play an important role in this, and variations may lead to formation or lost of particles, or even both. The main phenomena that influence the measurements in the smallest ELPI stage are:

- **Nucleation:** Nucleation is the formation of new particles from gas phase components, also referred to as spontaneous condensation. It is not significant for gravimetric measurements, due to the relatively small mass of nucleation mode particles. The number concentration however can be increased by an order of magnitude due to nucleation of hydrocarbons, sulphur compounds and water in the dilution tunnel.

  The dilution ratio plays a key role in the nucleation process. Particle nucleation is favoured by higher saturation ratios which occur at lower dilution ratios in the dilution tunnel. Furthermore, also the rate of nucleation is extremely dependent upon temperature and relative humidity.

  Nucleation may be homogenous, heterogeneous or binary homogenous. In the case of homogenous nucleation, there are no condensation nuclei, and volatile materials may condense at high saturation ratios. Typically for heterogeneous nucleation is the presence of foreign material acting as particle precursors, for instance solid carbonaceous compounds, metal or ash. Binary homogenous nucleation occurs with two vapour compounds, for instance sulphuric acid and water vapour. Sulphuric acid may be formed by conversion of SO_2 into SO_3 and subsequently into H_2SO_4. Hydrocarbons may again be absorbed by the sulphuric acid nuclei, causing them to grow.

- **Diffusiophoresis** is a phenomenon that occurs due to the Brownian motion of particles. Especially nucleation mode particles are sensitive to diffusiophoresis, due to their low mass. In case of fast nucleation rates and long residence times (long sampling lines) diffusiophoresis is promoted. This can cause a substantial particle loss to the walls and intercollision of nucleation mode particles, leading to coagulation.
- **Coagulation**: Particles may collide and stick together to form larger particles. This may result in a shift towards higher particle diameters. Particles formed by nucleation have a high collision probability due to their sensitivity for diffusiophoresis. If the residence time is high, for instance because of long sample lines, and the aerosol concentration is high, coagulation is very likely to occur.

The dilution tunnel ratio is not constant, but varies during the test cycle, because the exhaust flow varies with different engine load conditions. During the test cycle situations may occur, which are favourable to one or more of these phenomena. New particles may be formed by homogenous nucleation, while heterogeneous nucleation may cause pre-existing particles to grow by condensation and adsorption. Diffusiophoresis and coagulation may follow.

It should be noticed that nucleation and absorption onto particles are competing processes to some extent. The presence of absorbing particles may significantly suppress nucleation. Carbonaceous agglomerates provide a large surface for adsorption. Engines with a low PM emission may therefore have large particle number emissions.

Another consideration is that exhaust gas dilution which takes place in the dilution tunnel is not a good simulation of atmospheric dilution. Typical atmospheric dilution ratios are much higher than in the dilution tunnel. The dilution tunnel saturation ratios are much higher than those in the atmosphere, while the dilution rates are slower and the residence times are longer. As a result, particulate size distributions measured in a dilution tunnel may be very different from what would be seen in the atmosphere. Particles smaller than approximately 30 nm are much stronger influenced by variations in dilution ratio and rate than larger ones.

Considering the fact that nucleation, adsorption and coagulation during sampling are highly dependent upon many variables such as dilution ratio, residence time (length of sampling lines), humidity, temperature, concentrations of carbonaceous and volatile materials, and also given the fact that these parameters are not constant nor controllable unless to a certain extent, it was decided to exclude the additional ELPI stage for the current investigation.

The remainder of the exhaust gas component concentrations are obtained by analysing the sampling units at TNO Environment, Energy and Process Innovation's chemical laboratory. They include:

EC/OC

The quarts-filters containing EC/OC are analysed by using infrared detection (ASTM 1019) during staged combustion of the filters, from 550 to 600°C for OC and higher than 850°C for EC. The results are obtained in ng/sample. Using the constant flow and the tunnel dilution factor this is converted into ng/km.

C_1-C_5

The light hydrocarbons are analysed by gas chromatography with flame ionisation detection (GC-FID), in two steps. First methane is analysed. The other components have concentrations which are often much lower. Therefore they are concentrated first, and then analysed gas-chromatographically.

The following components are being analysed: methane and non-methane hydrocarbons: ethane, ethene, propane, propene, acetylene, n-butane, isopentane, n-pentane, isobutene, c-2-butene, t-2-butene, 1,3-butadiene and isoprene.

Results are obtained in concentration, and converted into ng/km following a calculation procedure similar to the regulated exhaust gas components.

C_6-C_{12}

The heavier hydrocarbons are desorbed from the Tenax absorbent and caught in a cold trap. The cold trap is subsequently heated and its contents is injected into a gas-chromatograph, and analysed using FID.

The following components are analysed: n-hexane, i-hexane, n-heptane, n-octane, i-octane, benzene, toluene, ethylbenzene, p,m-xylene, o-xylene, 1,2,3-trimethylbenzene, 1,2,4-trimethylbenzene and 1,3,5-trimethylbenzene.

Results of the analysis are obtained in ng/sample. Using the mass flow controller setting and the tunnel dilution factor, this can be converted into ng/test, and subsequently converted into ng/km.

NH_3

Ammonia is analysed using ion chromatography, based on suppressed conductivity. Results of analysis are obtained in ng/sample. Using the mass flow controller setting and the tunnel dilution factor, this can be converted into ng/test, and subsequently converted into ng/km.

Aldehydes

The solution that has been obtained after extraction of the filter cartridges with the acetonitrile solution, is analysed by Reversed Phase High Performance Liquid Chromatography (RP-HPLC) combined with a UV-detector. The formed hydrazones are sensitive to ultraviolet light.

The following components are analysed: formaldehyde, acetaldehyde, acrolein, acetone, propionaldehyde, crotonaldehyde, butyraldehyde, benzaldehyde, valeraldehyde, p-tolualdehyde, and hexanal.

Results of the analysis are obtained in ng/sample. By referring it to the original sample flow, obtained from the mass flow controller setting, and the tunnel dilution factor, this can be converted into ng/test, and subsequently converted into ng/km.

Solid and volatile PAH

The PAH containing particulate filters and the Amberlite XAD-2 absorbents, taken from the glass tube are extracted by means of Accelerent Solvent Extraction (ASE). The obtained extract is subsequently analysed using GC-MS isotope dilution. The following components are being analysed: naphthalene, acenaphthylene, acenaphthene, fluorene, fenanthrene, anthracene, fluoranthene, pyrene, benzo[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene, indeno[1,2,3-cd]pyrene, dibenzo[a,h]anthracene and benzo[g,h,i]perylene.

3.3 Accuracy

The concentration of the exhaust gas components is in many cases very low. This is partly because the vehicles are equipped with modern exhaust gas aftertreatment systems, and also because the raw exhaust gas is diluted with ambient air. The following measures are taken to overcome this problem:

- During the shortest test cycles, the CVS was equipped with a venturi with a lower flow capacity, leading to a lower tunnel dilution ratio. Consequently the concentrations in the diluted exhaust gas will be higher.
- For the different driving cycles and fuel types, a different setting of the adjustable mass flow controllers is applied. This is to ensure that each sampling unit receives sufficient sample, beyond the detection limit, but to not exceed the maximum capacity of the unit. For this purpose the experience of former measurements of unregulated exhaust gas components was used. Also a number of tests prior to the actual test had been performed, and settings were adjusted where necessary.
- For the ELPI measurements the range setting of the particle counter was determined by calibration during the preconditioning of the vehicle.
- During the tests, special effort is taken to keep background concentrations as low as possible by constantly refreshing the ambient air.

It is standard procedure to also sample dilution air in a Tedlar bag (see figure 3.1) during the sampling of the regulated exhaust gases and CO_2. These so-called blanks are also used to determine the background concentration of N_2O and NO/NO_2, and to correct for background concentration.

To obtain correction factors for the background concentration of the unregulated emission components, several blank samples (of ambient air) at different times of the day were taken. Blanks were taken by letting the CVS run for 1100 seconds, using the same venturi setting as usual, but only by drawing dilution air through the tunnel. The samples were analysed as usual, and the results for each unregulated component is used as correction factor for the actual measurements. For the ELPI measurements a different method is applied. Before the engine of the vehicle is started, the CVS and the ELPI are already running. The recorded data of approximately 2 minutes prior to the actual test serve as a correction for background particles.

4 Measurement results

4.1 General considerations

In the execution of the test programme a few problems occurred, and a few questions arose that had to be further investigated. They concerned the following items.

The bi-fuel LPG vehicles
One bi-fuel LPG vehicle showed a rather extreme NO_x emission during the cold start urban part of the CADC cycle. This behaviour partly persisted during the subsequent hot start urban CADC part, although the original hot start urban CADC part had not shown this high NO_x. The CO emission during the urban-cold CADC was surprisingly low and undetectable during the second urban-hot CADC, although that had not been the case during the earlier urban-hot CADC. This seemed to suggest a lambda-setting that had drifted away during the cold preconditioning or the 9ºC cold start, and was ‘learning back’ towards normal, although it had not yet reached its normal value yet. Possible causes could be:

- An individual problem with this particular vehicle
- Characteristic behaviour of this particular vehicle type, caused by the fact that it might not have been calibrated fully for the 9ºC starting condition.

By way of checking, a second vehicle was arranged and tested. Over the MVEG cycle it showed, within the reproducibility to be expected, the same behaviour as the first vehicle: both vehicles showed absolutely normal behaviour, and were well within the applicable emission limits. On LPG the second vehicle did not show the same extreme emission behaviour over the urban CADC as the first one, although a slight tendency to lean out and having to learn back still seemed to be present. A pure (monofuel) petrol vehicle did not show this tendency at all, so the behaviour did seem to be linked to the bi-fuel version and/or the LPG operation. Contact with the manufacturer did result in the statement that “the car is equipped with a rather sophisticated adaptation system”, and that they checked the vehicle’s behaviour at 9 ºC over the MVEG cycle, however not over the CADC urban driving cycles. Over the MVEG cycle they found very low emissions at 9 ºC. It was therefore decided that the test of the second vehicle had not fully solved the questions raised, and a third vehicle was subjected to a limited test programme (regulated emissions only, over the MVEG cycle and the CADC urban driving cycles). This vehicle showed similar lambda behaviour as the second one, so it was finally decided to regard the first vehicle as an individual outlier and to use the results of the second vehicle (which, in contrast to the third one, had been subjected to a full test programme including unregulated emissions) as typical for the vehicle type.

SO_2 measurements
The measurements of SO_2 showed a large spread. This was attributed to storage effects in the catalysts. By and large it was found, however, that the SO_2-emissions were in compliance with the sulphur content of the fuels used. For that reason it was decided to determine the SO_2-content, needed for the calculation of certain environmental indicators, by calculation from the sulphur content of the fuel, as was customary in the pre-catalyst era. As usual at that time, it was assumed that 95 % of the ‘sulphur-in’ is emitted as ‘SO_2-out’; the remainder being emitted in other forms (SO_3 included) or possibly retained in the system. Given the ever decreasing sulphur content of fuels and

the resulting small contribution of the SO_2 to the environmental indicators concerned, this may be regarded as sufficiently accurate.

SO_4^{--} measurements
SO_4^{--} is not reported since, given the problems outlined in the previous paragraph, it was not possible to measure it with sufficient accuracy, and calculation would not be acceptable since the SO_3 content of the SO_x is uncertain in the case of oxidation catalysts. In contrast to SO_2, it would not concern a small contributor to an environmental indicator largely determined by other components, but a component that would have to be judged in its own right. And determination by calculation is not sensible, since it would be exactly the different SO_3 content of oxidation catalyst equipped vehicles (in practice diesel vehicles) in comparison to the other technologies that would be of interest. It was therefore finally decided not to take this component into consideration at all. In theory this would look like an important omission from the results, but in practice, due to the nowadays very low fuel sulphur contents (see above), in contrast to earlier inventories the emission of SO_4^{--} is hardly of any significance anymore.

LPG and CNG vehicle starting
During the evaluation of the cold start behaviour of the LPG and CNG fuelled vehicles significant differences in behaviour became apparent. It was suspected that this might be caused by some bi-fuel vehicles starting on petrol, even when operating in the LPG/CNG mode, and others starting on LPG/CNG. This was checked and it was found that the vehicle types tested in practice use a complicated variety of strategies. For one CNG-vehicle it was found that even vehicles of one particular type may be equipped with different strategies, depending on the exact date of manufacture, and within that strategy may behave different for a warm start or a cold start. Additionally some vehicles may behave different for one start out of a fixed number or for one start per tankfilling. The reasons for such variety in behaviour in the case of bi-fuel vehicles is the necessity to keep the petrol injectors in working order and to prevent dry-out or hardening of its materials. The consequences of this strategy for the environmental performance are further discussed in Paragraph 6.2.

CNG vehicle results
As indicated in Paragraph 2.7 (Vehicle selection) only three vehicles were selected for the CNG testing. As it was, it appeared that two of these vehicles were calibrated relatively rich and the third one lean Unfortunately this resulted in a significant difference in emission behaviour and, given the small overall number of vehicles, in a very large statistical spread and hence a low statistical significance of the results.

Another problem resulting from the small CNG sample was that the average weight of these vehicles was not directly comparable to that of the other samples; even though a CNG vehicle can be expected to be heavier than a similar petrol fuelled vehicle, because of the higher weight of the equipment (especially the tanks), the actual difference in weight (187 kg) seemed more than could be accounted for this way. This meant that the fuel consumption, and hence the CO_2-emission, would not give a fair comparison. A small investigation (see below) showed that an additional weight of 140 kg would be a fair estimate. The measured fuel consumption and CO_2-emission were therefore ‘corrected’ for the ‘overweight’ of the actual sample.

An estimation was made for the weight of equipment typical for CNG vehicles. This weight is added up to the petrol weight that is taken as a reference. The CNG package of passenger cars nowadays generally consists of a few steel tanks, the amount of tanks and their volume depending on mounting space and desired driving range, a mounting brace for the fuel tank, stainless steel tubing, valves, ECU and injectors. From manufacturers data it was found that steel fuel tanks for CNG vehicles weigh about 1 kg per litre of tank volume. With an average tank volume of the test sample of 126 litre this adds 126 kg to the petrol reference vehicle. Another 15 kg were added for the other equipment. Together this adds 140 kg to the reference petrol vehicle weight. The corrected weight now amounts 1549 kg and is 38 kg less than the weight of the test sample of the 3 CNG vehicles. The relation between CO_2-emission and vehicle weight was established from the data set for the three different driver profiles in order to determine correction factors in CO_2/kg for the CO_2-emission of the CNG vehicles.

Although the tested CNG vehicles all have steel tanks, it can be expected that in the near future more CNG vehicles will be equipped with fuel tanks made of composite material. The application of composite CNG tanks is permitted by legislation and these tanks are already available on the market. The weight of the composite tanks is about 40% of the weight of steel tanks. Through this weight reduction, the application of composite tanks would further reduce the CO_2-emission of CNG vehicles.
For LPG vehicles the application of lightweight composite LPG tanks is recently permitted by legislation and these tanks are expected to be soon available on the market. For LPG vehicles, however, the CO_2-emission reduction will be less because the weight reduction is less than for CNG vehicles (the total tank weight at CNG vehicles is higher).

4.2 Detailed results

All measured emission values are presented in Annex B. The values are presented as tables of measured emissions, and as 3-D graphs showing profiles and differences between fuels. The Annex also contains all numerical values calculated for the environmental indicators.

4.3 Regulated emissions

For all vehicles the regulated emissions were determined in the official homologation procedure. This was done to check if the vehicles were in acceptable condition, and did not show any emission related defect that might influence the comparison. It turned out that all vehicles complied with the emission requirements valid for their level of the legislation. This is further shown in the figures below.

Figure 8 shows the CO and HC-emissions of the SI (spark ignition) engines. As can be seen the regulated emissions of most of these vehicles, although certified as Euro 3 vehicles, are below the Euro 4 limits. The same is true for the NO_x-emissions, as shown in *Figure 9*. Such behaviour (actual emission values one step ahead of the legislation) is quite characteristic for 3-way catalyst equipped vehicles. The relatively large margin to the type approval limit values (compared to diesel, see below) can also be seen as a safety margin with respect to the ageing effect of petrol vehicle emissions. It was concluded that all SI vehicles could be regarded as being in good running order.

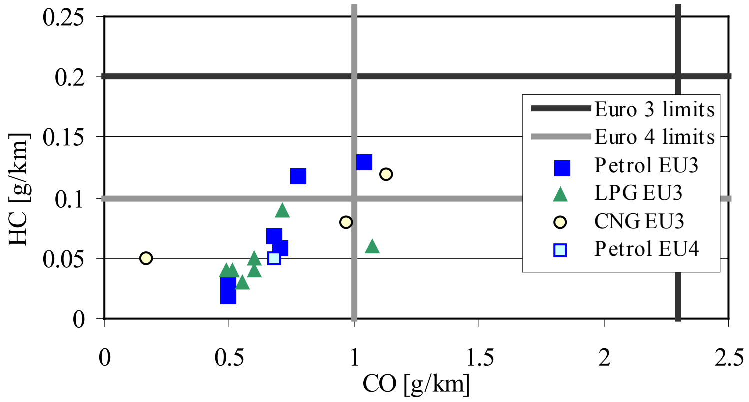


Figure 8: Spark ignition HC and CO, EURO 3 en 4

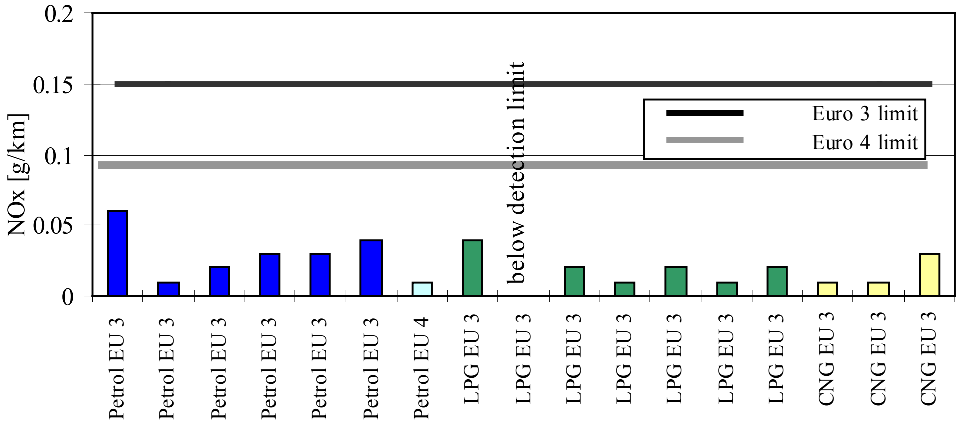


Figure 9: Spark ignition NO_x, EURO 3 en 4

For diesel vehicles the emissions of CO and HC are not a problem. Possible shortcomings may more readily expected concerning NO_x and PM. *Figure 10* shows the emissions of HC + NO_x against those of CO. It shows the HC + NO_x emissions to be closer to the Euro 3 limit than those of the SI engines; it is caused by the relatively high figures for NO_x, and not by the HC-emissions. *Figure 11* shows the situation with regard to NO_x and PM, which presents a similar picture. Such behaviour is characteristic for diesel vehicles. The emission behaviour of diesel vehicles in general is more stable with respect to ageing so that smaller margins to the limits can be allowed. The emission behaviour does not therefore need to be taken as a sign of marginal operational performance. For the diesel engined vehicles it was therefore also concluded that they were in good running order.

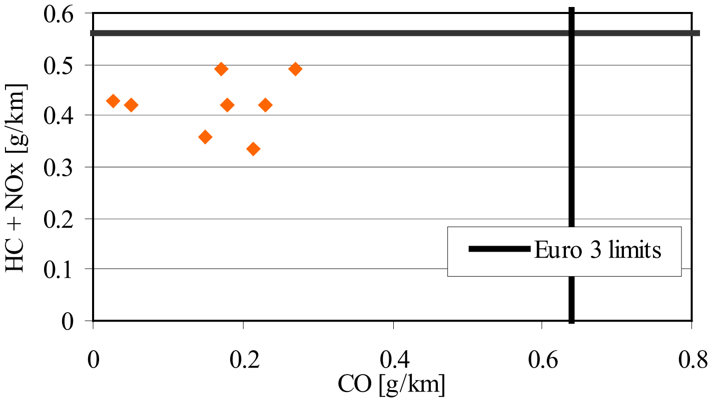


Figure 10: Diesel CO and HC+NO_x, EURO 3

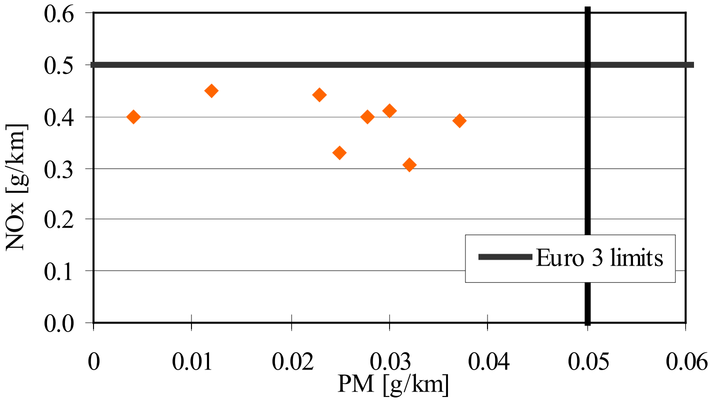


Figure 11: Diesel PM and NO_x, EURO 3

4.4 Unregulated emissions

With regard to the situation concerning the unregulated emissions one should bear in mind that the Dutch programme was extended, relative to the European Emission Test Programme (EETP), with additional components (NH_3 and EC/OC). Additionally for various reasons in the EETP not all measurements could be, or were, performed on all cars. Also in some cases the results of some laboratories could not be used due to different measurement set-up (e.g. one laboratory did not measure the volatile part of the PAH-emissions, which would not introduce a large error for diesel engines, but which might ignore the majority of PAH-emissions in the case of SI engines). In all cases that concerned the warm start CADC. Since the missing data only represents 0.5% of the total amount of data it was felt that this has not seriously flawed the value of the investigation.

In such cases the averages were determined from the vehicles on which they were measured, meaning that in those cases the sample size was less than 7. The tables below lists the missing measurements and the actual sample sizes respectively.

Table 5 Missing data

Passenger cars	*Fuel*	*Driving Cycle*	*Component (group)*
Renault Scenic	petrol, diesel, LPG	CADC	volatile PAH, NH_3, EC/OC
Peugeot 406	petrol, diesel, LPG	CADC	volatile PAH, NH_3, EC/OC
Opel Astra	petrol, diesel, LPG	CADC	NO_2, N_2O, NH_3, EC/OC
Opel Vectra	petrol, diesel, LPG	CADC	NO_2, N_2O, NH_3, EC/OC
Volvo V70	CNG	CADC	N_2O, CH_4, C_2-C_{12} with exception of BTX

Table 6 Sample size

Component (group)	*Fuel*	*n [-]* *CADC*	*n [-]* *CADC urban*
CO, HC, NOx, PM, CO_2, FC	Petrol	7	7
	Diesel	7	7
	LPG	7	7
	CNG	3	3
ELPI (particle size distribution)	Petrol	7	7
	Diesel	7	7
	LPG	7	7
	CNG	3	3
PAH	Petrol	**5**	7
	Diesel	**5**	7
	LPG	**5**	7
	CNG	3	3
Aldehydes	Petrol	7	7
	Diesel	7	7
	LPG	7	7
	CNG	3	3
C_1-C_{12}	Petrol	7	7
	Diesel	7	7
	LPG	7	7
	CNG	3	3
NO_2	Petrol	**6**	7
	Diesel	**6**	7
	LPG	**6**	7
	CNG	**2**	3
NH_3	Petrol	**4**	7
	Diesel	**4**	7
	LPG	**4**	7
	CNG	**2**	3
N_2O	Petrol	**6**	7
	Diesel	**6**	7
	LPG	**6**	7
	CNG	**2**	3
EC/OC	Petrol	**4**	7
	Diesel	**4**	7
	LPG	**4**	7
	CNG	**2**	3

4.5 Programme results

As outlined in the introduction (Chapter 1) the purpose of the programme was twofold:

- To arrive at a useful comparison of the environmental performance of the four fuels involved.
- To arrive at an up-to-date set of emission factors that can be used in various national or local inventories and studies.

The overall programme results relating to the first objective are presented in Chapter 5. The detailed numerical results are contained in Annex B. Similarly Annex B does also contain the emission factors needed for the second objective.

Some remarkable effects are set out below, however.

PAH emissions

The PAH emissions are the highest for all vehicles in the local driver situation. The petrol vehicles show a slightly higher PAH emission than the other fuels for all three driver situations. This is remarkable since the study from 1993 revealed the highest PAH emissions by far for the diesel vehicles. The relatively low PAH emissions of the diesel vehicles in this research can probably be attributed to application of an effective oxidation catalyst on these vehicles. This will be further discussed in Chapter 9.

Aldehydes

The emissions of aldehydes are again the highest for all vehicles in the local driver situation. The diesel vehicles clearly show the highest emission of the light aldehydes (formaldehyde, acetaldehyde and acrolein). The level of the heavier aldehydes in the measured range is almost the same for the petrol vehicles as for the diesel vehicles, whereas the LPG vehicles show a somewhat lower level and the CNG vehicles show levels near the detection limit.

C_1-C_{12}

As expected the CNG vehicles show relatively high emission of methane compared to the other fuels, the LPG vehicles show somewhat higher emission of propane and butane. These emissions most probably all stem directly from unburned fuel. For the other compounds of the C_1-C_{12} range the emissions are very low in the business driver situation. In that situation (engine and catalyst fully warmed up) the catalyst operate at the highest efficiency. In the local driver situation, however, the emissions of the light as well as the heavier hydrocarbons are higher for the spark ignition engines with 3-way catalyst (especially on petrol). The diesel engines show a much smaller cold start effect on the hydrocarbon emissions. Remarkable is the high level of benzene, toluene and xylene emission (BTX) by the petrol vehicles, followed by LPG and CNG. These emissions are again much lower for the diesel vehicles. The emissions of BTX by LPG and CNG vehicles in the local driver situation are probably caused by the fact that these vehicles start on petrol. This will be further discussed in Chapter 5.

NH_3

The emission of NH_3 is relatively high for the gaseous fuelled vehicles, followed by the petrol vehicles. The diesel vehicles show a very low emission of NH_3. The emission of NH_3 is relatively high in the business driver situation with again the exception for the diesel vehicles.

N_2O

The level of the N_2O-emission is very low for all vehicles in the business driver situation, although the diesel vehicles show somewhat more N_2O than the others. In the local driver situation the emission of N_2O is somewhat higher with again a slightly higher emission for the diesel vehicles. From former research it is known that N_2O is mainly a cold start phenomenon, this explains the low emission of N_2O while driving with a warm engine.

NO/NO_2

The share of NO_2 in the NO_X-emission of the diesel vehicles is around 55% in the business driver situation. For the local driver situation this share is somewhat lower (around 40%). For the other fuels the NO_2 share is much lower (15-25%), it should be remarked however that this figure is less accurate than for the diesel vehicles due to the low NO_2-emissions of the SI engines.

EC/OC

In accordance with the particulates emissions, the emissions of elementary carbon (EC) and organic carbon (OC) are the highest for the diesel vehicles. The EC/OC-emission is dominated by the EC part in the case of diesel. For the other fuels the EC and OC emissions are near the detection limit, with the exception of petrol and LPG in the local driver situation.

5 Environmental performance

In this chapter the results are presented of the comparison between the four fuels. The set-up is as follows:

- There are three paragraphs concerning the different environmental effects: Human health effects (5.1), Ecological effects (5.2) and Climatic effects (5.3), as set out in Paragraph 2.2 (The environmental effects). They are followed by an overall summary (5.4).
- For the first three paragraphs there is per paragraph an itemised summary of the most noticeable aspects (arranged per group of components or environmental indicators), followed by a ‘scoring table’ and a summary of the paragraph. At the end of each paragraph figures are giving a graphic representation of the various emission components or environmental indicators, and their relative composition where relevant.
- Paragraph 5.4 gives an overall summary of the environmental performance as an itemised list and an overall ‘scoring table’.

Driver profiles

The environmental effects are determined for the patterns of use indicated as ‘business driver’, ‘local driver’ and ‘average driver’, as set out in Paragraph 2.6 (Laboratory programme). For the business driver only hot starts were taken into account, in combination with a full CADC cycle. For the local driver a cold start at + 9ºC was used, in combination with urban traffic only. For the average driver again a full CADC (however extended with two urban parts of the CADC) was taken into account, but then combined with a representative cold start at + 9ºC. It should be noted that this does not make the average driver situation an average of the other two situations, since for the average driver the cold start effect, when expressed in g/km, is spread out over a longer trip length than in the case of the local driver. So in many cases the average driver situation looks more like the business driver, except for components or effects with a very high cold start contribution.

Rating

In each paragraph the results are summarised in a number of tables. For each of the effects an estimate is made of the relevance of the emission component or group of components. This relevance is based on the following considerations:

- What is the risk involved (nuisance is e.g. rated lower than life threatening aspects)
- Does the component/group represent a serious existing air quality problem (a substance or effect that does not, or no longer, cause an air quality problem is rated lower than one that does regularly exceed the air quality criteria)
- Does traffic make a sizable contribution to the overall emission of the substance or effect (an air quality problem that is mainly caused by other sources is rated lower that one where traffic is one of the main causes)

Using this ‘relevance’ in the overall evaluation allows to evaluate in a more adequate way e.g. fuel A, that may present a useful limitation of a pressing air quality problem X, against fuel B, that may show a higher emission of substance Y, when traffic in its totality hardly makes a significant contribution to the air quality problem caused by Y. The relevance as such was established with the help of the “MilieuCompendium” [7] and after consultation of experts in that particular field (National Institute of Public

Health and the Environment (RIVM) and TNO Environment, Energy and Process Innovation (TNO-MEP) in the Netherlands).

In each cell of the table a rating is established by giving a score '--' to the case with the highest impact potential for the effect under consideration (i.e. to the 'case' where the emission or environmental indicator is highest). Subsequently the results for the other 'cases' are scored relatively to this case on a scale between '--' and '++'. A 'case' in this context means a combination of fuel and driver profile. This approach allows both the mutual comparison of the fuels and the comparison of the driver profiles, plus the combination of both. It allows one to see e.g. that for the health effects, in the case of spark ignition engines the negative effects are limited to the 'local driver' profile (cold start effects), and even then mostly to the petrol engined vehicles. It was felt that by setting up the scoring this way, the 'problem cases' could be identified more easily than in the 1993 study.

Per paragraph a summarised score is made. To this end the following approach is taken:

- Only the environmental indicators are taken into account that had a medium or high overall relevance.
- In the case of the health effects (with many different indicators) both PM and PAH were included on the basis of one combined score.

Comparison with the European Emission Test Programme (EETP)

The EETP was set up with the intention to compare the environmental performance of the different fuels on the basis of only the CADC with a hot start, which is in fact the same situation as the business driver profile that is presented in this report. Since the ratings in the case of the EETP will be established relatively for only one driver profile, the results cannot be compared directly with the results presented in this chapter. To avoid possible misunderstandings with respect to the results of both test programmes, the evaluation of the business driver profile in this report was also carried out separately from the other two driver profiles. The table with the evaluation of the environmental performance indicators based on only the business driver profile can be found in Annex D. The rating in this table is established by giving a score 'o' to the average impact potential level of all fuels for the effect under consideration. Subsequently the results of the fuels are scored relatively to this average level on a scale between '--' and '++'. This approach allows the mutual comparison of the fuels for this particular driver profile.

Graphic representations

At the end of each paragraph figures are giving a graphic representation of the various emission components or environmental indicators The bars in the figures represent the average values per fuel and per driver profile. The thin lines upon the bars represent the calculated confidence intervals. The methodology of this calculation is explained in Chapter 8. If an environmental indicator is composed of more than one substance, a pie chart is given next to the bar chart in order to give an indication on how the composition is distributed over the total result.

The absolute values of the environmental indicators can be found in Annex C.

5.1 Human health effects

Discussion of CO-, NO_2-, particulate- and SO_2-emissions (see Figure 12):

- The emission of CO is mainly a concern of the 'local driver' situation and then only in the case of spark ignition engines. This is obviously the result of the catalyst warm-up effect. All other situations are hardly of significance. Generally speaking, however, the relevance of CO-emissions for local air quality is low anyway. For the large spread in the results for the CNG vehicles, see Paragraph 4.1.
- The NO_2-emission is only of importance for diesel engines, for all three patterns of use; there is no appreciable mutual difference between these three patterns of use. This is directly linked to the relatively high NO_x-emission of those engines, in combination with the high NO_2-content within this NO_x due to the use of an oxidation catalyst. The NO_2-content amounts approximately 50 to 60% for the diesel vehicles. For the petrol, LPG and CNG vehicles the NO_2-content is in the order of 10 to 25%. The values for the spark ignition vehicles are less accurate, however, since the measured level of NO_x-emission is much lower than for the diesel vehicles.
- As is to be expected the emission of primary PM is also of importance only for diesel engines, for all three patterns of use, although the emission is higher for the local driver (cold start) than for the business driver (no cold start). The emissions for the spark ignition engines, including those for the gaseous fuels, are still measurable though, being in the order of 5-20 % of those for diesel engines.
- The secondary PM potential shows a very similar pattern to that of the primary PM-emission, but the actual figures are a full order of magnitude higher. The composition of the weighed contributions shows that for the liquid fuels (and especially diesel) the contribution of the NO_x is the determinig factor. For the gaseous fuels there is a significant secondary contribution of NH_3, except for the 'local driver' situation, but in absolute terms this contribution is still very small. So the high NO_x-emission of the diesels turns out to be the determining factor.
- As set out in Paragraph 4.1, it was finally decided to determine the SO_2 contribution of the various fuels by calculation, rather than on the basis of the measured values. On that basis the emission of SO_2 turns out to be highest for petrol and lowest for CNG, with higher values for the local driver profile because of the higher fuel consumption. The absolute values are low, though, because of the current low sulphur contents.

Discussion of ELPI particulates size distribution results (see Figure 13 to Figure 16):

- For particulates the following nomenclature is generally used (this is graphically illustrated in *Figure 15*):
  - PM_{10} : all particles smaller than 10 μm
  - Fine particles: all particles smaller than 2.5 μm
  - Ultrafine particles: all particles smaller than 0.1 μm = 100 nm.
  - Nanoparticles: all particles smaller than 0.05 μm = 50 nm.

  As can be seen the particles of all four fuels can be classified as 'fine' or smaller, when their numbers are taken into account. Since the larger particles have a much higher mass, a gravimetric distribution would look completely different, of course.
- The different numbers of the cold start urban cycle against the hot start urban cycle (hence illustrating the cold start itself) are shown in *Figure 16*, for the diesel engines, and for the petrol engines as a typical example of the spark ignition engine. As can be seen the cold start effect is similar in shape in both cases. But for the petrol engines the additional cold start numbers are 5 to 20 times higher than the

hot numbers, whereas for the diesel engines the additional numbers are a factor of 1,5 to 4 times higher than the hot numbers. Even so the additional cold start numbers for petrol engines are still lower than those of the diesel engines. The major conclusion so far seems to be, however, that the general shape of the distributions is largely similar for all fuels. This is further investigated in *Figure 14*, however.

- *Figure 14* shows an indexed representation of the particle numbers, with diesel set at 100. From these figures it can be concluded that the numbers from the spark ignition engines are uniformly more than an order of magnitude lower than those from the diesel engine in the case of the local driver, but that they rise towards those of the diesel for the nanoparticles in the case of the business driver and the average driver (although much less so in the case of CNG). From a further analysis it was found that this is almost completely due to the results from the motorway part of the driving cycle. The most likely explanation seems to be that at 130 km/h and higher full load enrichment comes into play. It may however also be caused by a measurement artefact (see Paragraph 3.2.2). The numbers from the local driver situation of petrol and LPG result almost exclusively from the cold start phase, where a certain degree of enrichment also plays a role. In a similar indexed representation (not shown here) the numbers from the spark ignition engines hardly rise above the zero axis for the hot started urban part.

Discussion of the PAH emissions (see Figure 17):

The PAH-emissions considered are the sum of the 2A components (‘probably carcinogenic’), the sum of the 2B components (‘possibly carcinogenic’) and BaP. Generally speaking the four groups or individual components show similar patterns: high emissions for the local driver and low to negligible emissions for the other two driving patterns, especially that of the business driver. Noteworthy aspects are:

- The fact that the emissions are significantly higher for the local driver than for the other two driver profiles means that the emissions are especially caused by the cold start, even for the diesel vehicles.
- The spread in results is large relative to the average, meaning that the differences between vehicles of the same fuel group are large.
- Petrol fuellled vehicles show the highest PAH-emissions, whereas diesel fuelled vehicles emit equal or less PAH. This is an outstanding difference with the past; it seems to be a result of the use of effective oxidation catalysts at diesel vehicles nowadays.
- Depending on the group or individual component, the gaseous fuels emit equal to the liquid fuels or significantly less, without a clear overall trend. In combination with the fact that these emissions are primarily caused by the cold start, this seems to point to the starting on petrol (before switching to gas) as the primary cause. For a further discussion of these aspects see Paragraphs 6.2.

Discussion of other VOC components (see Figure 18):

The contributions of the other VOC components are to a very high degree determined by the cold start effect. This results either in a high emissions of the spark ignition engines, as in the case of 1,3-butadiene and BTX, or of the diesel engines, as in the case of the light aldehydes (LA). Further noteworthy aspects are:

- The emissions of the spark ignition engines are very close to zero for the business driver. This automatically means an excessive difference between the business driver and the local driver, resulting in a small but detectable contribution of the cold start to the average driver situation.

- The emissions of light aldehydes are still detectable for the business driver situation in the case of diesel engines.
- Considering the spread in results there is hardly a significant difference between petrol and LPG for the emission of 1,3-butadiene and BTX. CNG vehicles show lower emissions than LPG vehicles, but especially for BTX the spread is very large. Again this seems to be caused by differences in cold starting strategy.
- Formaldehyde dominates the LA-emissions for all fuels in almost all patterns of use, with acetaldehyde determining most of the rest; acrolein does not seem to play a large role.
- As expected the LA-emissions in the case of CNG are for the major part determined by formaldehyde formation, but in absolute terms this emission is still low, pointing to good catalyst activity.
- For the spark ignition engines toluene has the largest share in the BTX-emission, whereas for diesel engines this is true for benzene. The BTX-emission for the diesel engines is very low, however. Xylene plays a large secondary role in the case of the gaseous fuels. Again it must be assumed that starting on petrol is the main cause of the BTX-emissions for gaseous fuels, since these fuels themselves do not contain cyclic components.

Discussion of smog potentials (see Figure 19):
Both smog potentials are mainly cold start effects, although the TOFP is of importance for all three driving patterns in the case of diesel engines. Further noteworthy aspects are:

- The POCP indicator is largely determined by CO for the spark ignition engines, and we already saw that CO is largely a cold start effect.
- The differences between the different spark ignition engine fuels are either small or not significant considering the large spread in results.
- For diesel engines the POCP indicator is more determined by the organic emissions as contributors, except the C_6-C_{12} range of VOC. But the emissions of all of these are low in the case of diesel engines, or (as for aldehydes) the weighing factor is low. Hence diesel engines show particularly low values on this indicator.
- The TOFP indicator is also largely determined by CO in the case of spark ignition engines, although NO_x starts to be of a significant level for petrol and LPG, and for CNG in the case of the local driver. This means that the overall pattern is not largely different from that of the POCP indicator for the spark ignition engines, although the difference between the local driver and the business driver is less extreme than for the POCP indicator, due to a significant level of NO_x-emission on the motorway.
- For diesel engines the TOFP indicator is largely determined by the NO_x-emission (which is not taken into account for the POCP indicator), meaning that for this indicator the diesel engine has a higher impact potential than the spark ignition engines. In the case of the local driver the difference between the diesel engine and the spark ignition engines is much smaller than in the other driver situations. The general conclusion for the smog potential indicators is that the differences between the fuels for the spark ignition engines are not really of much, if any, consequence, and that the diesel either scores very low, or particularly high, depending on the indicator used.

Summary:
Below the results are summarised in a table, as explained in the introduction to this chapter.

Table 7: Summary of the results: Health effects

Business driver

Component/effect	relevance	Petrol	Diesel	LPG	CNG
CO	low	++	++	++	+
NO_2	high	++	--	++	++
Primary PM	high	++	-	++	++
Secondary PM	high	++	-	++	++
PM size distribution	high	o	--	o	+
SO_2	low	-	o	o	+
PAH 2A	high	++	++	++	++
PAH 2B	medium	++	++	++	++
Benz-a-pyrene	high	++	++	++	++
1,3-butadiene	high	++	++	++	++
Light aldehydes	high	++	++	++	++
BTX	medium	++	++	++	++
Smog potent. POCP	high	++	++	++	++
Smog potent. TOFP	high	++	-	++	++

Local driver

Component/effect	relevance	Petrol	Diesel	LPG	CNG
CO	low	--	++	--	o
NO_2	high	++	--	++	++
Primary PM	high	+	--	+	+
Secondary PM	high	+	--	+	+
PM size distribution	high	+	-	+	++
SO_2	low	--	o	o	+
PAH 2A	high	--	o	+	++
PAH 2B	medium	--	o	o	++
Benz-a-pyrene	high	--	-	+	++
1,3-butadiene	high	--	+	-	+
Light aldehydes	high	+	--	++	++
BTX	medium	--	++	-	+
Smog potent. POCP	high	--	++	-	o
Smog potent. TOFP	high	-	--	-	o

Average driver

Component/effect	relevance	Petrol	Diesel	LPG	CNG
CO	low	+	++	+	+
NO_2	high	++	--	++	++
Primary PM	high	+	-	+	++
Secondary PM	high	+	-	+	++
PM size distribution	high	o	--	o	+
SO_2	low	-	o	o	+
PAH 2A	high	+	+	++	++
PAH 2B	medium	+	+	++	++
Benz-a-pyrene	high	+	+	++	++
1,3-butadiene	high	+	++	+	++
light aldehydes	high	++	+	++	++
BTX	medium	+	++	+	++
Smog potent. POCP	high	+	++	+	+
Smog potent. TOFP	high	+	-	+	+

--	Very high impact potential	(highest impact potential of all cases for the effect under consideration; a 'case' means a combination of fuel and driver profile)
-	High impact potential	(relative to case with highest impact potential)
0	Average impact potential	(relative to case with highest impact potential)
+	Low impact potential	(relative to case with highest impact potential)
++	Very low impact potential	(relative to case with highest impact potential)

The most outstanding points are:

- For the business driver and the average driver the emissions relevant for human health effects are very low with the exception of PM and NO_x for diesel engines, plus all NO_x-related effects for these engines.
- The cold start effect (local driver) is highest for petrol, LPG and diesel, and considerably less for CNG.

The overall situation

The overall evaluation is presented in the following table. As discussed in the introduction to this chapter only the effects with a medium or high relevance have been included in this overall evaluation.

Table 8: Overall evaluation of the health effects

Business driver

Component/effect	relevance	Petrol	Diesel	LPG	CNG
NO_2	high	++	--	++	++
Overall PM	high	+	-	+	++
overall PAH	high	++	++	++	++
1,3-butadiene	high	++	++	++	++
Light aldehydes	high	++	++	++	++
BTX	medium	++	++	++	++
Smog potent. POCP	high	++	++	++	++
Smog potent. TOFP	high	++	-	++	++

Local driver

Component/effect	relevance	Petrol	Diesel	LPG	CNG
NO_2	high	++	--	++	++
Overall PM	high	+	--	+	+
Overall PAH	high	--	o	+	++
1,3-butadiene	high	--	+	-	+
Light aldehydes	high	+	--	++	++
BTX	medium	--	++	-	+
Smog potent. POCP	high	--	++	-	o
Smog potent. TOFP	high	-	--	-	o

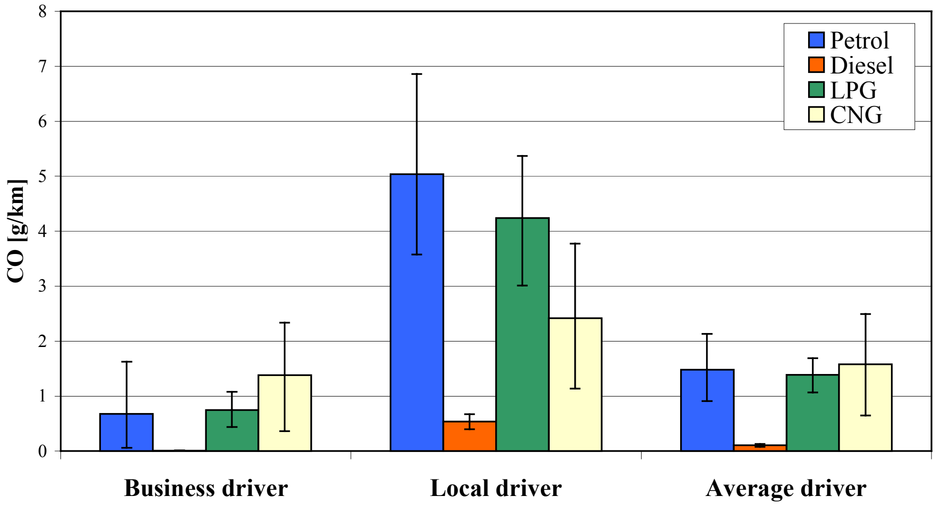
Average driver

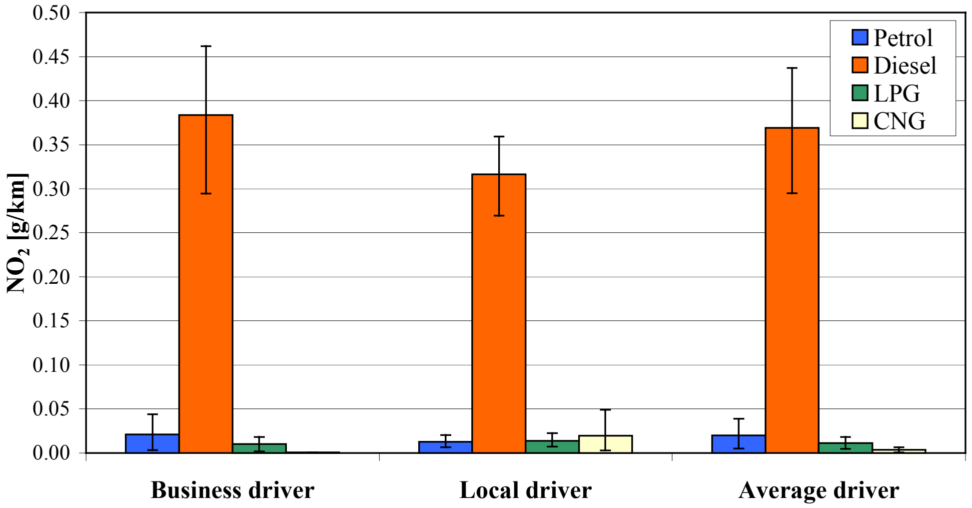
Component/effect	relevance	Petrol	Diesel	LPG	CNG
NO_2	high	++	--	++	++
Overall PM	high	+	-	+	++
Overall PAH	high	+	+	++	++
1,3-butadiene	high	+	++	+	++
Light aldehydes	high	++	+	++	++
BTX	medium	+	++	+	++
Smog potent. POCP	high	+	++	+	+
Smog potent. TOFP	high	+	-	+	+

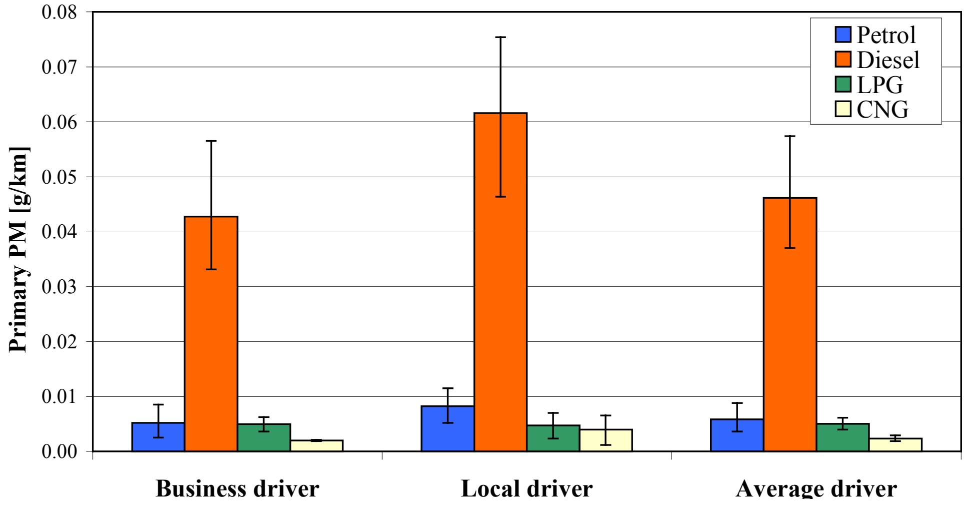
--	Very high impact potential	(highest impact potential of all cases for the effect under consideration; a 'case' means a combination of fuel and driver profile)
-	High impact potential	(relative to case with highest impact potential)
0	Average impact potential	(relative to case with highest impact potential)
+	Low impact potential	(relative to case with highest impact potential)
++	Very low impact potential	(relative to case with highest impact potential)

The most outstanding points are:

- The overall evaluation shows that for a hot engine the human health effects are very low in the case of SI engines. Diesel engines show higher impact potentials due to higher PM and NO_x.
- In local situations (with cold start) another picture emerges. Here the petrol engine shows the highest impact potentials, followed by the diesel engine and the LPG engine. CNG suffers the least from the cold start.
- It is assumed that the additional cold start emissions from the LPG and CNG engines are primarily caused by their starting on petrol.
- For the average driver only the result of the petrol engine is significantly influenced by the cold start, because of the magnitude of the cold start effect in that case.
- In general the gaseous fuels show the lowest emissions for the average driver, and diesel the highest emissions.


CO [g/km]
0
1
2
3
4
5
6
7
8
Petrol
Diesel
LPG
CNG
Business driver
Local driver
Average driver


NO_2 [g/km]
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
Petrol
Diesel
LPG
CNG
Business driver
Local driver
Average driver


Primary PM [g/km]
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
Petrol
Diesel
LPG
CNG
Business driver
Local driver
Average driver

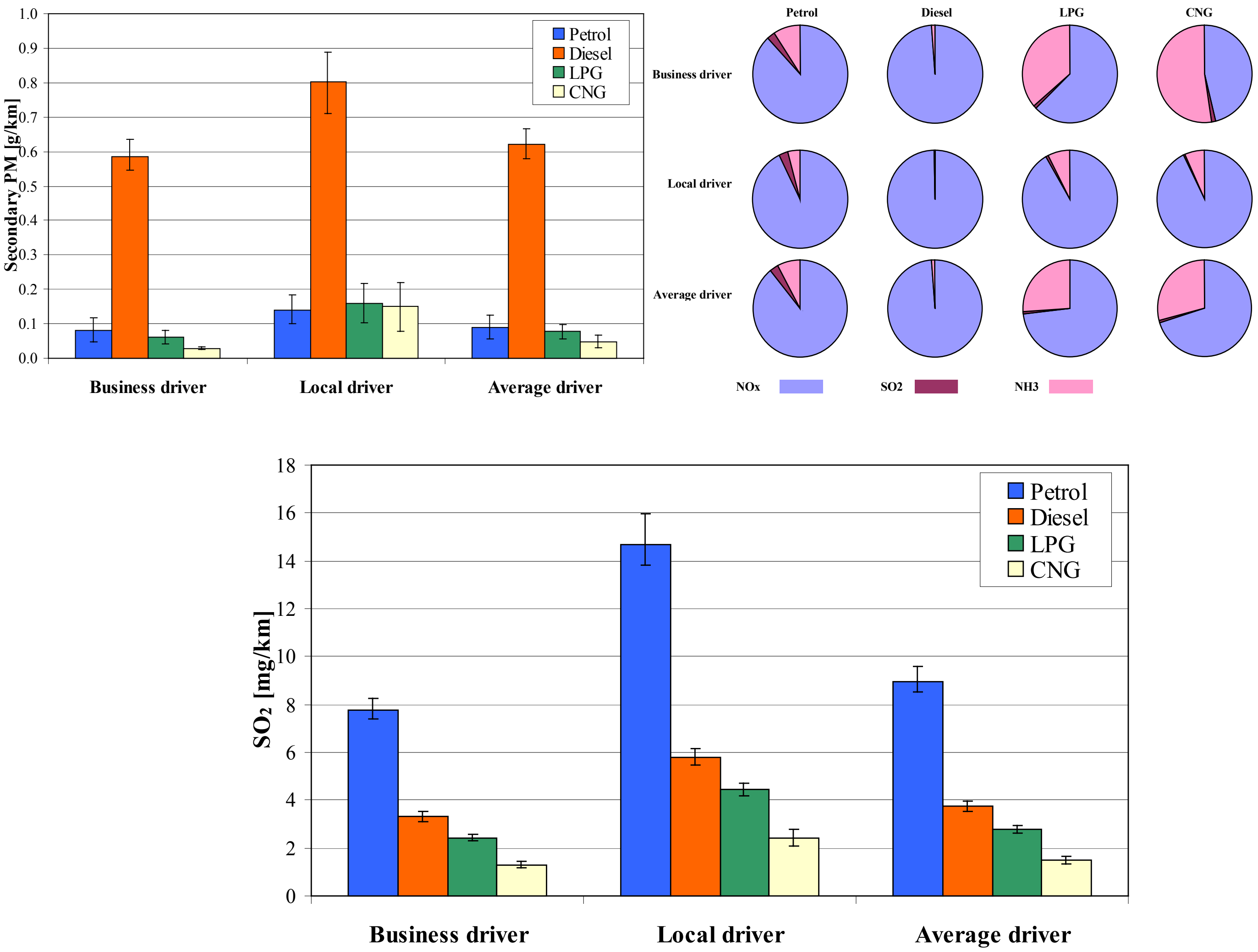


Figure 12: The measured health effect indicators CO, NO_2, particulates and the calculated SO_2-emission (bars) and the relative weighed contributions of the components involved to the calculation (pies).

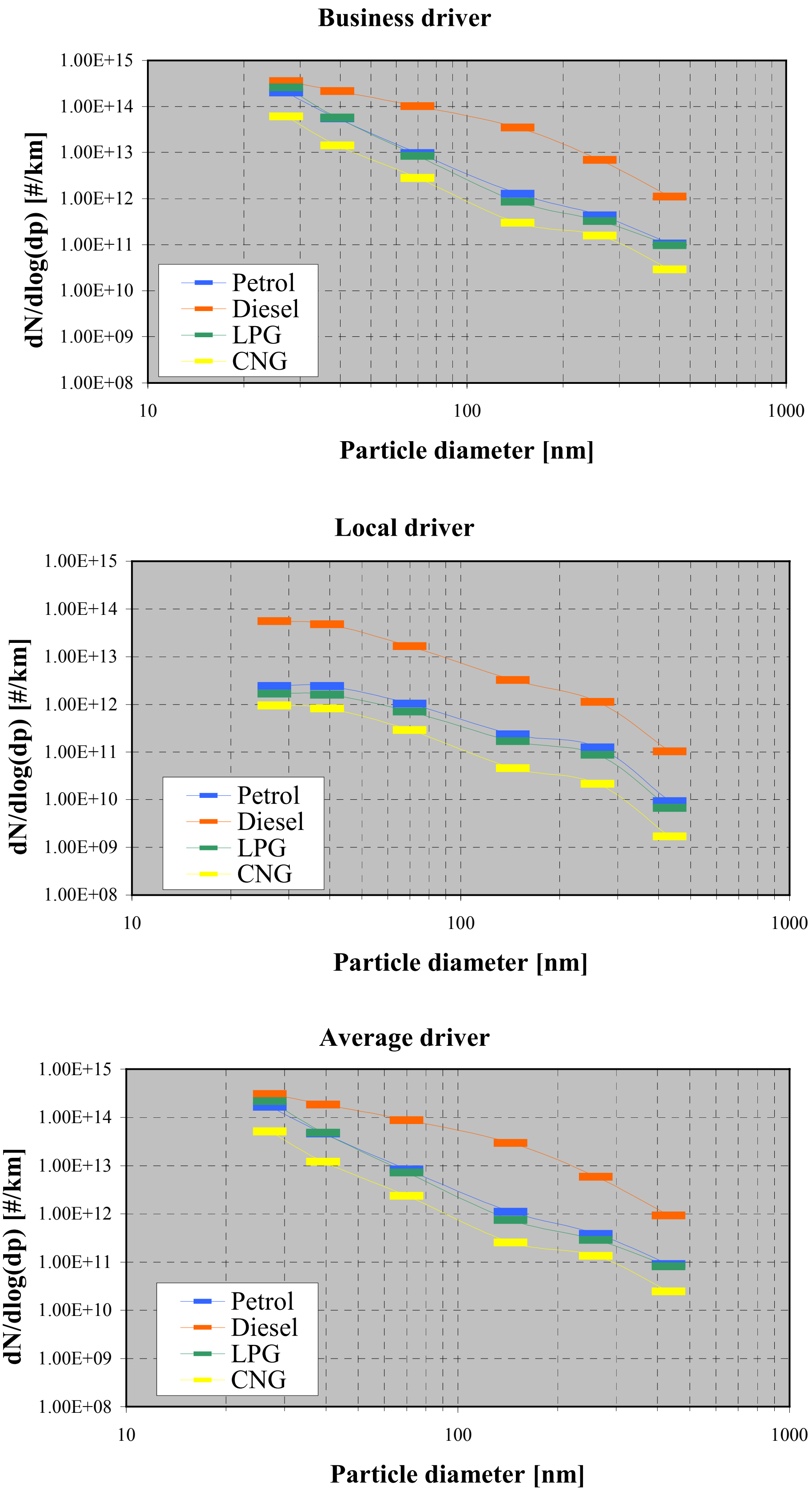


Figure 13: Particle size distribution as measured by the ELPI

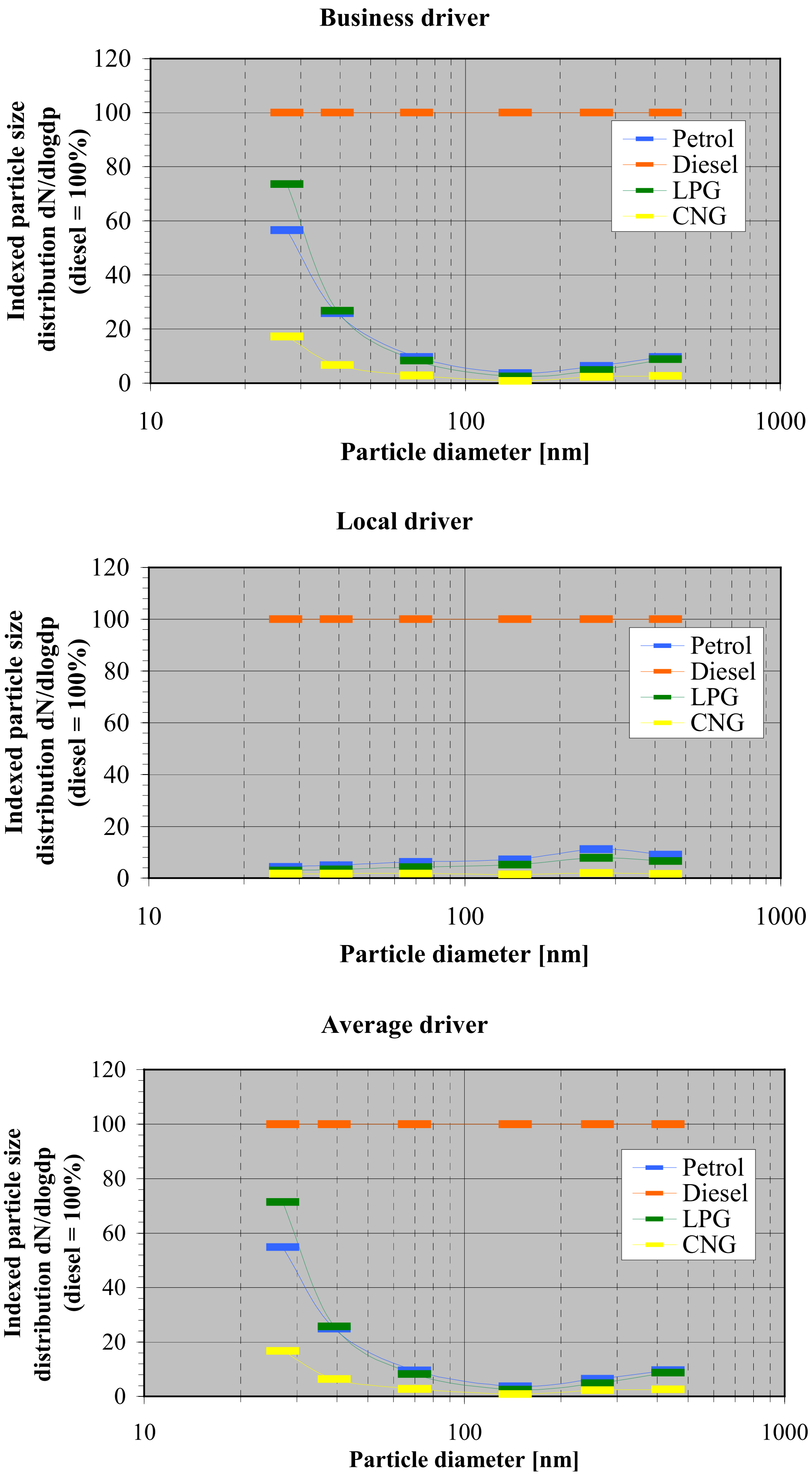


Figure 14: *Particle size distribution as measured by the ELPI (diesel = 100%)*

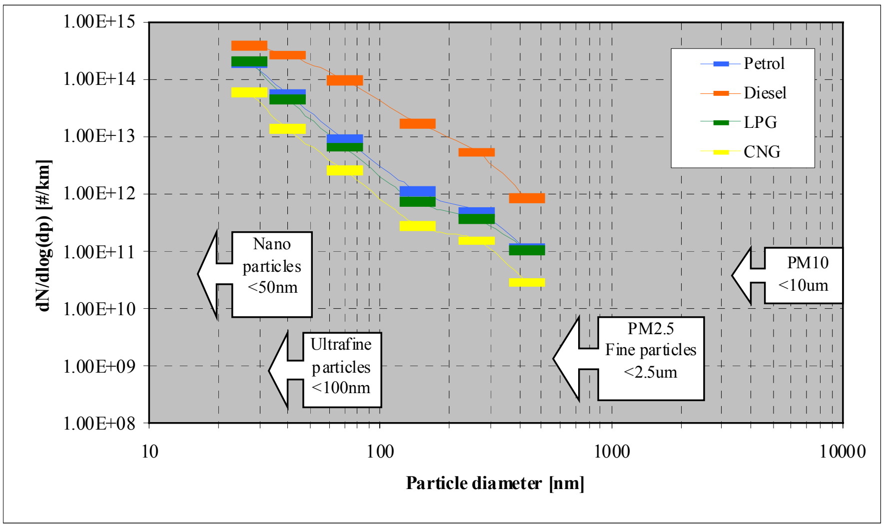


Figure 15: Definition of particle sizes

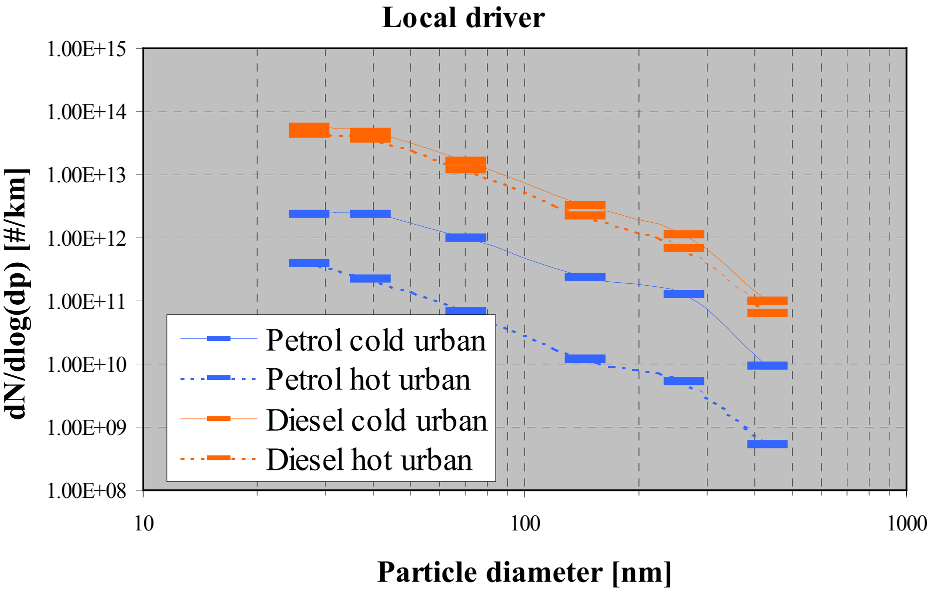


Figure 16: Particle size distributions for cold started and hot started urban driving, as measured by the ELPI

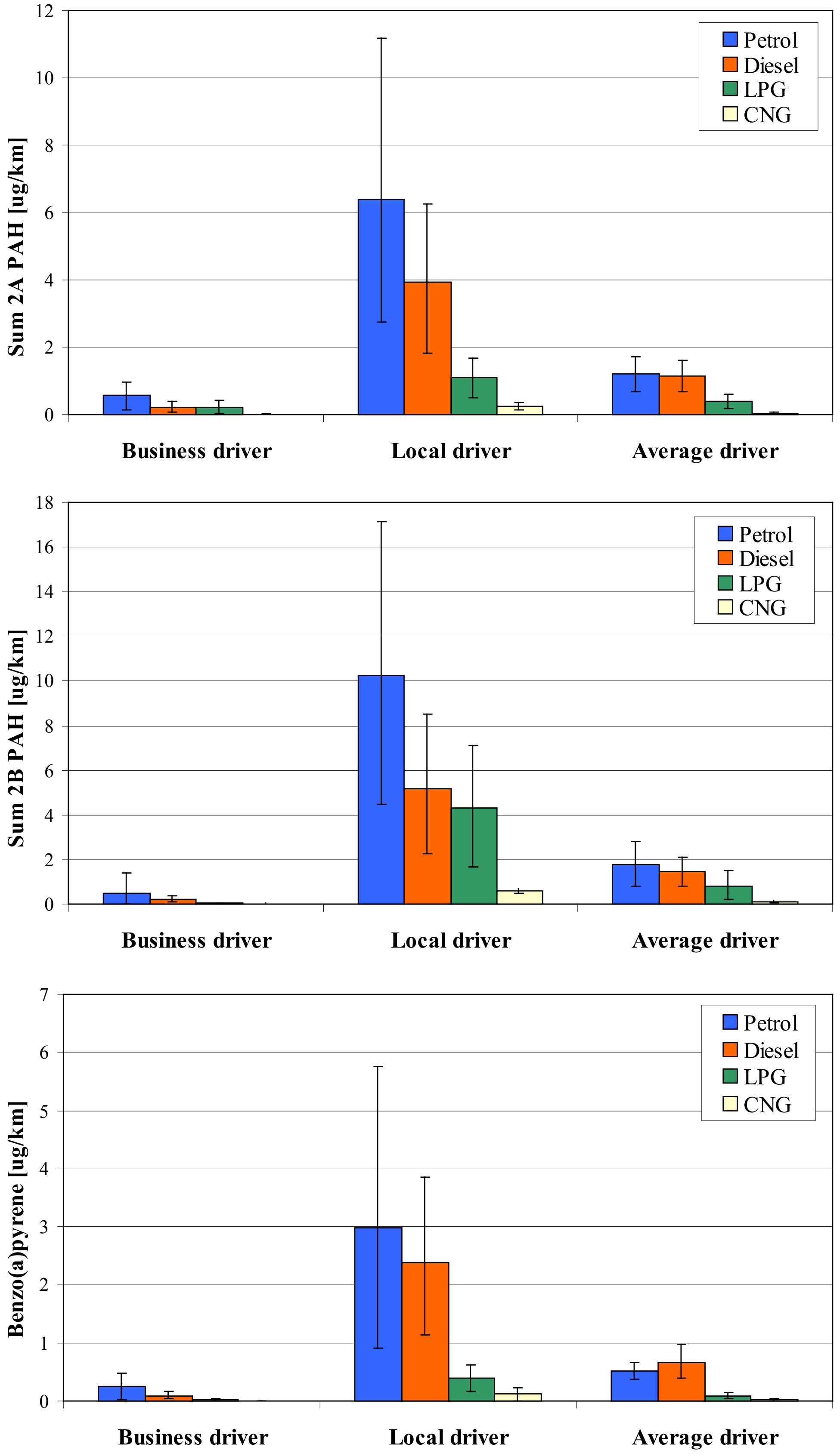


Figure 17: The measured or calculated health effect indicators: PAH

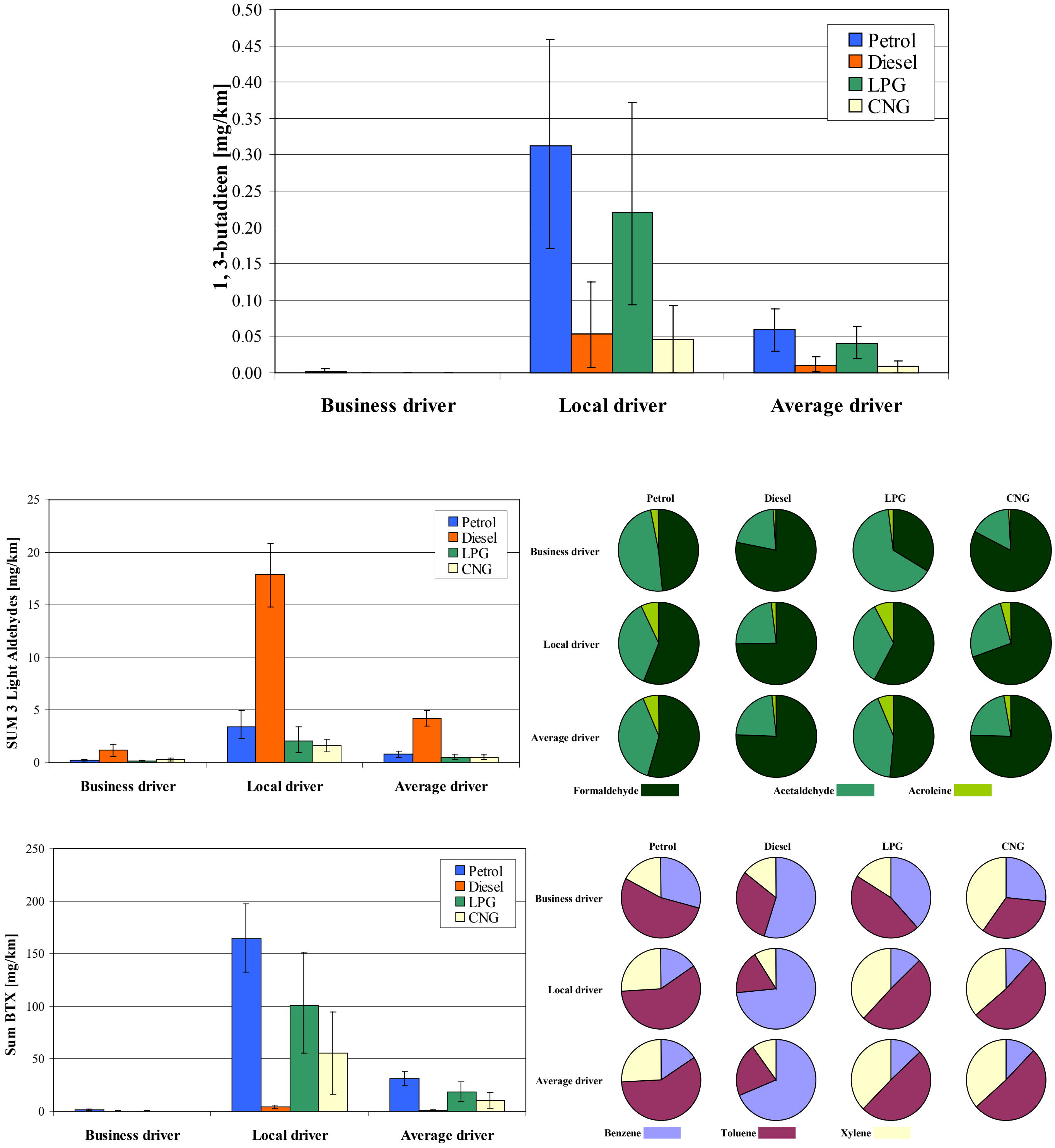


Figure 18:The measured or calculated indicators 1,3-butadiene, light aldehydes and BTX (bars) and the relative weighed contributions of the components involved to the calculation (pies).

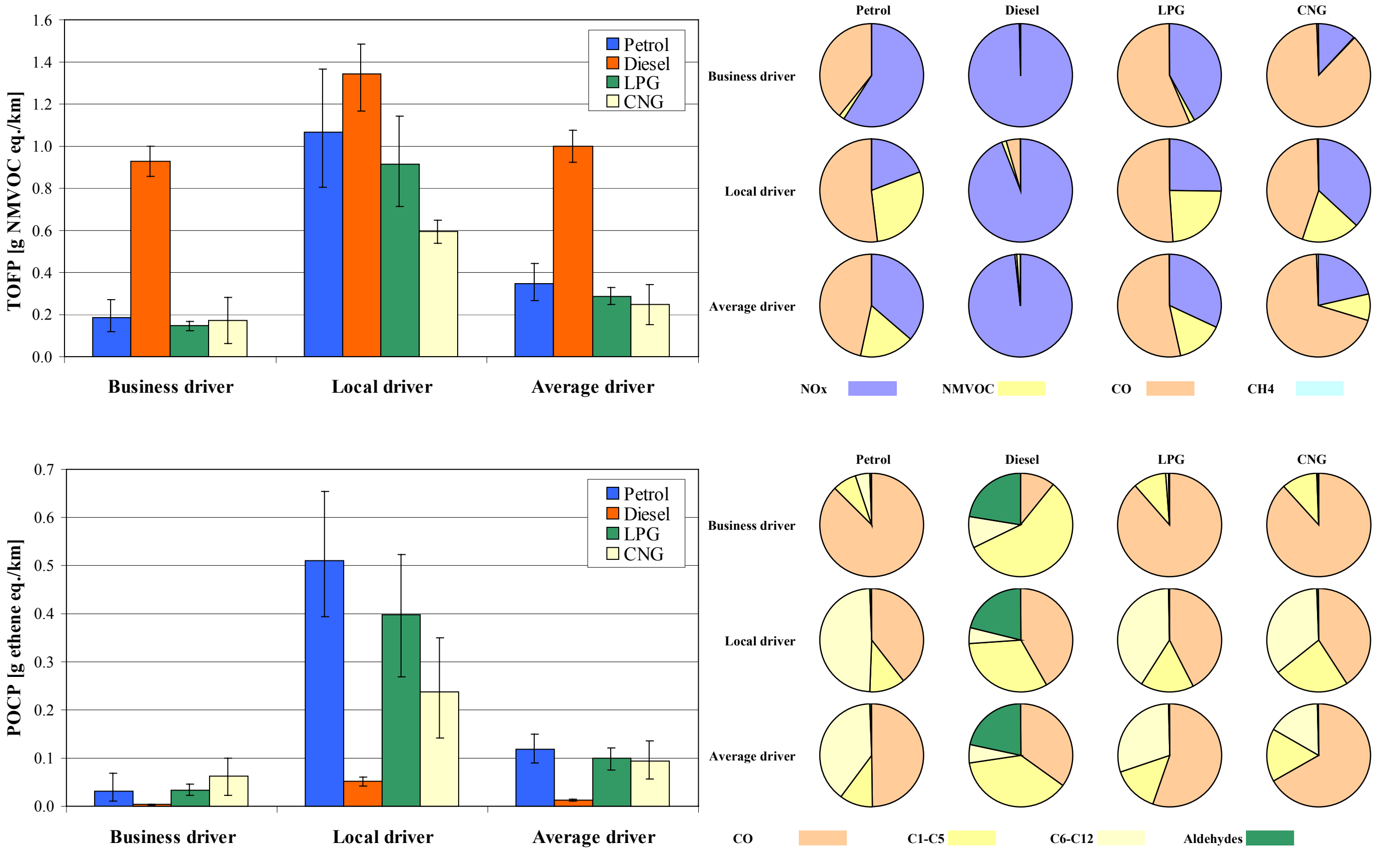


Figure 19: The measured or calculated health effect indicators (bars) and the relative weighed contributions of the components involved in the calculation (pies): smog potentials

5.2 Ecological effects

Discussion of the ecological effects (see Figure 19 and Figure 20):

- The TOFP (see *Figure 19*) is mainly a cold start effect for spark ignition engines, largely determined by CO, although NO$_x$ starts to be of a significant level (for CNG only in the case of the local driver). For diesel engines the TOFP is almost exclusively determined by NO$_x$, and is therefore significantly higher for all three driving patterns.
- The indicators for acidification and euthrophication only differ in the contribution by SO$_2$, but with the current very low sulphur contents of the fuels this makes the difference of minor importance in practice.
- Acification and euthrophication are for a large part determined by NO$_x$ for petrol, for LPG and CNG in the case of the local driver, and almost exclusively by that component for diesel; the remaining contribution stems from NH$_3$.
- Diesel engines show high impact potentials for all three driving patterns and the spark ignition engines emit more or less equal at about a quarter or less than the diesel engines (CNG even somewhat lower).

The overall situation

The overall conclusion is that diesel engines show high to very high impact potentials in all three driver sitiations. Petrol and LPG engines show low impact potentials, with the exception of TOFP that is mainly a cold start effect. CNG engines show the best overall results.

Table 9 summarises the measured results, as explained in the introduction to this chapter.

Table 9: Summary of the results: Ecological effects

Business driver

Component/effect	relevance	Petrol	Diesel	LPG	CNG
Smog potent. TOFP	high	++	-	++	++
Acidification potent.	medium	+	-	+	++
Euthrophication potent.	high	+	-	+	++

Local driver

Component/effect	relevance	Petrol	Diesel	LPG	CNG
Smog potent. TOFP	high	-	--	-	o
Acidification potent.	medium	+	--	+	+
Euthrophication potent.	high	+	--	+	+

Average driver

Component/effect	relevance	Petrol	Diesel	LPG	CNG
Smog potent. TOFP	high	+	-	+	+
Acidification potent.	medium	+	-	+	+
Euthrophication potent.	high	+	-	+	+

--	Very high impact potential	(highest impact potential of all cases for the effect under consideration; a ‘case’ means a combination of fuel and driver profile)
-	High impact potential	(relative to case with highest impact potential)
0	Average impact potential	(relative to case with highest impact potential)
+	Low impact potential	(relative to case with highest impact potential)
++	Very low impact potential	(relative to case with highest impact potential)

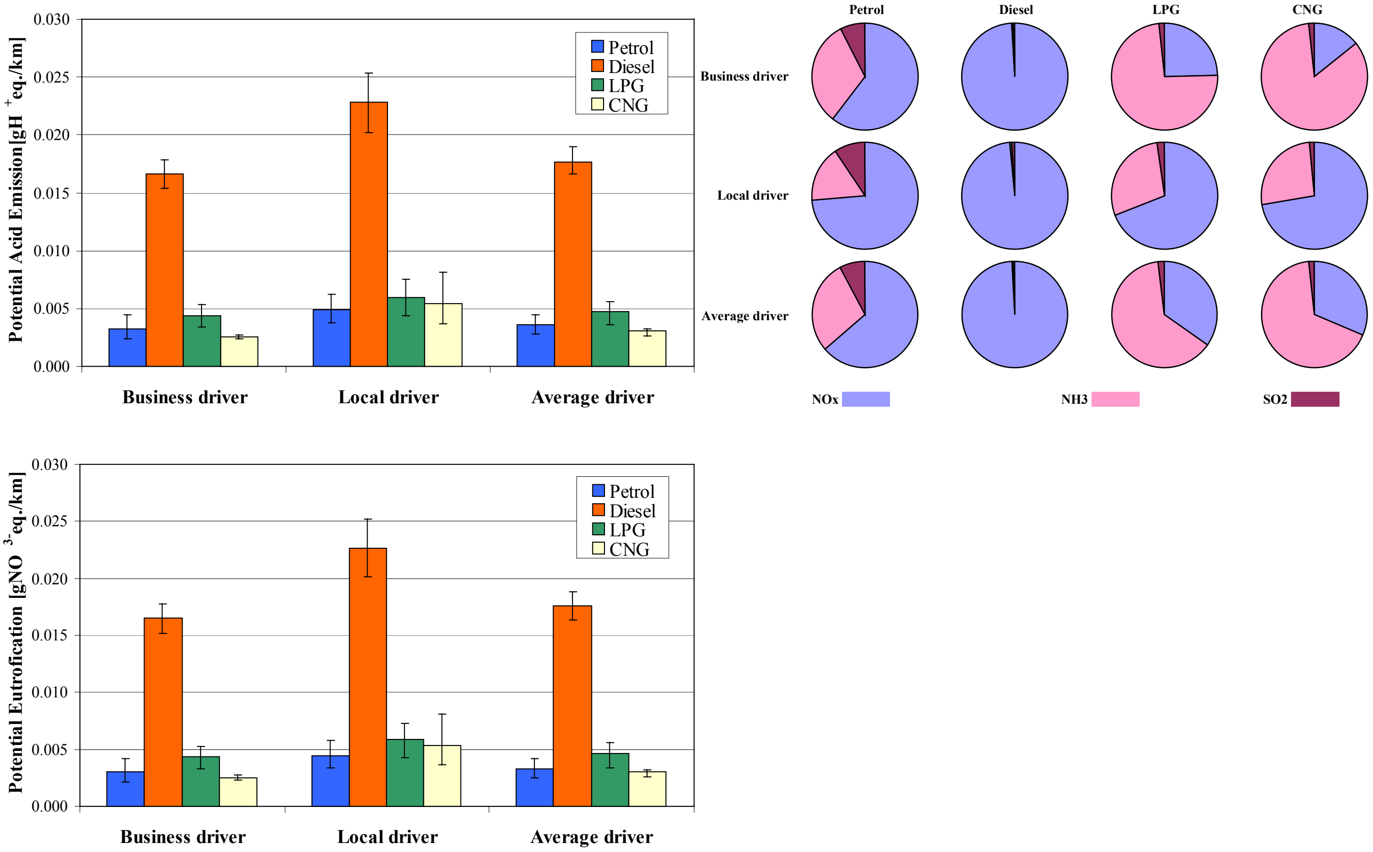


Figure 20: The measured or calculated ecological effect indicators (bars) and the relative weighed contributions of the components involved to the calculation (pies)

5.3 Climatic effects

Discussion of the climate effects (see Figure 21):

- The direct global warming potential (GWP) is almost exclusively determined by the CO_2-emission. Although in theory CH_4 and N_2O, with very high CO_2-equivalent values, could contribute to the GWP, their emission values are so low that they do not or hardly contribute in a measurable way. Even CNG with its theoretically significant CH_4-emission hardly shows an actual CH_4 contribution. The absolute N_2O emissions may be judged from the ozone depletion graph.
- Petrol shows the highest GWP. Diesel shows an advantage over petrol of about 12 % for the business driver and about 14% the average driver; its biggest advantage would be for the local driver, with about 17 %. However, this is not the situation for which diesel engined vehicles will be bought. The gaseous fuels show almost the same result (for LPG) or noticeably better (CNG) than diesel for the business and average driver; but they do suffer from a cold start effect and/or a part load inefficiency in the case of the local driver: the relative gain to petrol is equal (CNG) or better (LPG) for the local driver than for the other two driver profiles, but cannot duplicate the extra gain of the diesel.
- The indirect GWP (organic carbon OC + elementary carbon EC) does show much bigger differences. The gaseous fuels are close to zero or undetectable for all three driver situations. Petrol shows a small effect for the local driver. But diesel shows a

significant contribution for all three driver situations, and especially for the local driver. See further below.

- The indirect GWP is mainly caused by organic carbon for petrol engines in the business driver and average driver situations. In all other cases elementary carbon is the main contributor, especially so in the case of the gaseous fuels.
- The ozone depletion potential of the spark ignition engines is mainly a local driver problem. This is a result from the fact that the formation of N_2O (the relevant component) is a typical catalyst warm-up phenomenon. Surprisingly the N_2O-emission of diesel engines is higher than that of the spark ignition engines for all three driver situations, though. Although for the local driver the spread in results may make the differences not statistically significant. Furthermore it should be noted that in practice ozone depletion is primarily linked to haloginated compounds, and that the contribution of N_2O, at the levels measured here for cars, is almost negligible by comparison.

The indirect GWP is not yet an established effect. But there are strong indications that it may be of importance. Given this discussion, and so as to avoid the risk that this investigation will be quickly outdated by newer insights, determination of the contributions to this possible effect was included into the project. For the moment the overall judgement will be made without this effect. But if this effect turns out to be of importance indeed, then the measured data are already available, and a re-evaluation will be possible without further measurements.

The overall situation

The results are summarised in *Table 10*, as explained in the introduction to this chapter.

Concerning the ozone depletion potential, it is recognised that in itself this is a serious aspect and consequently should be rated with a high relevance. However, as pointed out above, in the case of passenger cars it is only the emission of N_2O that is related to the ozone depletion potential, whereas the main contributing substances are haloginated compounds. Hence the ozone depletion potential for passenger cars was rated as of low relevance.

Therefore the overall conclusion is based on only the direct GWP: Petrol shows the highest GWP. Diesel and LPG show an advantage for the business and average driver, however LPG suffers from a cold start effect and/or a part load inefficiency in the case of the local driver. CNG shows equal results for the local driver situation compared to diesel, and for the other driver situations CNG is the best option of the four fuels.

Table 10: Summary of the results: Climatic effects

Business driver

Component/effect	relevance	Petrol	Diesel	LPG	CNG
Direct GWP	high	-	+	+	++
EC-OC (GWP)	uncertain	++	o	++	++
Ozone depletion	low	+	o	+	++

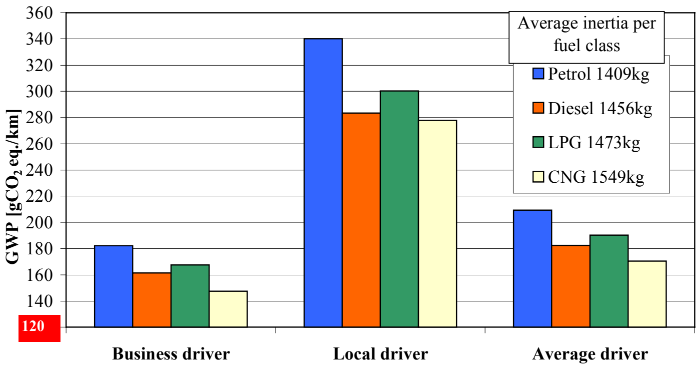
Local driver

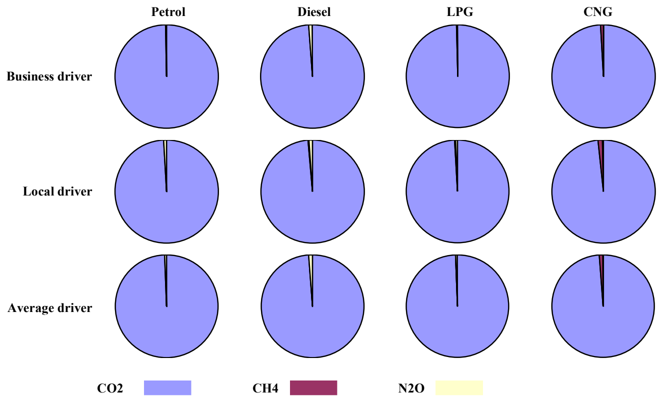
Component/effect	relevance	Petrol	Diesel	LPG	CNG
Direct GWP	high	--	+	o	+
EC-OC (GWP)	uncertain	+	--	++	++
Ozone depletion	low	-	--	-	+

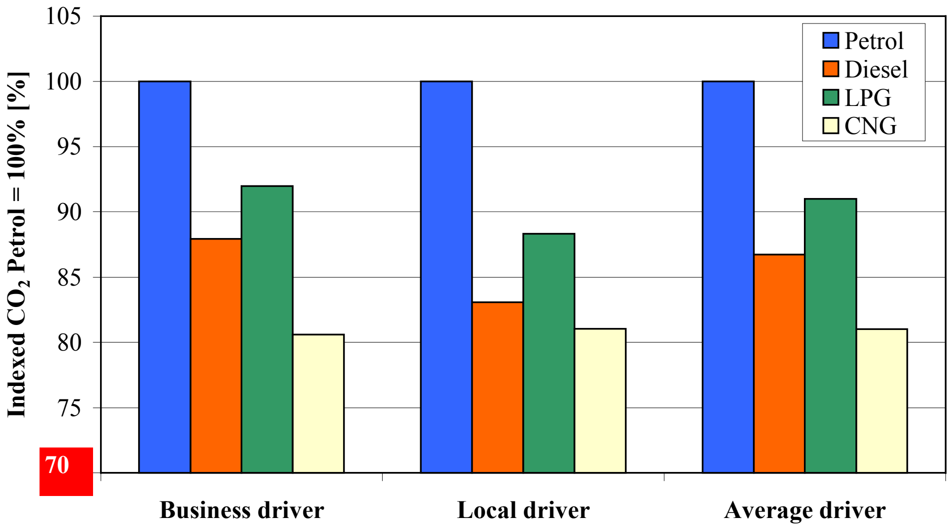
Average driver

Component/effect	relevance	Petrol	Diesel	LPG	CNG
Direct GWP	high	-	+	+	++
EC-OC (GWP)	uncertain	++	o	++	++
Ozone depletion	low	+	-	+	++

--	Very high impact potential	(highest impact potential of all cases for the effect under consideration; a ‘case’ means a combination of fuel and driver profile)
-	High impact potential	(relative to case with highest impact potential)
0	Average impact potential	(relative to case with highest impact potential)
+	Low impact potential	(relative to case with highest impact potential)
++	Very low impact potential	(relative to case with highest impact potential)







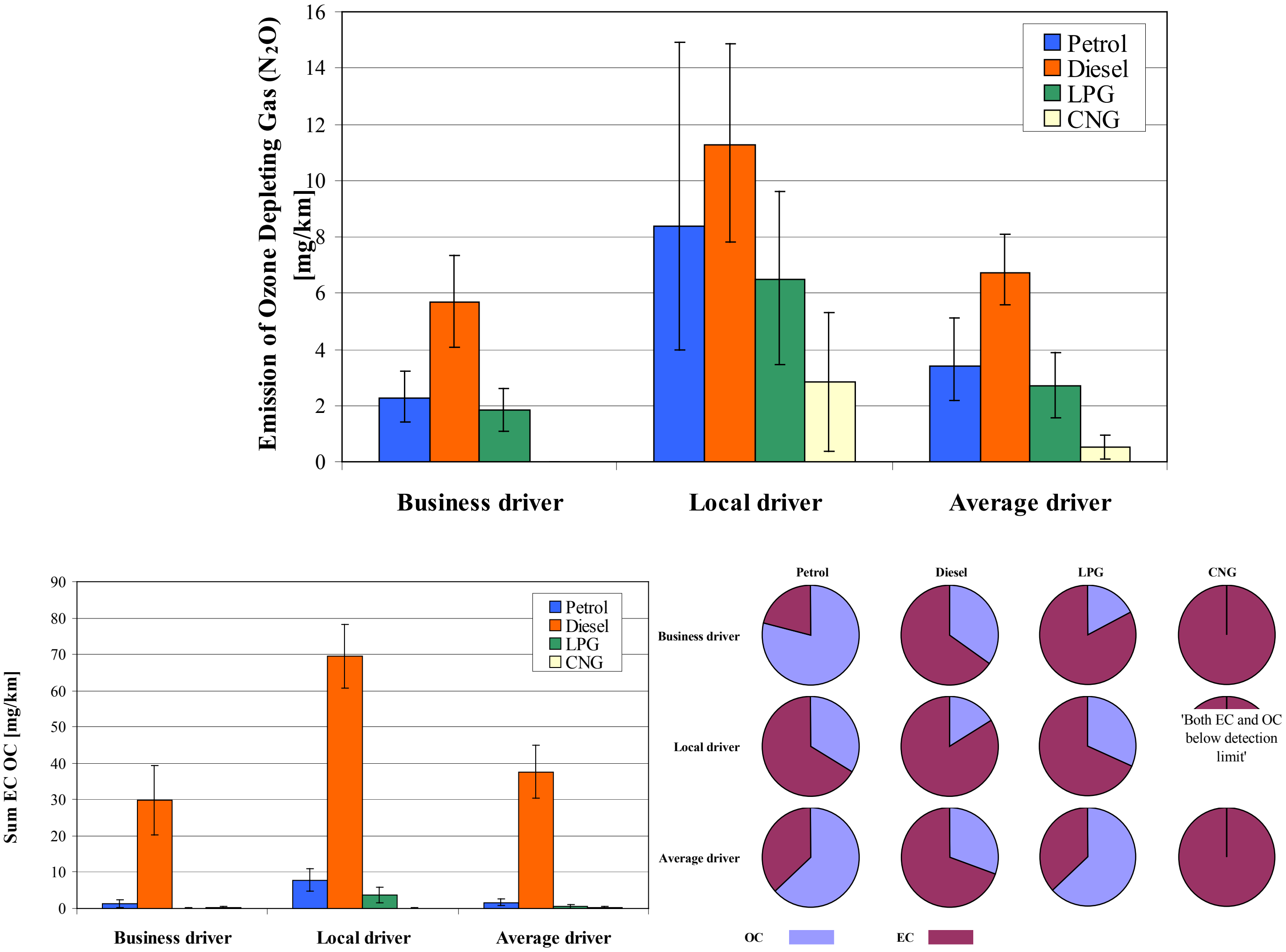


Figure 21:The measured or calculated climatic effect indicators (bars) and the relative weighed contributions of the components involved to the calculation (pies)

5.4 Summary

Table 11 summarises the overall measured results.

In the table no further summary score has been indicated, since it is felt that it is a matter of policy which effect, in a given situation, has priority over another one, and to which extent. The four fuels simply have different impacts in different fields.

However, the following can be concluded:

- Petrol shows lower impact potentials concerning health effects and/or ecological effects compared to diesel, however diesel shows a lower CO_2-emission and hence a lower direct GWP. Although the ‘indirect GWP’ (EC/OC) might change that again if it turns out to be an effect with a high relevance.

- The gaseous fuels LPG and CNG show the best overall results, especially CNG shows (very) low impact potentials on almost all effects in all driver situations.
- It is believed that the results of the gaseous fuels can be further improved in the local driver situation if a different (cold) start strategy will be applied. Instead of starting on petrol, it is recommended to start on the gaseous fuel itself.

Taking into account the statistical analysis to determine if the difference in environmental performance between two fuels is significant (Chapter 8), the following can be said:

- The overall score of the fuels, as stated above, is in most cases confirmed by the results of the paired-t-test.
- However, the advantage of CNG compared to LPG, concerning the human health and ecological effects, is in many cases not significant. Beforehand it was recognised that the small sample size of the CNG vehicles (3 vehicles are measured) would result in a lower level of statistical confidence.
- See further Chapter 8.

Table 11: Overall environmental performance

Business driver

	Relevance	Petrol	Diesel	LPG	CNG
Health effects					
NO_2	high	++	--	++	++
overall PM	high	+	-	+	++
overall PAH	high	++	++	++	++
1,3-butadiene	high	++	++	++	++
light aldehydes	high	++	++	++	++
BTX	medium	++	++	++	++
smog potent. POCP	high	++	++	++	++
smog potent. TOFP	high	++	-	++	++
Ecological effects					
Smog potent. TOFP	high	++	-	++	++
Acidification potent.	medium	+	-	+	++
Euthrophication potent.	high	+	-	+	++
Climatic effects					
Direct GWP	high	-	+	+	++
EC-OC (GWP)	uncertain	++	o	++	++

Local driver

	Relevance	Petrol	Diesel	LPG	CNG
Health effects					
NO_2	high	++	--	++	++
overall PM	high	+	--	+	+
overall PAH	high	--	o	+	++
1,3-butadiene	high	--	+	-	+
light aldehydes	high	+	--	++	++
BTX	medium	--	++	-	+
smog potent. POCP	high	--	++	-	o
smog potent. TOFP	high	-	--	-	o
Ecological effects					
Smog potent. TOFP	high	-	--	-	o
Acidification potent.	medium	+	--	+	+
Euthrophication potent.	high	+	--	+	+
Climatic effects					
Direct GWP	high	--	+	o	+
EC-OC (GWP)	uncertain	+	--	++	++

Average driver

	Relevance	Petrol	Diesel	LPG	CNG
Health effects					
NO_2	high	++	--	++	++
overall PM	high	+	-	+	++
overall PAH	high	+	+	++	++
1,3-butadiene	high	+	++	+	++
light aldehydes	high	++	+	++	++
BTX	medium	+	++	+	++
smog potent. POCP	high	+	++	+	+
smog potent. TOFP	high	+	-	+	+
Ecological effects					
Smog potent. TOFP	high	+	-	+	+
Acidification potent.	medium	+	-	+	+
Euthrophication potent.	high	+	-	+	+
Climatic effects					
Direct GWP	high	-	+	+	++
EC-OC (GWP)	uncertain	++	o	++	++

--	Very high impact potential	(highest impact potential of all cases for the effect under consideration; a 'case' means a combination of fuel and driver profile)
-	High impact potential	(relative to case with highest impact potential)
0	Average impact potential	(relative to case with highest impact potential)
+	Low impact potential	(relative to case with highest impact potential)
++	Very low impact potential	(relative to case with highest impact potential)

6 Other comparisons

6.1 Diesel technology

As indicated in Paragraph 2.7 (Vehicle selection) for the Dutch programme an extra diesel vehicle with an additional aftertreatment system was selected so as to obtain an idea about the further emission reduction potential of such technology. This was a Peugeot 307 with diesel particulate filter (DPF).

Generally speaking a DPF would primarily reduce the PM-emissions, but could also be expected to reduce the PAH-emissions since these are very PM related. In contrast to a deNOx catalyst a pure DPF would not as such make any difference to the NO_x-emission, the other main diesel problem. In practice, however, the presence of a DPF could allow the manufacturer to shift the calibration of his engine towards less NO_x and more PM (engine out) since this PM-emission would be dealt with in the aftertreatment system. Such a shift in calibration might also reflect in a slight increase in fuel consumption, and hence in the CO_2-emission.

Before discussing the results of this experiment a word of caution is in place, however. The DPF system as used by this particular manufacturer is of the periodically regenerating type. Regeneration takes place by a periodical ‘rich’ spike in the fuelling. This may temporarily increase the PM-emission and will certainly increase the overall fuel consumption by a small percentage. For this reason the type approval procedure prescribes the measurement of a regenerative cycle, the results of which should be ‘spread out’ over the average distance between two regenerations. Within the time constraints of the present programme it proved not possible to measure such a regenerative cycle, however (in a laboratory test this must be ‘forced’ by manipulation of the control software with the help of the manufacturer). So the results obtained only represent the operation between two regenerations, and does inevitably present a slightly too optimistic picture. Nevertheless it was felt that even in this form the results would show a direction into which the environmental performance of diesel vehicles can move. It is planned to measure the regulated and unregulated emissions during the regeneration phase with the help of the manufacturer in January 2004. The results will be described in a supplement that will become available at the beginning of 2004.

Since only one vehicle with such aftertreatment system was measured, the results are compared with those of the total sample of the other diesel equipped vehicles, and only in a largely qualitative way. It was found then that the emissions of PM generally were reduced by a factor of 7 for the hot condition (the ‘business driver’ profile) and by a factor of 15 for the ‘local driver’ profile. As argued above, this outcome should be modified with the regeneration emissions, but even so a large reduction of PM over that of the current technology seems possible. The PAH-emissions (all relevant groups and individual components) were reduced by a factor of about 3.

Concerning the ELPI particle size distribution, the number emission of the diesel vehicle with DPF is also reduced considerably compared to the average of the diesel vehicles without DPF (see *Figure 23*). Furthermore, it can be seen that the DPF is very effective over the whole size range.

Concerning the calibration it was found that the NO_x did not differ in any measurable way from the average of the diesel vehicles without particulate filter.

To have a fair comparison of the CO_2-emission with the average of the diesel vehicles without particulate filter, the weight of the vehicles should be comparable. However, the weight of the diesel vehicle with DPF is lower than the average weight of the 7 other diesel vehicles tested. The measured fuel consumption and CO_2-emission were therefore 'corrected' for the 'underweight' of the diesel vehicle with DPF. After correction, the diesel vehicle with DPF shows a slightly higher CO_2-emission of about 2% for the three driver situations. One should take care, however, not to ascribe too much accuracy to such small differences in the case of non-identical vehicles.

Concerning the organic components the total HC (THC) was less for the 'local driver' and more for the 'business driver', but again it is difficult to draw hard conclusions from non-identical vehicles and (in this case) the low absolute numbers involved. Light aldehydes tended to be less (by a factor of 3) for the 'local driver' and about equal for the 'business driver'. Ammonia was non-detectable and the secondary GWP (EC/OC) turned out to be a good order of magnitude lower. Other components were not determined or too low to compare in a sensible way anyway.

So the final conclusion is that the DPF technology has a good potential to reduce the PM-emission (including the ELPI number emission) between two regeneration phases, without noticeable adverse effects with regard to the NO_x- and CO_2-emission (see *Figure 22* and *Figure 23*).

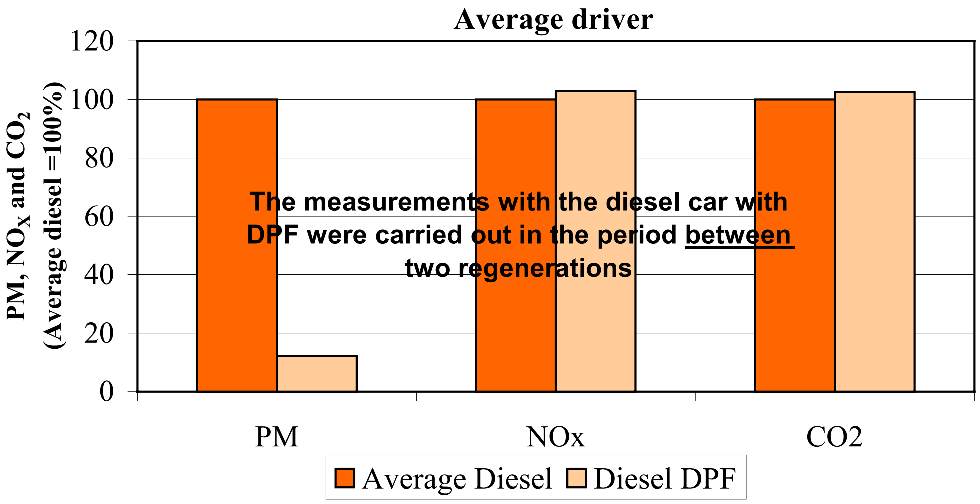


Figure 22: Effect of a DPF on the emissions of PM, NO_x and CO_2 (The CO_2 figure was corrected for the difference in mass between the two samples)

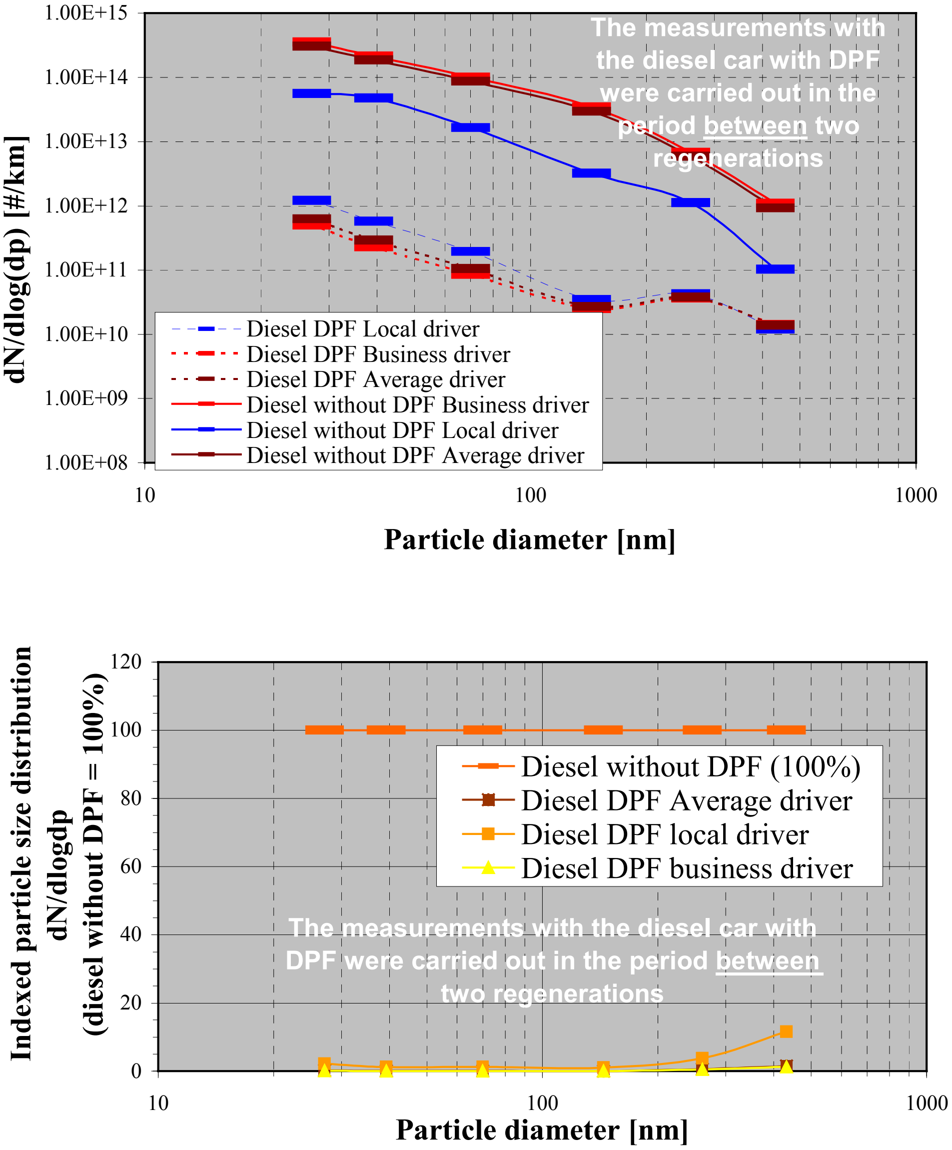


Figure 23: Effect of a DPF on the particle size distribution as measured by the ELPI

6.2 Gaseous fuels

Evaluation of the gaseous fuelled vehicles (both automotive LPG and CNG) shows a number of remarkable aspects. Especially in the ‘local driver’ situation several emission results do not differ from those of the petrol fuelled vehicles to the extent that one would have expected. Furthermore there are organic substances under those circumstances that are characterised by longer HC-chains or cyclic (benzene-like) structures. These are not present in the fuels concerned. Typical examples concerning the individual components are:

- Unexpectedly high CO-emission, with a large spread especially in the case of CNG
- Especially in the case of LPG: significant emissions of 1,3-butadiene and BTX (especially toluene); CNG too shows unexpectedly high emissions of toluene, even if less than LPG

Of the environmental indicators, the ozone formation potentials POCP and TOFP are both relatively high in the ‘local driver’ situation, with contributions of the various individual components very similar to those of the petrol fuelled vehicles: much CO and C_6-C_{12} for the POCP, and additionally much NO_x for the TOFP. Again it is especially the longer chain hydrocarbons that are the unexpected element; in the hot started ‘business driver’ situation this element is completely absent.

Although this aspect has not been further investigated the most logical explanation would seem to be that it is a regularly used strategy in bi-fuel vehicles to start on petrol every time (or at least often) when the vehicle is cold started. The emissions and effects noticed are very obviously a cold start effect, and the emission profiles are very like those on petrol. Immediately after the cold start, when the catalyst is still cold, or warming up, there is no (or insufficient) catalytic conversion of the CO and HC. And since at that time the vehicle is running on petrol, what one gets is obviously the cold start emission profile of a petrol vehicle. Once the vehicle is running on the gaseous fuel, the catalyst is also operating.

This strategy in the case of bi-fuel vehicles, to start the vehicle on petrol with some regularity, is incorporated to keep the polymeric materials in the petrol injection system from drying out, and the injectors in working order, during possible long periods of exclusive gaseous fuel operation. As this investigation shows, the consequence is, however, that exactly during the critical cold start and warming up phase, when the catalyst is not or insufficiently operating, the advantages of the gaseous fuel are not coming into play, since at that very time the vehicle is petrol fuelled. We feel that the manufacturers might do well to seriously consider a different strategy for keeping the petrol system in working order, such as using hot starts rather than cold starts for this purpose. This would seem a relatively easy way to take much more advantage of the favourable characteristics of gaseous fuels for the local situation.

Another aspect that appears from this investigation is that the acidification and euthrophication indicators under hot conditions are very much determined by the emissions of NH_3; during cold starts they are much more determined by the emission of NO_x. It might be useful to look further into the hot NH_3 formation mechanism, since it may very well be possible to largely eliminate this by e.g. an adapted catalyst formulation.

6.3 Light vans

So as to be able to say anything at all about the environmental performance of small vans, one van was included in each of the samples of petrol, diesel and LPG fuelled vehicles. This was a Ford Transit, as shown in the table of Paragraph 2.7 (Vehicle selection). Since only one van model was tested, and since there was no way to know to which extent this particular model would be representative for the group as a whole, no detailed results are shown here. Instead the emission results for each of the three fuels are compared to the average results of the passenger cars in that fuel group to see if there are any outstanding differences in the van’s behaviour. For the sake of the comparison the same three driver profiles are used, although they could be argued to have less significance for vans.

General observations

In general it should be said that a van is heavier than a comparable passenger car, usually without a comparable increase in engine power. This will mean that the van will need more engine power to drive the cycle, but that it will do so by using a higher relative share of the engine power installed. The first observation will mean that a higher fuel consumption should be expected, with consequently a higher emission of CO_2. The second observation will mean that vans equipped with a spark ignition engine might go into full load enrichment quicker than a comparable passenger car, whereas vans equipped with a diesel engine may be expected to emit disproportionately more NO_x and possibly PM.

In fact the increase in fuel consumption for the 'business driver' and the 'average driver' turned out to be roughly around 65-70 % for the petrol van, about 55 % for the diesel van and about 60 % for the LPG van. In the case of the 'local driver' the fuel consumption of the spark ignition engines was 30-40 % higher for the van, and that of the diesel engine in the order of 10 % higher.

The diesel van

The following further observations could be made concerning the diesel van:

1. As expected the diesel engined van produced approximately 80 % more NO_x and between 2.5 and 4.5 times as much PM, with generally lower figures for the 'local' driver and higher ones for the 'business' driver.
2. The emission of NO_2 generally tends to scale with that of the NO_x.
3. The emissions of CO and total HC (THC) tend to be equal to that of the passenger cars, notwithstanding the higher power used (as reflected by the higher fuel consumption), except for CO in the case of the 'business' driver, which, for some unknown reason, was about 3 times as high.
4. Concerning the organic substances:
   - The methane share of THC tended to be less for the van.
   - PAH emissions tended to be about half of that of the passenger cars.
   - Of the light aldehydes (LA) acrolein tended to be higher for the local driving (up to 4 times), but since it was low in absolute numbers it did not affect the overall LA score in a significant way.
5. The emission of SO_2 scales with the overall fuel consumption and the sulphur content of that fuel, but since the absolute emissions are low (due to a low sulphur content) this does hardly seem to be an issue.
6. The emission of N_2O was low or not measurable.
7. The EC/OC emission was low or not measurable, except for EC (elementary carbon) under motorway conditions, which tended to be high.
8. Of the composite environmental effects, all indicators containing NO_x obviously score higher than in the case of passenger cars. These are secondary PM formation potential, TOFP ozone formation potential, acidification potential and euthrophication potential.

<u>The petrol van</u>

The following further observations could be made concerning the petrol van:

1. The regulated components generally score similar as those of the passenger cars, with the following additional remarks:
   - THC and PM generally scored half or less
   - For the 'local' driver THC scored relatively high and NO_x relatively low, but this seems to suggest a slight lambda shift relative to the average passenger car rather than a typical 'van effect'.
2. Concerning the organic substances:
   - PAH emissions tended to be about half of that of the passenger cars, but motorway emissions tended to be higher than local emissions
   - Light aldehydes tended to be between half and equal to that of the passenger cars

<u>The LPG van</u>

The following further observations could be made concerning the LPG van:

1. Of the regulated components the CO tended to be higher (up to 5 times), THC also tended to be higher (1.5-3 times) and the NO_x and PM lower (0.5-1 times) than those of the passenger cars. The THC for the 'local driver' was the lower figure (1.5 times) and the NO_x for the 'local driver' was only 0.1 times that of the passenger cars.

2. Concerning the organic substances:
   - The methane share of the THC tended to be somewhat higher than for the passenger cars
   - PAH emissions tended to be 2-4 times those of the passenger cars for the 'local driver', but less than half that of the passenger cars for the other two driver profiles.

3. The behaviour of the other components was very similar as in the case of the petrol van.

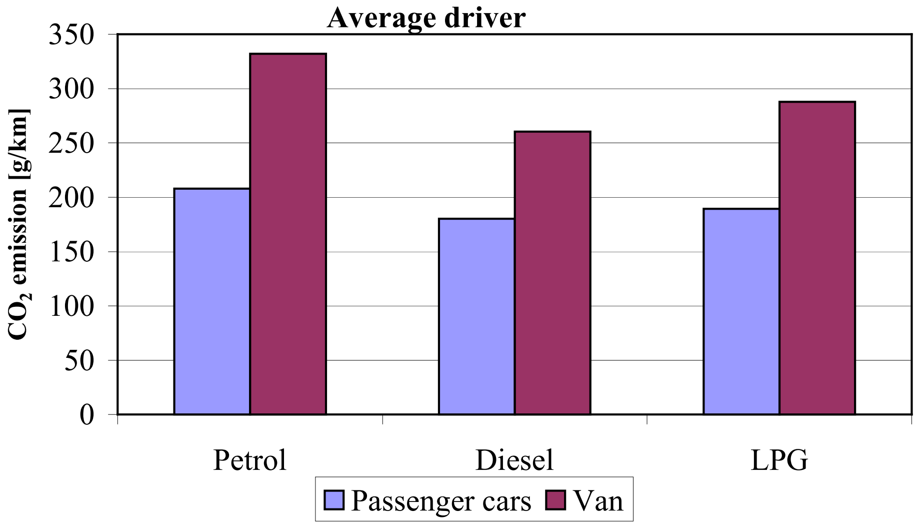
Although these results at first sight seem to point to significant differences between LPG fuelled vans and passenger cars for some components, after comparison with the petrol engined vehicle it seems likely that most of this is caused by a difference in the calibration of this particular vehicle relative to the calibration of the average LPG fuelled passenger car. This would need to be further substantiated by a bigger sample of course.

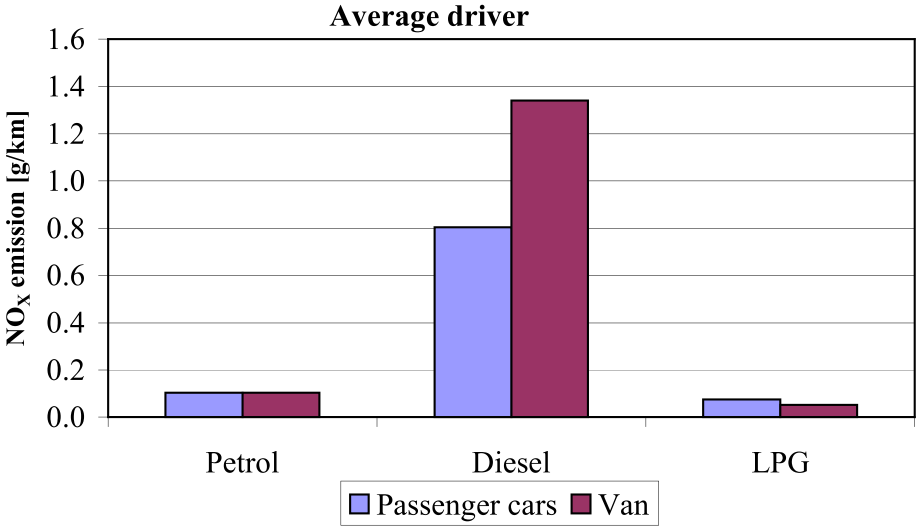
<u>Overall evaluation</u>

The overall conclusion seems to be that on the basis of the current knowledge there is no fundamental reason to assume a significant difference in environmental performance of small vans relative to passenger cars, except for the following (see *Figure 24* for the situation of the average driver):

- The fuel consumption is significantly higher, and consequently the CO_2-emission is higher in proportion. Typical differences would need to be established on a bigger sample, but amounted to 30-70 % increase for spark ignition engines and 10-40 % for diesel engines, depending on driver profile, in this particular case.

- The emissions of NO_x and PM of diesel vans tends to be significantly higher than that of passenger cars. Again typical differences would need to be established on a bigger sample. They amounted to 80 % higher for NO_x and to 2.5-4.5 times for PM, depending on driver profile, in this case. The NO_x increase would reflect in all environmental indicators that contain a NO_x-component.
- There is a suspicion that certain organic components (notably PAH) might score lower for a van. If true this might perhaps be attributed to a higher engine loading, but the effects observed do not allow any real trend to be confirmed, let alone any numerical indication.





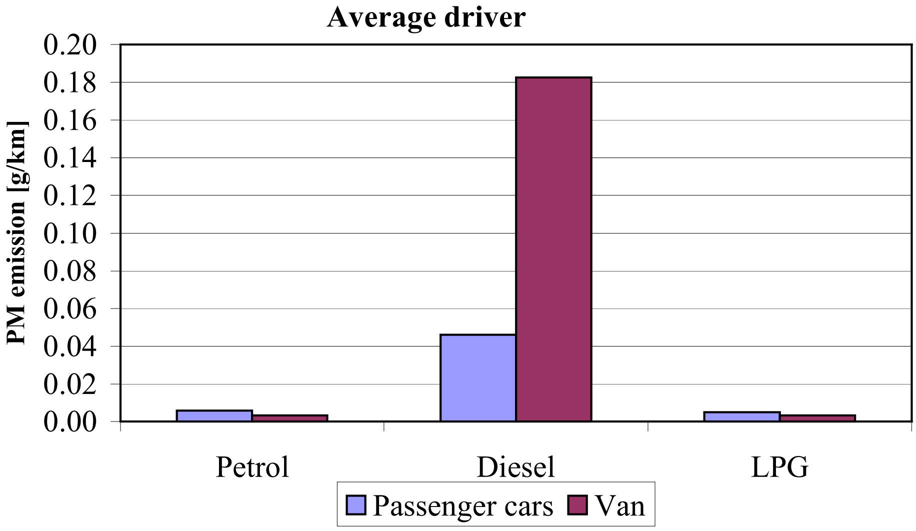


Figure 24: Environmental performance of a small van relative to passenger cars (CO_2-, NO_x- and particulates-emissions)

7 Indirect emissions from the energy chain

7.1 Introduction

Tailpipe emissions only constitute part of the environmental impact of vehicles. Tailpipe emissions are called direct emissions because they are directly related to the use of the vehicle. Indirect environmental impacts originate from:

- the production of materials used for manufacturing the vehicle
- the manufacturing of the vehicle
- disposal of the vehicle and recycling of materials
- the production and distribution of the fuel used by the vehicle
- evaporative emissions from filling stations
- evaporative emissions from the vehicle's fuel system
- (particle) emissions from wear of tyres and brakes

Depending of the definition used, the total of the direct and indirect emissions related to the production, use and disposal of the vehicle are called life-cycle emissions (or Cradle-to-Grave emissions). Assessment of these emissions is done in a so-called Life-Cycle Analysis (LCA).

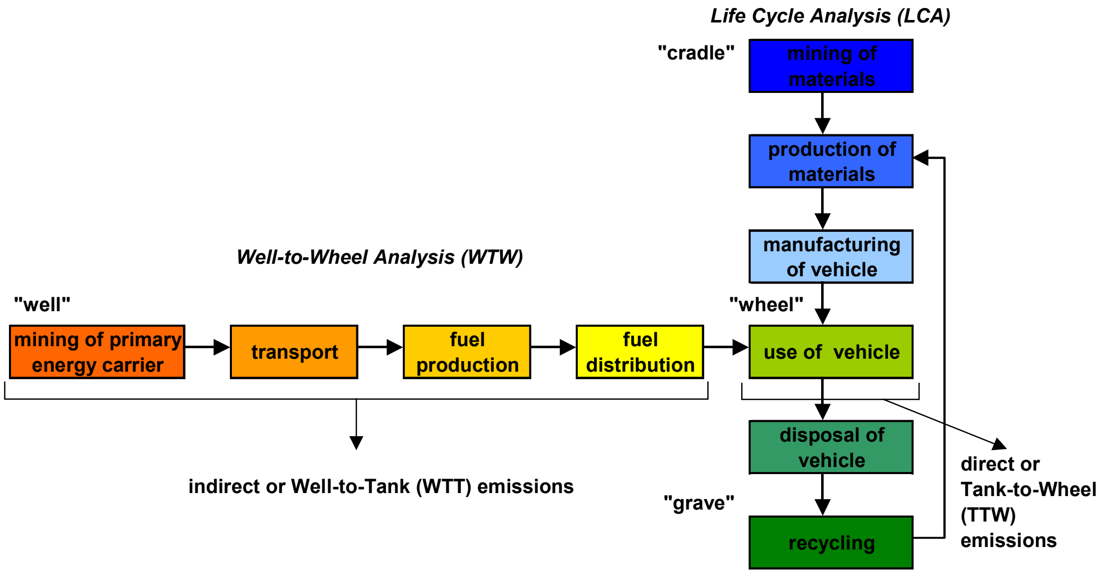


Figure 25: Energy chain and life-cycle chain associated with the use of a vehicle.

Well-to-Wheel emissions

For the technologies compared in this report the environmental impacts related to the production and disposal of the vehicles will not differ significantly. Therefore these life-cycle aspects have not been analysed in the context of this study.

The energy chains for the production of petrol, diesel, LPG and CNG, however, may have significantly different efficiencies and indirect emissions. An analysis of the direct and indirect emissions related to the energy chain is called a Well-to-Wheel (WTW) analysis. Well-to-Wheel emissions can be separated into:

- Well-to-Tank (WTT) emissions, expressed in g/kg fuel or g/MJ fuel, originating from the production and distribution of the fuel;
- Tank-to-Wheel (TTW) emissions, expressed in g/km, originating from the use of the vehicle.

The purpose of this chapter is to assess the order of magnitude of the WTT-emissions of several relevant components, and to analyse to what extent the inclusion of these WTT-emissions might alter the conclusions of the comparison, based on direct (TTW) emissions only, as presented in the previous chapters.

A Well-to-Wheel comparison is especially relevant to the emissions of greenhouse gases (in this case CO_2, CH_4 and N_2O) as the impact of these emissions on the global greenhouse effect is not depending on the location of the emissions. However, for other emission components, which contribute to regional or local environmental problems, the emissions originating from different stages in the Well-to-Wheel energy chain can not be added in a straightforward manner. Their impacts strongly depend on local or regional air quality, meteorological, and geographical conditions and on the presence of human populations which can be affected by the emissions. The CO- or NO_x-emissions for example produced by an oil tanker on the Atlantic Ocean or by oil recovery in the Saudi Arabian desert probably do not contribute to smog formation at these locations, and certainly not to smog formation at the location where the vehicles are used. On the other hand, emissions from oil tankers in the port of Rotterdam or from refineries in the Botlek area do contribute to local air quality and acidification problems in the (western) part of the Netherlands. Furthermore the introduction of clean fuels in the Netherlands should not cause or increase environmental problems in other countries where the fuels are mined or produced. Therefore it does make sense to also investigate the WTT-emissions of the regulated and unregulated components studied in this report.

Scope of this chapter

In this chapter the indirect, well-to-tank emissions of petrol, diesel, LPG and CNG vehicles are assessed based on available data. The scope is limited to the indirect emissions related to the energy chains of the different fuels.

Using the same formula's as applied to the exhaust emissions, these indirect emissions are translated into impact potentials, which can be compared to the impact potentials resulting from the direct emissions. Given the fact that the contribution of indirect emissions to certain impacts strongly depends on the location of the emissions, the impact potentials calculated for indirect emissions should be considered as an indication of the upper limit. If these upper limits are found to be a significant fraction of the impact values calculated for the direct emissions, they may be considered to have an influence on the overall comparison. In such instances a closer examination of the quantities and locations of the emissions and their possible contribution to various health and ecological effects should be carried out. This, however, is beyond the scope of this report.

Given the uncertainties related to the assessment of indirect emissions the comparison presented in this chapter should be considered as indicative. If, based on the data used here, indirect emissions are found to influence the result of the comparison between the fuels, further research to establish more accurate and reliable indirect emissions data is justified and necessary before more definitive conclusions can be drawn.

Evaporative emissions

Evaporative emissions are not considered in detail in this study. The evaporative emissions associated with refilling at a gas station are included in the data used in this chapter concerning WTT-emissions of the energy chains. Evaporative emissions from the vehicles have not been measured in the programme. The total evaporative HC-emissions, however, can be quite considerable compared to the HC emissions from the exhaust. Due to EU legislation and the subsequent application of canisters, the evaporative emissions of petrol vehicles have been greatly reduced in the recent past, but the reduction of HC exhaust emissions has been greater.

Consultation of various sources (e.g. CORINAIR and the German Handbuch Emissionsfaktoren) shows that diurnal evaporative emissions of petrol vehicles can be around 0.3 g/day. The hot-soak emissions of petrol vehicles, occurring after shut-down of the vehicle, can be around 0.3 g/stop. Assuming an annual mileage of 15,000 km for the average driver and an average trip length of 15 km in the Netherlands, the evaporative HC emissions of petrol vehicles can be some 0.03 g/km. The evaporative emissions of diesel vehicles is not regulated and is expected to be much smaller. In comparison the total NMHC exhaust emissions measured in the programme for the average driver profile amount 0.13 g/km for petrol vehicles, 0.02 g/km for diesels, 0.09 g/km for LPG and 0.03 g/km for CNG.

The LPG- and CNG-vehicles measured in the program are all bi-fuel vehicles, meaning that they also have a petrol tank and fuel systems. With a smaller petrol tank the evaporative emissions of LPG- and CNG-vehicles may be somewhat smaller than those of petrol vehicles, but overall they can be expected to be of the same order of magnitude. Dedicated LPG- or CNG-vehicles with a closed fuel system, on the other hand, could have near-zero evaporative emissions.

Including the evaporative emissions in the comparison between petrol, diesel, LPG and CNG can thus significantly influence the outcome of the comparison, especially between diesel and the other three fuels. This would, however, require further study, not only to quantify the evaporative HC-emissions of the different vehicle types but also to examine the composition of these emissions (e.g. benzene content) and the impact of different components on effect potentials as compared in this study for exhaust emissions.

7.2 Data sources

Data on indirect emissions are scarce. Most WTW-studies confine themselves to greenhouse gas emissions, and do not investigate regulated or unregulated emission components. A second problem with WTW-studies is that the data are strongly dependent on the focus of the study, e.g.:

- *Time horizon*
  Emissions of future technologies will generally differ from those of today's technology. Available data in fact often concern yesterday's technology, because

this kind of emission inventories are not frequently made, and measured data are obviously only available from existing technology;

- *Country or region*
  The technologies used in energy chains differ from country to country or region to region. Also the state (age and state of maintenance) may differ strongly. Furthermore e.g. transport distances, and consequently the energy consumption and emissions associated with transport of raw energy carriers or distribution of final products, are dependent on the location of a country with respect to the origins of the raw energy carriers and on the size of the country itself.

Data for the energy chains of petrol, diesel, and LPG

For petrol, diesel and LPG the indirect emission data for CO, NMHC, NO_x, SO_2, PM, CO_2, CH_4 and N_2O, used in this study, are based on studies performed by ECN. These studies apply to the Dutch situation. Indirect emission values for the year 2003 have been derived by interpolation between data available for 1993 (taken from [1], see also [13]) and estimates for 2020 obtained from [9] (see also [10]).

Indirect emission data on formaldehyde, acetaldehyde, 1,3 butadiene, and benzene are taken from [11]. These data apply to the US situation, but their order of magnitude may be considered an indication for the Dutch situation.

Data for the natural gas energy chain

For estimating the indirect emissions of CO, NMHC, NO_x, SO_2, and PM associated with the natural gas energy chain, the 1993 data from [1] (based on [13]) have been used. For these components complete energy chain data for the present 2003 situation in the Netherlands are not available. The 1993 data assume the use of average Dutch natural gas, without any imports. Since 1993 the emissions of some of these components may have been reduced, but quantitative estimates are difficult to make. As the first priority of this WTW-analysis is to check whether upper limit estimates of the indirect emissions would influence the overall outcome of the environmental comparison between petrol, diesel, LPG and CNG vehicles, the data from [1] are used without correction. For each component or effect discussed in this chapter an evaluation will be made of the necessity to update the indirect emission inventory.

Over the next decades reduction of greenhouse gases will become a major policy issue, and natural gas may play a role in reducing greenhouse gas emissions from road transport. For this reason, and because of the fact that for greenhouse gases smaller relative differences between the fuels are relevant in the environmental comparison than is the case for the other emission components, the indirect emissions of CO_2, CH_4 and, to a lesser extent, N_2O have to be assessed more carefully.

Data for the 2003 situation in the Netherlands concerning the indirect greenhouse gas emissions originating from the natural gas energy chain have been derived on the basis of [12]. This recent study assesses WTW greenhouse gas emissions for an average European situation, and to this end calculates WTT greenhouse gas emissions for an EU-mix with gas originating from the UK, Netherlands, Russia, Algeria and Norway, as well as for 100% Russian gas imported through long distance pipelines. From the underlying data reported in [12], however, also an estimate can be derived for the Dutch situation, assuming 100% Dutch low calorific natural gas. This estimate, presented in

Table 12, is representative for CNG obtained from the low pressure distribution grid, including the associated energy needs for compression. Incidentally, the emission values found in this way for CO_2 and CH_4 are roughly equal to the 1993 data given in [1].

For natural gas the indirect emission data of formaldehyde, acetaldehyde, 1,3 butadiene, and benzene are taken also from [11]. As mentioned, these data apply to the US situation, but their order of magnitude may be considered an indication for the Dutch situation.

The above considerations have resulted in the data presented in *Table 12*.

Table 12: Indirect emissions from the fuel chains of petrol, diesel, LPG and CNG estimated for the Dutch situation in 2003.

		Petrol	Diesel	LPG	CNG
CO	[g/kg fuel]	1.38	1.28	1.37	0.03
NMHC	[g/kg fuel]	1.58	0.57	0.82	0.50
NO_x	[g/kg fuel]	1.23	0.96	1.20	0.13
SO2	[g/kg fuel]	2.84	2.32	2.40	0.05
PM	[g/kg fuel]	0.13	0.09	0.11	0.00
CO_2	[g/kg fuel]	627	498	417	205
CH_4	[g/kg fuel]	3.5	3.2	3.1	5.0
N_2O	[mg/kg fuel]	13.3	11.6	8.3	0.0
Formaldehyde	[mg/kg fuel]	1.24	1.03	1.04	2.62
Acetaldehyde	[mg/kg fuel]	0.38	0.35	0.27	0.27
1,3 butadiene	[mg/kg fuel]	0.36	0.36	0.07	0.01
Benzene	[mg/kg fuel]	4.77	2.93	0.39	0.16

Data on other emission components measured on the vehicles in this study are not available. Using the above data the size of indirect impacts has been estimated for those impacts for which indirect emission data are available.

7.3 Comparison of direct and indirect emissions and impacts

The indirect emission values in g/kg fuel, as presented in *Table 12*, have been translated to a g/km basis by multiplying with the average fuel consumption (in kg fuel per km driven) for each fuel type of the vehicles tested in the project. For this comparison fuel consumption data for the “average driver” have been used. The resulting indirect emissions have subsequently been translated into impact levels using the same relations as applied to the direct emissions. In the next paragraphs for various impacts the results of these calculations are compared to the direct impacts calculated for the case of the “average driver”.

7.3.1 *Emissions related to human health effects*

Carbon Monoxide

CO has health impacts by itself and is an important component for ozone formation. As can be seen from *Figure 26* the indirect emissions of CO are relatively small compared to the direct emissions for petrol, LPG and CNG. For this component the WTT-emissions therefore do not influence the outcome of the comparison between the different fuels.

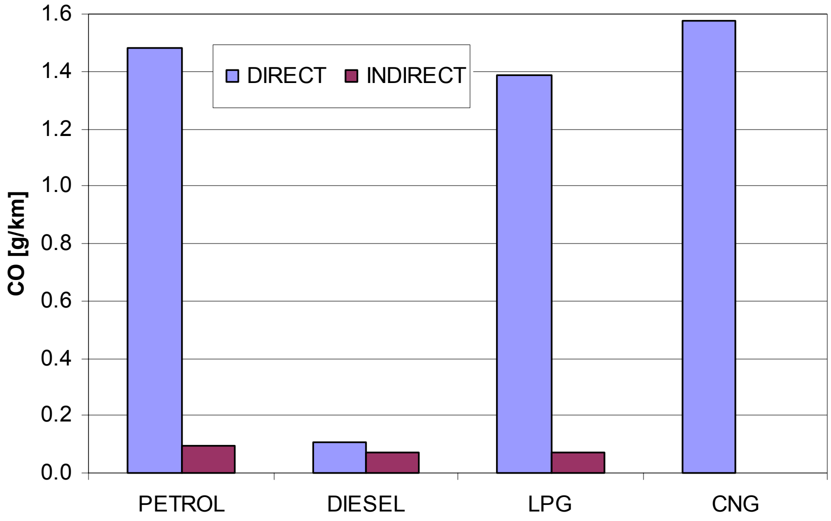


Figure 26: Comparison of direct and indirect emissions of CO for vehicles running on petrol, diesel, LPG and CNG (average driver).

Nitrogen oxides (NO_x)

NO_x-emissions contribute to a wide range of environmental effects, ranging from ozone formation to secondary particle formation and acidification. As can be seen from *Figure 27* the indirect emissions of NO_x are comparable to the direct emissions in the case of petrol and LPG, but are much smaller than the direct emissions in the case of diesel and CNG. For this component the WTT-emissions therefore do influence the outcome of the comparison between petrol, LPG and CNG in the sense that they increase the advantage of CNG compared to the other two fuels. The benefits of petrol, LPG and CNG compared to diesel, however, are not significantly influenced by the inclusion of WTT emissions of NO_x.

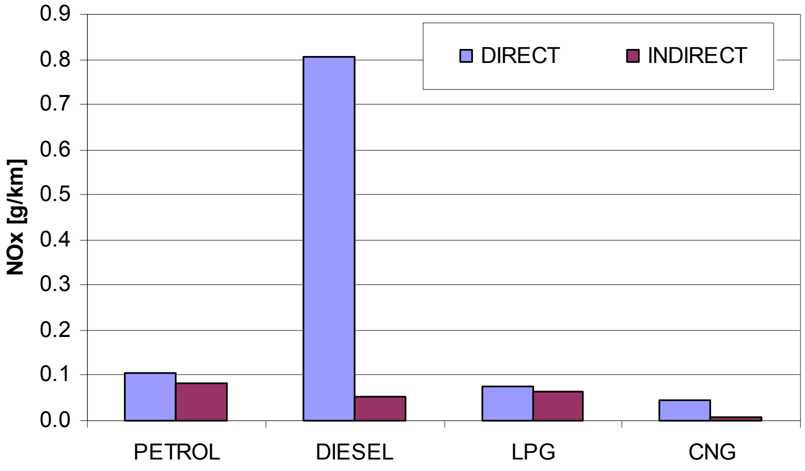


Figure 27: Comparison of direct and indirect emissions of NO_x for vehicles running on petrol, diesel, LPG and CNG (average driver).

Ozone formation

In the TOFP-method the ozone formation potential is calculated on the basis of emissions of NO_x, NMVOC, CO, and CH_4. If all indirect emissions are considered to contribute to the ozone formation potential, the resulting TOFP-value for the indirect emissions, as depicted in *Figure 28*, is found to be about half of the direct value for petrol and LPG. For diesel and CNG the indirect TOFP-values are a somewhat lower fraction of the direct TOFP-values. Including the full indirect TOFP-potential would therefore slightly reduce the advantage of petrol and LPG relative to diesel, and would give CNG a slight benefit compared to petrol and LPG. However, as ozone formation is a local phenomenon, strongly dependent on local meteorological, geographical and air quality characteristics, the contribution of the indirect emissions to ozone formation will in practice be much smaller than the upper limits estimated here.

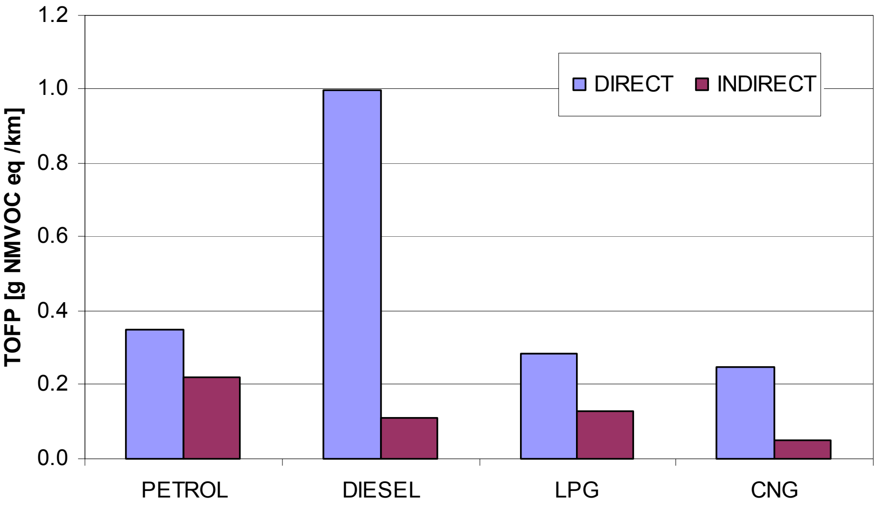


Figure 28: Comparison of direct and indirect ozone formation potential (TOFP-method) for vehicles running on petrol, diesel, LPG and CNG (average driver).

Primary particulate matter

As can be seen from *Figure 29*, the emissions of primary PM in the fuel chains of petrol and LPG are of the same order of magnitude as the direct emissions. For CNG the indirect PM emissions are negligible. Including indirect emissions in the comparison will therefore give CNG a larger advantage compared to petrol and LPG. The comparison between these three fuels and diesel, however, is not significantly affected by the indirect emissions.

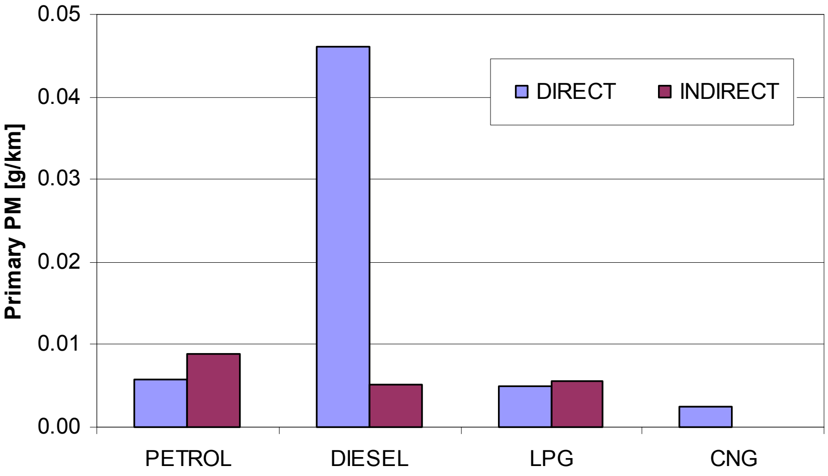


Figure 29: Comparison of direct and indirect primary PM emissions for vehicles running on petrol, diesel, LPG and CNG (average driver).

Secondary particulate matter

Formation of secondary PM is related to the emissions of NO_x, SO_2 and NH_3. For NH_3 no emission data for the energy chains are available. The indirect secondary PM-emissions estimated here are therefore based only on the indirect emissions of NO_x en SO_2. As can be seen from *Figure 30*, the picture for secondary PM emissions is about the same as for primary PM. Indirect emissions in the fuel chains of petrol and LPG are of the same order of magnitude as the direct emissions. Including indirect emissions in the comparison increases the advantage of CNG compared to petrol and LPG, but does not affect the comparison between these three fuels and diesel.

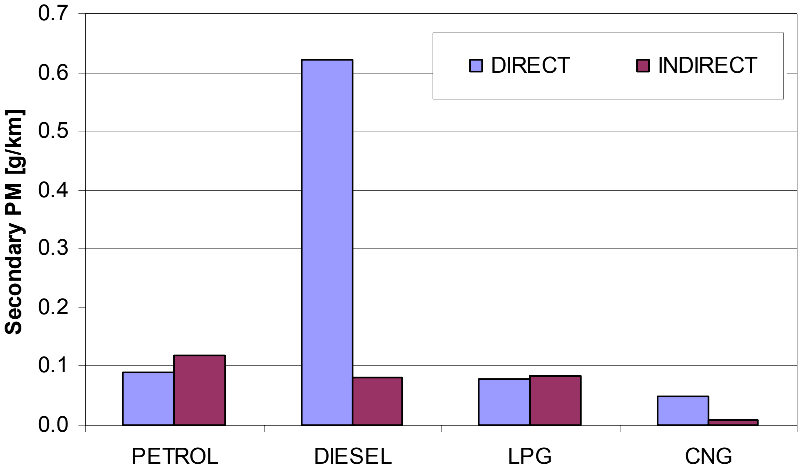


Figure 30: Comparison of direct and indirect secondary PM emissions for vehicles running on petrol, diesel, LPG and CNG (average driver).

Benzene

Figure 31 shows that the indirect benzene emissions are relatively small for petrol and diesel and negligible for LPG and CNG, and therefore do not influence the comparison between the fuels.

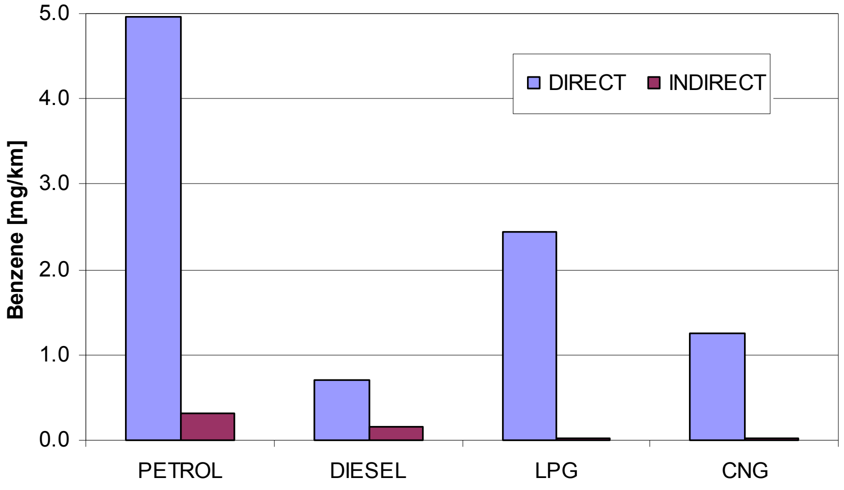


Figure 31: Comparison of direct and indirect benzene emissions for vehicles running on petrol, diesel, LPG and CNG (average driver).

1,3 butadiene

The indirect emissions of 1,3 butadiene are depicted in *Figure 32*. For petrol and diesel these emission are relatively high, both in absolute terms and compared to the direct emissions. For LPG and CNG the indirect emissions are much smaller and therefore insignificant compared to the direct emissions. Including the indirect emissions, thus reduces the advantage of diesel compared to petrol and LPG, and increases the advantage of LPG and especially CNG relative to petrol. Closer examination of the origins of the indirect emissions of 1,3 butadiene, and quantification of these emissions for the Dutch or European situation (instead of using the US data from [11]) would be necessary to draw more exact conclusions.

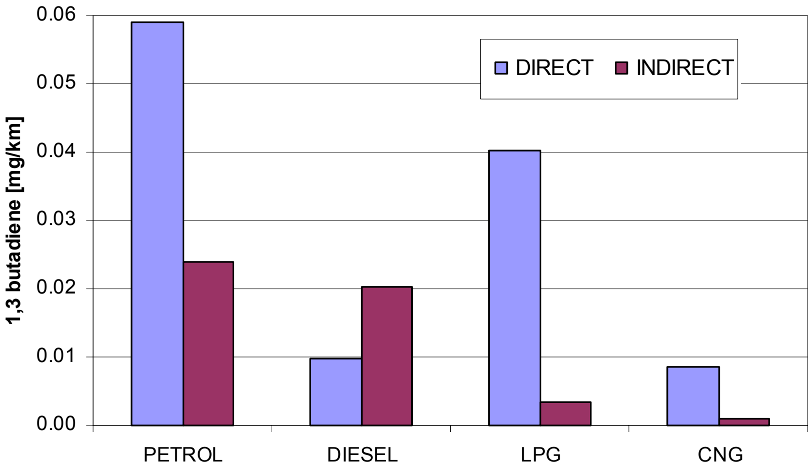


Figure 32: Comparison of direct and indirect emissions of 1,3 butadiene for vehicles running on petrol, diesel, LPG and CNG (average driver).

Aldehydes

For the three aldehydes (formaldehyde, acetaldehyde and acroleine) only WTT-data are available for formaldehyde and acetaldehyde. WTT-emissions of acrolein are not expected to be very much higher than the emissions of the other two aldehydes. As can be seen from *Figure 33* the indirect emissions of aldehydes are relatively small compared to the direct emissions for all fuels. For this component the WTT-emissions therefore do not influence the outcome of the comparison between the different fuels.

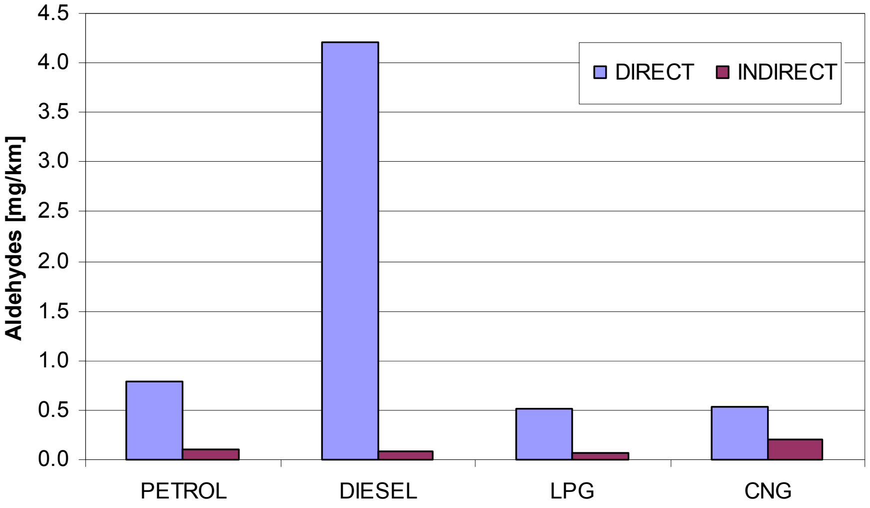


Figure 33: Comparison of direct and indirect emissions of aldehydes for vehicles running on petrol, diesel, LPG and CNG (average driver).

Impacts of indirect emissions on the overall evaluation of health effects

In *Table 8* of Chapter 5 an overall evaluation is given of the comparison of the four fuels with respect to the different health effects by translating the relative differences in the assessed impact potentials into relative scores expressed between "- -" and "+ +". Taking the impact potentials into account which result from indirect emissions, the scores in the table for the average driver profile would remain the same except for the "+ +" score for diesel on 1,3-butadiene, which would reduce to a "+" score.

7.3.2 *Ecological effects*

Acidification

Emissions of NO_x, NH_3 and SO_2 contribute to the acidification potential, expressed in grams H^+-equivalent per km. For NH_3 no data on indirect emissions are available. In *Figure 34* therefore only the impact of the indirect emissions of NO_x and SO_2 on the acidification potential is accounted for. As for petrol, diesel and LPG the indirect emissions of both NO_x and SO_2 are relatively high, the estimated upper limits for the acidification potential resulting from indirect emissions are of the same order of magnitude as the potential due to direct emissions. Including the total indirect acidification potential, the advantages of petrol and LPG relative to diesel would be significantly reduced. In the comparison between petrol, LPG and CNG, the indirect emissions increase the advantage of CNG. A closer examination of the NO_x-emissions from the natural gas energy chain seems appropriate to further substantiate this conclusion.

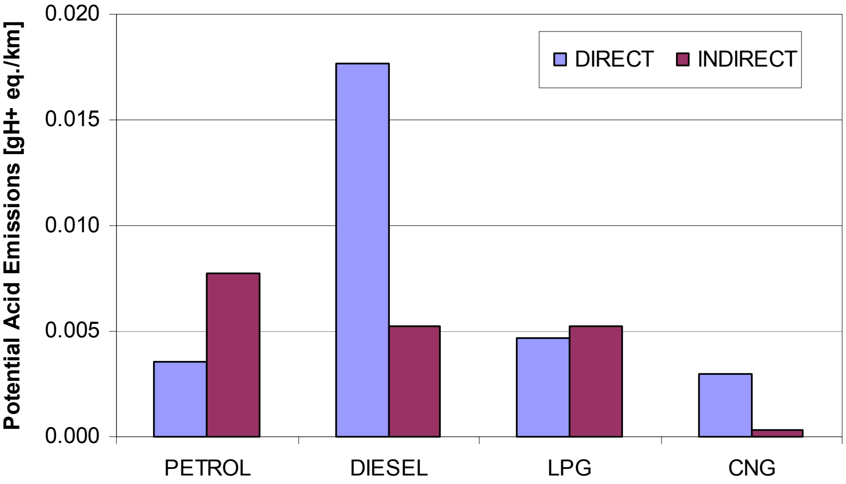


Figure 34: Comparison of the potential impact of direct and indirect emissions on acidification for vehicles running on petrol, diesel, LPG and CNG (average driver).

Impacts of indirect emissions on the overall evaluation of ecological effects

In *Table 9* of Chapter 5 an overall evaluation is given of the comparison of the four fuels with respect to different ecological effects by translating the relative differences in the assessed impact potentials into relative scores expressed between "- -" and "+ +". Taking into account the above presented upper limit estimates for the impact potentials for acidification which result from indirect emissions, the score for CNG in the table for the average driver tends to become a "+ +" instead of a "+". The scores for TOFP, which also contributes to ecological impacts, would not be affected.

7.3.3 Climatic effects

Carbon Dioxide

As can be seen from *Figure 35*, the indirect CO_2-emissions associated with the fuel chains of petrol, diesel, LPG and CNG are significant compared to the direct emissions, and are different for the different fuels. The differences between the indirect emissions of the fuels are such that they amplify the differences between the total CO_2-emissions of the fuels.

It should be noted that in the comparison presented here, the direct CO_2-emission values are measured on CNG-vehicles running on high calorific natural gas. In the Netherlands, however, CNG-vehicles consume low calorific natural gas. Average Dutch low calorific gas typically contains 15 mol% N_2 and up to 1 mol% CO_2. This means that the volumetric or gravimetric fuel consumption of vehicles running on this gas will be higher than for vehicles running on high calorific gas. The emissions, however, need not be significantly different if the adaptation function is performing well. The CO_2 content in the fuel will typically result in a 1% higher gross CO_2 content of the exhaust gases. Using low calorific gas will therefore not significantly alter the comparison between CNG and the other three fuels.

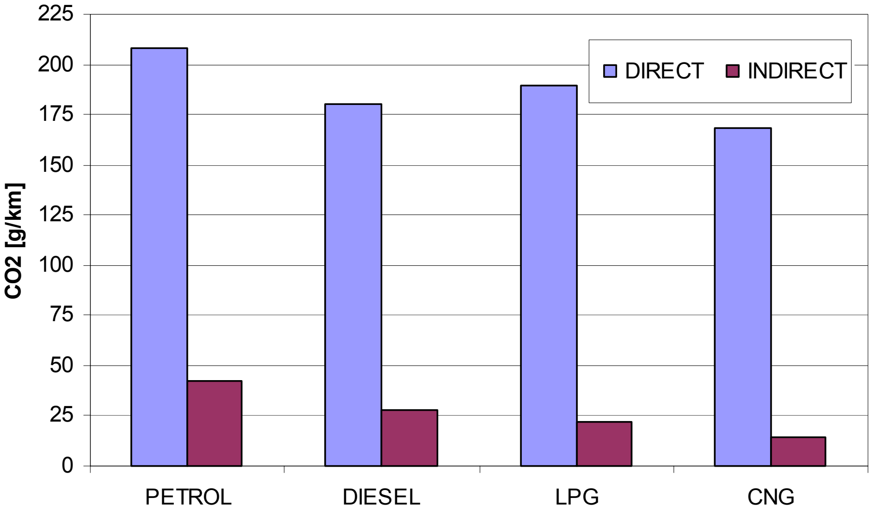


Figure 35: Comparison of direct and indirect CO_2-emissions for vehicles running on petrol, diesel, LPG and CNG (average driver).

Methane

Expressed in CO_2-equivalents (global warming potential) the direct emissions of methane are negligible for all vehicle types. However, as can be seen from *Figure 36*, the indirect emissions (also expressed in CO_2-equivalents) are much higher than the direct emissions. For petrol, diesel, and LPG they are of about the same magnitude, but still relatively small (about 2%) compared to the total greenhouse gas emissions (see *Figure 37*). For CNG the indirect methane emissions are higher and amount some 4% of the total greenhouse gas emissions. How the indirect methane emissions affect the overall comparison can be seen from *Figure 37*.

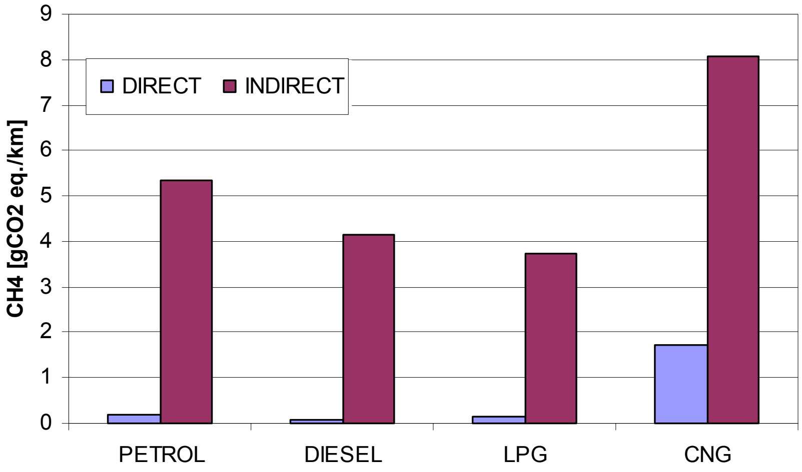


Figure 36: Comparison of direct and indirect CH_4-emissions (expressed in gram CO_2-equivalents per kilometre) for vehicles running on petrol, diesel, LPG and CNG (average driver).

Total greenhouse gases

Figure 37 shows the total greenhouse gas emissions for the different fuels. For comparison also an estimate is presented based on the indirect greenhouse gas emissions associated with EU-mix natural gas as derived in [12]. The total emissions comprise the direct and indirect emissions of CO_2, CH_4 and N_2O, all expressed in grams CO_2-equivalents using the respective global warming potentials (23 for CH_4 and 296 for N_2O according to recent IPCC information). As explained in the introduction, for greenhouse gas the well-to-wheel emissions from different sources at different locations can be summed to assess the total impact.

Based on the vehicle data measured in this project (direct emissions) and the data on indirect emissions as presented in *Table 12*, it can be concluded that the well-to-wheel greenhouse gas emissions from diesel and LPG vehicles are both some 16% lower than the WTW greenhouse gas emissions from petrol vehicles. The WTW greenhouse gas emissions from CNG vehicles, running on average Dutch gas from the low pressure grid, are found to be some 25% lower than those of petrol vehicles.

Including the indirect emissions thus increases the advantage of diesel and LPG compared to petrol, and further increases the advantage of CNG compared to petrol as well as diesel.

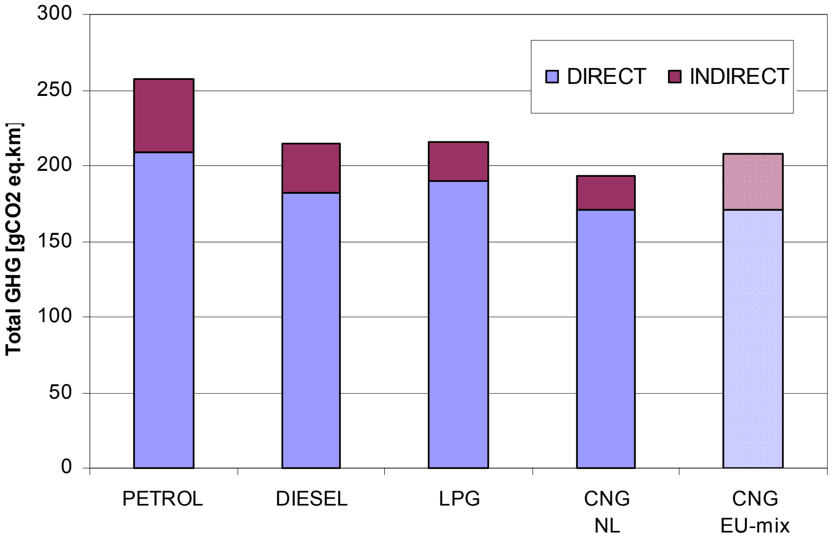


Figure 37: Comparison of total greenhouse gas emissions (expressed in gram CO_2-equivalents per kilometre) for vehicles running on petrol, diesel, LPG and CNG (average driver).

Assuming the indirect emission data for average EU-mix gas (also low pressure grid), as given by [12], the WTW greenhouse gas emissions of CNG vehicles are found to be about 19% lower than those of petrol vehicles. The difference with the Dutch situation is mainly caused by the high share of Russian gas in the EU-mix (21%) and the large indirect CO_2- and CH_4-emissions reported in [12] for mining and long distance transport of this gas. In the longer term future (2020 and beyond) gas imports from Russia could also constitute a significant part of the Dutch gas use. Calculating with indirect emission data from [9] and [10] for a 2020 import mix of 70% gas from Russia and 30% gas from Norway the total greenhouse gas emission benefit of CNG vehicles compared to petrol vehicles is found to reduce to about 7%. It does, however, seem that a large part of the indirect emissions associated with gas import from Russia are a result of the technical state of the pipelines and other equipment used, and could be significantly reduced by applying modern technology and appropriate “chain management”. The latter is of paramount importance if natural gas is to maintain its greenhouse gas emission benefits over the longer term. As a matter of fact Gasunie is already initiating cooperation with Gazprom to improve the situation.

Besides this potential risk for reduced emission benefits as a result of possible future gas imports, also potential future improvements should be mentioned. If in the future the fuel supply to natural gas vehicles can be arranged directly from the high pressure grid using high calorific gas, the lower energy needs for compression will lead to lower WTT CO_2-emissions and consequently a higher WTW greenhouse gas benefit than the value estimated in *Figure 37* for the present situation.

A survey of available WTW-assessments from literature shows that the estimated greenhouse gas emission advantages of diesel, LPG and CNG compared to petrol vary strongly from study to study. The differences can be attributed partly to the use of different data sources and partly to differences in the assumptions and precise cases studied. The comparison presented here, however, does show advantages that are roughly in correspondence with the values typically found in literature. The main exception is that the difference in WTW greenhouse gas emissions between diesel and petrol is somewhat smaller than values reported in e.g. [12] (24%) and other sources. This is largely due to a smaller difference in the direct CO_2-emissions. Analysis of other measurement data on real-world driving cycles available in the TNO Automotive database, also provides indications that for modern Euro3 vehicles the difference in real-world CO_2-emissions between diesel and petrol is declining compared to older data. The origin of this trend is still to be analysed.

Impacts of indirect emissions on overall evaluation of climatic effects

In *Table 10* of Chapter 5 an overall evaluation is given of the comparison of the four fuels with respect to climatic effects by translating the relative differences in the assessed impact potentials into relative scores expressed between “- -“ and “+ +”. Taking into account the above presented direct greenhouse warming potentials resulting from indirect emissions further justifies the scores in the table for the average driver on this aspect

8 Statistical considerations

One of the goals of the study is to compare the environmental performance of 4 groups of differently fuelled modern passenger cars. In order to make this comparison one needs to know if a difference in environmental performance found between two fuels is statistically significant or not.

Additionally this report presents absolute emission factors that are derived from the measurements carried out in the test programme. The sample size was 7 vehicles in most cases, which means that the calculated mean of the samples might not represent the vehicle population as a whole. Statistically, the sample mean is only an estimate of the mean of the population. For this reason the presented mean value has to be accompanied by a statistical indicator that represents the level of confidence.

So, for this study two cases are of importance. Both will be considered:
- Are differences found between the fuels significant?
- What are the confidence intervals of the calculated mean values?

In this chapter the methods will be discussed that were chosen to solve these cases. In Paragraph 8.1 the method for the determination of the level of significance will be presented, together with the results of this analysis. In Paragraph 8.2 the method for the second case will be discussed.

8.1 Significance of difference between the fuels

The samples of the petrol, diesel and LPG fuelled vehicles were chosen in such a way that every vehicle in one fuel group matches a similar vehicle in another fuel group regarding it’s functionality and engine performance (make and type are the same). This allows to compare the environmental performance per matching pair of vehicles. When the comparison of all pairs of vehicles of two fuel groups are observed together and a trend can be noticed that most pairs show, for example, an increase of the environmental performance for one of the fuels, one can say that the difference is significant. For an example, see *Figure 38*.

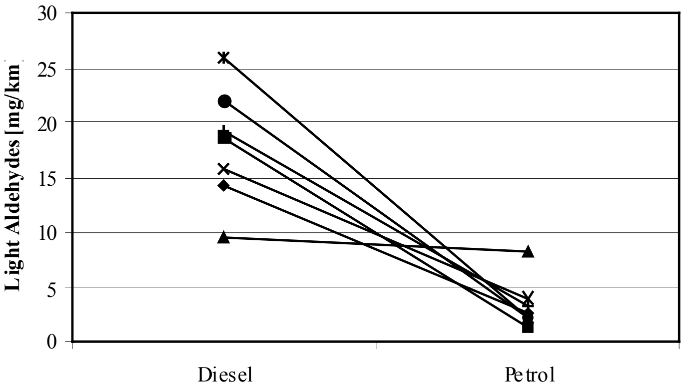


Figure 38: An example of comparing the results by pairs

A statistical method is available for this kind of analysis and it is called 'the t-test for matching pairs'. The method takes the magnitude of the difference between pairs into account together with the number of pairs analysed. So, a difference found between two fuels becomes more significant when more pairs show larger differences. Furthermore the level of confidence selected is of importance. It is clear that for a high level of confidence it is necessary that the differences found between the vehicles of the pairs should point in the same direction and should be sufficiently large relative to the scatter of the individual differences. For this study a confidence level of 95% and 90% was chosen. The number of pairs is limited to 7 and this in turn determines the influence of the differences found between the vehicles of every pair.

Concerning the CNG fuelled vehicles the following remark should be made. For the group of CNG vehicles there were only two matching pairs available (the Volvo V70 series and the Opel Astra series). The third CNG vehicle (Fiat Multipla Bi-Power) had no matching vehicle in the test sample of the other fuels. Therefore, for the Multipla the comparison was made with the mean values of the other fuel groups, which assumes that it may be compared with the 'average' petrol, diesel and LPG vehicles.

The t-test for matching pairs was performed for all possible combinations of fuels, for all of the 3 driving situations. The results of this statistical analysis have been taken into account when assessing the programme results (see Chapter 5). This means that a fuel can only obtain a better or lower score than another fuel when the difference is statistically significant. The results of the t-test for matching pairs is presented in the following tables. In these tables every combination of fuel groups is made in a small matrix. Matrices are presented for all environmental performance indicators, for the three different driver profiles.

- '++' in these tables means that there is a statistically significant difference between the performance indicators of the two fuels (95% confidence level).
- '+' means that there is a difference, but less significant than in the first case: it is probable that there is a difference (90% confidence level).
- '-' means that there is no significant difference.

The tables below show the results of the statistical analysis for the various environmental indicators. The following general statements can be made:

- The measured or calculated differences concerning NO_2, PM (both primary and secondary) and ozone formation potential (both POCP and TOFP) are significant in about half the possible pairings.
- The measured differences in PAH-emissions are mainly significant in pairings where at least one of the two gaseous fuels is involved.
- The other organic components only show significant differences for the local driver profile, except in the case of CNG where no significant differences are observed anywhere due to a combination of a small sample and a large spread in their calibration.
- Concerning the ecological effects it is mainly the diesel engine that shows a significant difference relative to the other fuels, due to the high impact of the diesel's NO_x.
- The differences in direct GWP are significant for almost all pairings, notwithstanding the much smaller differences in term of percentage, due to the

consistently good reproducibility of the fuel consumption (and hence CO_2) measurements.

- The differences in indirect GWP (EC/OC-emission) are mainly significant in the case of the diesel engine in the local driver situation.
- The differences in N_2O (ozone depletion potential) are significant for almost all pairings in the extra-urban situations; in the local driver situation only the two gaseous fuels are significant relative to each other.

Table 13: The significance of the differences between the emissions or indicators relevant for human health effects of the 4 fuels

Business driver

CO	Diesel	LPG	CNG
Petrol	-	-	-
Diesel		++	-
LPG			-

NO_2	Diesel	LPG	CNG
Petrol	++	-	-
Diesel		++	++
LPG			-

Primary PM	Diesel	LPG	CNG
Petrol	++	-	-
Diesel		++	++
LPG			++

Secondary PM	Diesel	LPG	CNG
Petrol	++	-	-
Diesel		++	++
LPG			-

SO_2	Diesel	LPG	CNG
Petrol	++	++	++
Diesel		++	++
LPG			++

2A PAH	Diesel	LPG	CNG
Petrol	-	+	-
Diesel		-	-
LPG			+

2B PAH	Diesel	LPG	CNG
Petrol	-	-	-
Diesel		++	+
LPG			+

BaP	Diesel	LPG	CNG
Petrol	-	+	-
Diesel		-	-
LPG			-

Fluoranthene	Diesel	LPG	CNG
Petrol	-	-	-
Diesel		-	-
LPG			-

1,3-Butadieen	Diesel	LPG	CNG
Petrol	-	-	-
Diesel		-	-
LPG			-

3 aldehydes	Diesel	LPG	CNG
Petrol	++	-	-
Diesel		++	-
LPG			-

BTX	Diesel	LPG	CNG
Petrol	+	+	++
Diesel		-	-
LPG			-

TOFP	Diesel	LPG	CNG
Petrol	++	-	-
Diesel		++	++
LPG			-

POCP	Diesel	LPG	CNG
Petrol	-	-	-
Diesel		++	-
LPG			-

Local driver

CO	Diesel	LPG	CNG
Petrol	++	-	-
Diesel		++	-
LPG			-

NO_2	Diesel	LPG	CNG
Petrol	++	-	-
Diesel		++	++
LPG			-

Primary PM	Diesel	LPG	CNG
Petrol	++	-	-
Diesel		++	++
LPG			-

Secondary PM	Diesel	LPG	CNG
Petrol	++	-	-
Diesel		++	++
LPG			-

SO_2	Diesel	LPG	CNG
Petrol	++	++	++
Diesel		++	++
LPG			++

2A PAH	Diesel	LPG	CNG
Petrol	-	+	++
Diesel		+	++
LPG			-

2B PAH	Diesel	LPG	CNG
Petrol	-	-	+
Diesel		-	++
LPG			-

BaP	Diesel	LPG	CNG
Petrol	-	+	++
Diesel		++	++
LPG			-

Fluoranthene	Diesel	LPG	CNG
Petrol	-	-	-
Diesel		-	-
LPG			-

1,3-Butadieen	Diesel	LPG	CNG
Petrol	++	-	-
Diesel		+	-
LPG			-

3 aldehydes	Diesel	LPG	CNG
Petrol	++	++	-
Diesel		++	++
LPG			-

BTX	Diesel	LPG	CNG
Petrol	++	++	-
Diesel		++	-
LPG			-

TOFP	Diesel	LPG	CNG
Petrol	-	-	-
Diesel		++	++
LPG			+

POCP	Diesel	LPG	CNG
Petrol	++	-	-
Diesel		++	+
LPG			-

Average driver

CO	Diesel	LPG	CNG
Petrol	++	-	-
Diesel		++	-
LPG			-

NO_2	Diesel	LPG	CNG
Petrol	++	-	-
Diesel		++	++
LPG			-

Primary PM	Diesel	LPG	CNG
Petrol	++	-	+
Diesel		++	++
LPG			++

Secondary PM	Diesel	LPG	CNG
Petrol	++	-	-
Diesel		++	++
LPG			-

SO_2	Diesel	LPG	CNG
Petrol	++	++	++
Diesel		++	++
LPG			++

2A PAH	Diesel	LPG	CNG
Petrol	-	++	++
Diesel		+	++
LPG			++

2B PAH	Diesel	LPG	CNG
Petrol	-	++	+
Diesel		++	++
LPG			-

BaP	Diesel	LPG	CNG
Petrol	-	++	++
Diesel		-	++
LPG			-

Fluoranthene	Diesel	LPG	CNG
Petrol	-	+	-
Diesel		-	-
LPG			-

1,3-Butadieen	Diesel	LPG	CNG
Petrol	++	-	-
Diesel		-	-
LPG			-

3 aldehydes	Diesel	LPG	CNG
Petrol	++	++	-
Diesel		++	++
LPG			-

BTX	Diesel	LPG	CNG
Petrol	++	++	-
Diesel		-	-
LPG			-

TOFP	Diesel	LPG	CNG
Petrol	++	-	-
Diesel		++	++
LPG			-

POCP	Diesel	LPG	CNG
Petrol	++	-	-
Diesel		++	+
LPG			-

Table 14: The significance of the differences between the ecological effects of the 4 fuels

Business driver

Acidification	Diesel	LPG	CNG
Petrol	++	-	-
Diesel		++	++
LPG			-

Eutrophication	Diesel	LPG	CNG
Petrol	++	-	-
Diesel		++	++
LPG			-

TOFP	Diesel	LPG	CNG
Petrol	++	-	-
Diesel		++	++
LPG			-

Local driver

Acidification	Diesel	LPG	CNG
Petrol	++	-	-
Diesel		++	++
LPG			-

Eutrophication	Diesel	LPG	CNG
Petrol	++	+	-
Diesel		++	++
LPG			-

TOFP	Diesel	LPG	CNG
Petrol	-	-	-
Diesel		++	++
LPG			+

Average driver

Acidification	Diesel	LPG	CNG
Petrol	++	-	-
Diesel		++	++
LPG			-

Eutrophication	Diesel	LPG	CNG
Petrol	++	+	-
Diesel		++	++
LPG			-

TOFP	Diesel	LPG	CNG
Petrol	++	-	-
Diesel		++	++
LPG			-

Table 15: The significance of the differences between the climate effects of the 4 fuels

Business driver

GWP	Diesel	LPG	CNG
Petrol	++	++	++
Diesel		+	-
LPG			+

OC	Diesel	LPG	CNG
Petrol	-	-	-
Diesel		+	-
LPG			-

EC	Diesel	LPG	CNG
Petrol	++	-	-
Diesel		++	++
LPG			-

Ozone Layer Depl.	Diesel	LPG	CNG
Petrol	++	-	+
Diesel		++	++
LPG			++

Local driver

GWP	Diesel	LPG	CNG
Petrol	++	++	++
Diesel		++	-
LPG			+

OC	Diesel	LPG	CNG
Petrol	+	-	-
Diesel		++	++
LPG			-

EC	Diesel	LPG	CNG
Petrol	++	++	+
Diesel		++	++
LPG			-

Ozone Layer Depl.	Diesel	LPG	CNG
Petrol	-	-	+
Diesel		+	-
LPG			++

Average driver

GWP	Diesel	LPG	CNG
Petrol	++	++	++
Diesel		+	+
LPG			+

OC	Diesel	LPG	CNG
Petrol	++	-	-
Diesel		+	+
LPG			-

EC	Diesel	LPG	CNG
Petrol	++	-	-
Diesel		++	++
LPG			-

Ozone Layer Depl.	Diesel	LPG	CNG
Petrol	++	-	+
Diesel		++	++
LPG			++

8.2 Confidence level of the mean values

Most populations show a normal distribution. A normal distribution means that the dispersion of the data is symmetrical with a decreasing frequency of occurrence towards the extreme values in both positive and negative direction. This is the well-known 'bell' shape. From automotive tail pipe emissions it is known, however, that the frequency distribution is limited to zero on the lower side and may extend to relatively high values on the upper side. This kind of distribution is called a skewed distribution. For this type of distribution the calculation of the confidence interval (CI) cannot be made in a straightforward way but demands a more intricate statistical method. All data first has to be analysed on certain statistical characteristics before it can be decided what statistical method should be used to determine an appropriate CI.

Since a skewed distribution has an extra degree of freedom, the actual shape of the distribution is the most important characteristic of the data to analyse. In order to find out if a data set is skewed an indicator can be calculated that indicates if the data set is skewed and how much. This indicator characterises the degree of asymmetry of a distribution around its mean. Positive skewness indicates a distribution with an asymmetric tail extending toward the high end. Negative skewness indicates a distribution with an asymmetric tail extending toward the low end.

Analysis of the emission data from the test programme shows that many data sets have a positive skewness. The level of skewness varies from little to very much. Exceptions generally are the data sets where most values are relatively far from ‘0’, for example the NO_X-emission of diesel vehicles, and for all vehicle groups the CO_2-emission. However, in some cases skewness was also found for these emissions, that was often the result of one relatively high emitting vehicle.

A generally accepted method for the calculation of confidential intervals, dealing with skewed data, is the so-called ‘bootstrapping’ method. With this method the distribution of the data can be analysed by calculating the average from randomly sampled values from a data set. Doing this several (more than 500) times will result in a distribution of the calculated averages. From this distribution statistical indicators can be derived which make it possible to characterise the data set. For this study the confidence intervals had to be determined, this can be done by cutting off a certain, equal amount of data from both tails of the calculated distribution. The boundaries of the remainder of this data, in this research 90% of the data, give the confidence intervals.

With the bootstrapping method, skewed data sets will give confidence intervals for positive and negative deviation from the mean that may differ in size. For positive skewed data sets, the confidence intervals are limited towards zero and are stretched out in positive direction.

The calculated confidence intervals are presented in the Figures of Chapter 5.

9 Comparison with the 1993 project

As mentioned in Chapter 1 (Introduction), a similar project was carried out in 1992 and reported in 1993. In this chapter we will try to compare the results, so as to see if another 10 years of development in vehicle technology has resulted in significant further emission improvements.

9.1 General approach of the 1993 project

To start with, one should realise that the two projects, although similar in objectives, were not fully identical in their approach. Especially the following points are of importance:

- The vehicles were not tested over the same driving cycles. Ten years ago research institutes had at best only started to realise the impact of real-world driving behaviour for catalyst equipped cars. And although TNO may be counted among the firsts to do so, the development of actual real-world driving patterns had only just begun. So even though real-world driving patterns had actually been included in the programme, they were not the same ones that exist today. The consequence is that the cycle results cannot be compared straightaway: a certain degree of ‘interpretation’ concerning the influence of the different test conditions is needed, and conclusions drawn from these comparisons can only be approximate.
- In the context of the real-world approach of the current project it was decided to start the ‘cold start’ tests at the average Dutch annual temperature of 9 °C. In the 1993 project all cold starts were performed within the ‘standard’ temperature window for certification tests (20-30°C, in practice that amounted to 22-23°C in the TNO laboratory).
- In the 1993 project there were 5 SI vehicles and 5 diesel vehicles. In both categories there were 4 passenger cars, and 1 small van. The SI vehicles were petrol vehicles, that were retrofitted for the use of LPG. Additionally one passenger car and the van were also retrofitted for the use of CNG. This means that the samples for petrol, diesel and LPG were comparable in size to that of the current project, but that there was only one passenger car tested on CNG, plus a van. As it was, there were some doubts afterwards as to the PM emission of the van, which could have been caused by a somewhat increased oil consumption.

The environmental performance indicators

Further differences between the two programmes were the selection of the components that were measured. The full list of PAH compounds was not identical, but by going back to the individual components a useful comparison is still possible. Additionally in 1993 an attempt was made to measure nitro-PAH, but this was not very informative due to the low absolute emissions concerned, which did hardly, or not at all, rise above the detection threshold. Hence this group of components was not included in the current programme. Emissions of N_2O could only be established in an approximate way for some of the test runs, giving an order of magnitude, but not a full inventory over all test conditions. EC/OC measurements were not performed at that time.

Concerning the environmental performance, to a large degree the same components and effects were determined, although the contributions of the components to certain environmental indicators were rated with different weighing factors due to different opinions of the experts of IPCC and similar bodies in those early days. The environmental effects were categorised as:

- Human health effects; directly toxic
- Human health effects; long-term toxic (these two are not separated in the current project, but are otherwise largely the same)
- Regional effects (the 'ecological effects' of the current project)
- Global effects (at that time only the current 'direct GWP').

In the current project the item 'winter smog formation potential' was dropped, but the largely similar 'indirect PM formation potential' was included. To the ecological effects 'euthrophication' was added. As it is, in the case of road vehicles this does not differ much from the 'acidification potential'.

The vehicle technology

The vehicles of the 1993 project were vehicles complying with Euro 1 standards. The SI engined vehicles were all fitted with 3-way catalyst. The diesel vehicles were all fitted with indirect injection (IDI) engines, with exception of the van, but 3 of those were already turbocharged. On the other hand only 2 of them were already fitted with oxidation catalyst. As stated above, the LPG and CNG equipment was retrofitted in all cases, although in all cases the most modern equipment was used, and it was installed by the equipment manufacturers themselves.

For the 2003 project the vehicles all complied with Euro 3 (or Euro 4 in a few cases). The petrol vehicles were still straight 3-way catalyst equipped vehicles, but with modern 'quick light-off' catalysts. The diesel vehicles now were all DI turbocharged vehicles with high pressure injection systems, and all fitted with oxidation catalyst. The LPG and CNG vehicles were all OEM-equipped vehicles.

9.2 Comparison of the project results

From the report of the 1993 project the following overall conclusions are summarised:

General:
It was stated: "The first impression regarding the measured values is that the exhaust gas quality of modern cars has improved very much over that of 20 years ago".

When the results of the current project are set against those of the previous one we must conclude that in a further 10 years not nearly a similar progress has been made. Although the legal limits have been further reduced by about 40 % for CO and about 75 % for THC and NO_x (Euro 3 versus Euro 1), and the vehicles were shown to comply with those requirements, we see that for the real-world situation the gains have not been in proportion. Although the hot emissions of the SI engines have decreased dramatically, those for the 'average driver' situation only show a modest decrease in NO_x-emission, and practically none in CO and HC. The non-regulated PM-emissions of the SI engines are much lower in the current programme, however. The most likely cause for this apparent non-improvement of the CO and HC-emissions would seem to be the decision to start the cold test at a realistic ambient temperature (9 °C). It should be noted, of course, that, since the 1993 vehicles were not tested at 9 °C, their actual performance at that temperature is not really known. A rough estimate on the basis of other testdata would seem to indicate, however, that in reality the real-world emissions have decreased by about a third for CO and by about half for HC and NO_x. Our estimate is further that the 9 ºC effect has increased over this period. We will have to wait and see if the inclusion of a -7 °C test in the type approval procedure is going to make a significant difference here. For the diesel engines the CO and HC-emissions were much improved (diesels suffer much less, or not at all, from low temperature starting), but for diesels these components are already negligible anyway. PM (reduction of the limit about 60 %) was noticeably better, but NO_x (reduction of the limit about 50 %) was more or less equal. The first remark here should be that in the current test programme the engine loads have been higher, due to a more ‘severe’ cycle; this tends to generate more NO_x. Nevertheless this also reflects the tendency of the manufacturers to calibrate their engines towards lower PM (where the limits are critical), at the expense of NO_x (for which the current limits are still less critical). This tendency had already been observed in the in-use compliance programme, where the emissions are measured over the standard type approval test cycle. In that programme the NO_x-emissions over the certification cycle had decreased from Euro 1 to Euro 2, but have increased to the Euro 1 level again with the introduction of Euro 3 (the available margin to the certification limits did allow this). The Euro 4 step, that will enter into force in 2005, will necessitate a real further reduction, though.

Catalyst equipped vehicles:
Under this heading in 1993 the remark was made that catalysts need some warming-up before they become effective, which results in a short period of relatively elevated emissions, which are, however, more than cancelled out by the excellent performance once the catalyst is hot. But it was pointed out that these cold start emissions still are an issue “in local circumstances, such as an urban environment, where many cold starts take place, or in situations where only very short trips are made.”

The inclusion of a ‘local driver’ profile in the current project has underlined the fact that, at least in a relative sense, this is still the case today. Most of the emission indicators for 3-way catalyst equipped vehicles turned out to be only significant for this local driver profile. In the hot tests especially the organic components (with the exception of PAH, see below) hardly rose above the detection limits.

Petrol:
Concerning petrol engines it was pointed out that the cold start effect is very noticeable on all indicators in which organic components play a part. An interesting observation was that in the case of PAH the cold start effect was more pronounced for the real-world urban cycle than for the ‘standard’ (type approval) urban cycle. PM was stated to be low, but GWP was the highest of the four fuels.

In the current project for the ‘average driver’ profile the total HC (with the cold start at 9°C) showed no real reduction relative to the 1993 situation (but with cold start at 22°C). Nevertheless the emissions of methane and light aldehydes are about half that of 1993; the same is true for the PM-emissions. The emissions of BTX scale with those of THC but the emissions of PAH are higher than in the previous project. Under hot conditions both THC and the specific individual organic components (with the exception of PAH) are an order of magnitude lower than in 1993. So one may conclude that the cold start influence is much more pronounced in the current results. The emissions of PAH under hot conditions, although in absolute terms much lower than under cold conditions, are as such up to an order of magnitude *higher* than before, which in combination with the one order of magnitude *lower* THC means that under hot conditions the PAH share of the total HC must have increased. This is discussed below in some more detail.

Diesel:
Concerning the diesel it was remarked in 1993 that it scores high to very high on both direct and long-term toxic effects (CO excepted), and also for the regional effects. On GWP it scores between petrol and LPG. Detailed evaluation of the effects that led to this conclusion shows that this is due to NO_x / NO_2, PM and light aldehydes. PAH was also high, but BTX scored average. The moderate score on GWP was caused by the fact that at that time the IPCC assumed a significant contribution of NO_x and various organic compounds towards the GWP.

Comparison with the 2003 results shows that the emission of CO (already low in 1993) has further dropped by almost an order of magnitude, that of THC by a factor of 3 (hot urban) to 6 (average), and that of PM by a factor of 2. But NO_x remains the Achilles' heel of the diesel. The legal limit is already high in comparison to that for SI engines (0.5 versus 0.15 g/km for Euro 3), and yet the results show no clear reduction even relative to that higher limit since 1993 (note that the dropped temperature for the cold start does hardly affect diesel engines). As explained above this is caused by the manufacturers shifting their calibration towards less PM and consequently more NO_x. This then obviously translates into all environmental indicators with an NO_x component. The emission of NO_2 has actually about doubled because of the much higher (and since 1993 further increased) share of NO_2 within the total NO_x. Both the remarkable reduction in organic compounds and the increase in the share of NO_2 have of course to do with the widespread introduction of oxidation catalysts. It is therefore all the more remarkable that, notwithstanding a reduction in PAH of about half in absolute numbers, the relative share of PAH in the THC has increased in the case of diesels too, at least for the 'average driver' profile.

Gaseous fuels:
It was stated in 1993: "The gaseous fuels score better than the liquid fuels on all accounts (except CO for LPG). When comparing the two fuels CNG often scores better than LPG, although LPG scores better than CNG on particulates." Further evaluation of this statement shows that the less than expected score on CO for LPG was the result of the system calibration not being able to cope with the stop and go pattern of the 'traffic jam' cycle that had been part of the 1993 project. The lesser score of CNG on particulates was the result of a relatively high PM-emission on one of the only two vehicles that were tested on CNG; this vehicle was believed to have a slight oil consumption problem.

Comparing the 2003 results with the 1993 ones, LPG showed the same relative tendencies as petrol, whereas CNG behaved somewhat erratic, with relatively high CO, relatively low THC, and NO_x remarkably reduced for the 'average' driver profile but about equal for the hot start local situation. PM from LPG also behaved somewhat erratic; for CNG it was clearly better than in the previous project, but as stated the 1993 results were somewhat spurious. As discussed in Chapter 5 and 6, the results from the gaseous fuels were strongly influenced by two aspects. On the one hand the three CNG vehicles showed a noticeable difference in calibration strategy, leading to mutually incomparable emission results. This could explain the seemingly erratic differences between the 1993 and 2003 results. On the other hand, and more important, it was pointed out that the results from all the SI engines were strongly determined by their cold start behaviour, and that the LPG and CNG vehicles generally tend to start on petrol when cold. So their behaviour in the local driver situation reflects the petrol situation rather than the gaseous fuel situation. Apart from other consequences this tends to result in large differences between hot and cold operation. Again, with both fuels the share of PAH in the total HC was larger than in 1993, generally leading to emissions that were higher even in absolute terms (although the PAH of the hot CNG tests were too low to attach much importance to relative tendencies). This may be assumed, however, to reflect the petrol behaviour during cold start.

Some further observations

In the discussion above we pointed to the remarkable PAH behaviour. This behaviour may not be so evident in the 'compounded' driver profiles, but do show clearly in some of the elements from which these overall results have been composed. Part of the explanation could be the tendency for PAH to be higher in a more dynamic real-world test cycle (as used in the current project) than in the less dynamic certification test cycle (as in the 1993 project). Another part of the explanation could be that at lower absolute values, measurement uncertainties start to play a bigger part, although an increased spread should be expected to result in anomalies both ways, which was in fact not observed. It seems unlikely, however, that such elements may provide the full explanation. A first quick analysis showed that there are some individual results that seem to influence the overall averages, but a more detailed evaluation (down to individual vehicle level and individual test condition) seems to be required. It is recommended to start such detailed evaluation.

Nevertheless at the present state of affairs it must be concluded that the remarkable finding of Chapter 5 that the PAH of diesels is now equal to, or even less than, that of petrol engines is only partly caused by a reduction in PAH from diesel engines (probably due to their use of an effective oxidation catalyst) and at least to the same extent caused by an actual increase of the PAH from petrol engines.

Another outlier result was the emission of light aldehydes from the CNG vehicles. The measured value meant that its share in THC would have been 4 times higher than in 1993 for the average driver situation. Similar, though less extreme behaviour was observed from the BTX emissions of the LPG and CNG vehicles. These effects seem to stem primarily from the cold start phase, so the most ready explanation here would again be the tendency to start on petrol. If true, this would mean that it is not an LPG/CNG aspect, but a petrol aspect.

Finally, the current emissions of N_2O, when compared to the 'order of magnitude' determination of 1993 show that they are lower but still of the same order. So the figures of 1993, however crude, can not have been very much away from reality.

9.3 Recommendations

On the basis of the outcome of this comparison it is recommended that the PAH situation is further evaluated, to see what might be the cause of its remarkable behaviour. Such evaluation needs to start with a detailed analysis of the individual results, to see if the apparent effects are characteristic for the overall situation or only suggested by certain individual measurements with a possible outlier character. If this does not lead to a clear answer, it would seem that the items for further investigation might be:

1. Possible changes in the sampling and analysing techniques used.
2. The use of a real-world test cycle.
3. Changes in the vehicle’s technologies.
4. Changes in the specifications of the fuels used.

It is further recommended that the emission behaviour of SI engines is monitored for the coming model years, to check if the inclusion of the –7 ºC test in the type approval procedure does actually improve the emission performance under real-world driving circumstances at real-world ambient temperatures.

The last recommendation would be to investigate if a cold start on LPG/CNG might significantly further improve the overall environmental performance of gaseous fuelled vehicles.

10 Conclusions and recommendations

10.1 Conclusions

In the following paragraphs the main conclusions are summarised.

10.1.1 Regulated emission components

- The regulated emissions of most of the spark ignition (SI) engined vehicles, although certified as Euro 3 vehicles, are already below the Euro 4 limits. Such behaviour (actual emission values one step ahead of the legislation) is quite characteristic for 3-way catalyst equipped vehicles. It was therefore concluded that all SI vehicles could be regarded as being in good running order.
- For diesel vehicles the emissions of CO and HC are not a problem; possible shortcomings may more readily be expected concerning NO_x and PM. The checks showed the HC + NO_x emissions to be closer to the Euro 3 limit than those of the SI engines; this was caused by the relatively high figures for NO_x, and not by the HC-emissions. Similar behaviour was observed for the PM-emissions. Such behaviour is characteristic for diesel vehicles and does not therefore need to be taken as a sign of marginal operational performance. For the diesel engined vehicles it was therefore also concluded that they were in good running order.

10.1.2 Evaluation of the environmental performance (direct emissions)

Human health effects:

- The overall evaluation shows that for a hot engine the human health effects are very low in the case of SI engines. Diesel engines show higher impact potentials due to higher PM and NO_x.
- In local situations (with cold start) another picture emerges. Here the petrol engine shows the highest impact potentials, followed by the diesel engine and the LPG engine. CNG suffers the least from the cold start.
- It is assumed that the additional cold start emissions from the LPG and CNG engines are primarily caused by their starting on petrol.
- For the average driver only the result of the petrol engine is significantly influenced by the cold start, because of the magnitude of the cold start effect in that case.
- In general the gaseous fuels show the lowest emissions for the average driver, and diesel the highest emissions.

Ecological effects:

The overall situation is that diesel engines show high to very high impact potentials in all three driver sitiations. Petrol and LPG engines show low impact potentials, with the exception of TOFP that is mainly a cold start effect. CNG engines show the best overall results.

Climatic effects:

The ozone depletion potential for passenger cars is rated as of low relevance. Therefore the overall conclusion of the climatic effects is based on only the direct Global

Warming Potential (GWP). Petrol shows the highest GWP. Diesel and LPG show an advantage for the business and average driver, however LPG suffers from a cold start effect and/or a part load inefficiency in the case of the local driver. CNG shows equal results for the local driver situation compared to diesel, and for the other driver situations CNG is the best option of the four fuels.

Overall situation:

The table below summarises the overall measured results. In each cell of the table a rating is established by giving a score '--' to the case with the highest impact potential for the effect under consideration (i.e. to the 'case' where the emission or environmental indicator is highest). Subsequently the results for the other 'cases' are scored relatively to this case on a scale between '--' and '++'. A 'case' in this context means a combination of fuel and driver profile. This approach allows both the mutual comparison of the fuels and the comparison of the driver profiles, plus the combination of both.

In the table no further summary score has been indicated, since it is felt that it is a matter of policy which effect, in a given situation, has priority over another one, and to which extent. The four fuels simply have different impacts in different fields.

However, the following general conclusions can be made:

- Petrol shows lower impact potentials concerning health effects and/or ecological effects compared to diesel, however diesel shows a lower CO_2-emission and hence a lower direct GWP. Although the 'indirect GWP' (EC/OC) might change that again if it turns out to be an effect with a high relevance.
- The gaseous fuels LPG and CNG show the best overall results, especially CNG shows (very) low impact potentials on almost all effects in all driver situations.

Taking into account the statistical analysis to determine if the difference in environmental performance between two fuels is statistically significant, the following can be said:

- The overall score of the fuels, as stated above, is in most cases confirmed by the results of the paired-t-test.
- However, the advantage of CNG compared to LPG, concerning the human health and ecological effects, is in many cases not statistically significant. Beforehand it was recognised that the small sample size of the CNG vehicles (3 vehicles are measured) would result in a lower level of statistical confidence.

Business driver

	Relevance	Petrol	Diesel	LPG	CNG
Health effects					
NO_2	high	++	--	++	++
Overall PM	high	+	-	+	++
Overall PAH	high	++	++	++	++
1,3-butadiene	high	++	++	++	++
Light aldehydes	high	++	++	++	++
BTX	medium	++	++	++	++
Smog potent. POCP	high	++	++	++	++
Smog potent. TOFP	high	++	-	++	++
Ecological effects					
Smog potent. TOFP	high	++	-	++	++
Acidification potent.	medium	+	-	+	++
Euthrophication potent.	high	+	-	+	++
Climatic effects					
Direct GWP	high	-	+	+	++
EC-OC (GWP)	uncertain	++	o	++	++

Local driver

	Relevance	Petrol	Diesel	LPG	CNG
Health effects					
NO_2	high	++	--	++	++
Overall PM	high	+	--	+	+
Overall PAH	high	--	o	+	++
1,3-butadiene	high	--	+	-	+
Light aldehydes	high	+	--	++	++
BTX	medium	--	++	-	+
Smog potent. POCP	high	--	++	-	o
Smog potent. TOFP	high	-	--	-	o
Ecological effects					
Smog potent. TOFP	high	-	--	-	o
Acidification potent.	medium	+	--	+	+
Euthrophication potent.	high	+	--	+	+
Climatic effects					
Direct GWP	high	--	+	o	+
EC-OC (GWP)	uncertain	+	--	++	++

Average driver

	Relevance	Petrol	Diesel	LPG	CNG
Health effects					
NO_2	high	++	--	++	++
Overall PM	high	+	-	+	++
Overall PAH	high	+	+	++	++
1,3-butadiene	high	+	++	+	++
Light aldehydes	high	++	+	++	++
BTX	medium	+	++	+	++
Smog potent. POCP	high	+	++	+	+
Smog potent. TOFP	high	+	-	+	+
Ecological effects					
Smog potent. TOFP	high	+	-	+	+
Acidification potent.	medium	+	-	+	+
Euthrophication potent.	high	+	-	+	+
Climatic effects					
Direct GWP	high	-	+	+	++
EC-OC (GWP)	uncertain	++	o	++	++

--	Very high impact potential	(highest impact potential of all cases for the effect under consideration; a 'case' means a combination of fuel and driver profile)
-	High impact potential	(relative to case with highest impact potential)
0	Average impact potential	(relative to case with highest impact potential)
+	Low impact potential	(relative to case with highest impact potential)
++	Very low impact potential	(relative to case with highest impact potential)

10.1.3 Additional technology assessments

Concerning diesel particulate filter (DPF) technology:

- The results obtained only represent the operation between two regenerations. Regeneration takes place by a periodical 'rich' spike in the fuelling. This may temporarily increase the PM-emission and will certainly increase the overall fuel consumption by a small percentage. For this reason the type approval procedure prescribes the measurement of a regenerative cycle, the results of which should be 'spread out' over the average distance between two regenerations. It is planned to measure the regulated and unregulated emissions during the regeneration phase in January 2004. The results will be described in a supplement that will become available at the beginning of 2004.
- The overall evaluation of the DPF technology indicates that this has a good potential to reduce the PM-emission (including the ELPI number emission), without noticeable adverse effects with regard to the NO_x- and CO_2-emission.

Concerning gaseous fuelled vehicles:

- Evaluation of the gaseous fuelled vehicles (both automotive LPG and CNG) showed a number of remarkable aspects. Although they were not further investigated their most logical explanation would seem to be the regularly used strategy in bi-fuel vehicles to cold-start the vehicle on petrol. There are practical operational reasons for such strategies, but, as this investigation shows, the consequence is that exactly during the critical cold start and warming up phase the advantages of the gaseous fuel are not coming into play, since at that very time the vehicle is petrol fuelled.

Concerning small vans:
On the basis of the current knowledge there is no fundamental reason to assume a significant difference in environmental performance of small vans relative to passenger cars, except for the following:

- In general it should be said that a van is heavier than a comparable passenger car, usually without a comparable increase in engine power. This will mean that the van will need more engine power to drive the cycle, but that it will do so by using a higher relative share of the engine power installed.
  The first observation is reflected in the significantly higher fuel consumption compared to passenger cars, and consequently the CO_2-emission is higher in proportion. Typical differences would need to be established on a bigger sample, but amounted in the measurements results to 30-70 % increase for spark ignition engines and 10-40 % for diesel engines, depending on driver profile.
  The second observation will mean that vans equipped with a diesel engine may be expected to emit disproportionately more NO_x and possibly PM than a diesel passenger car. From the measurement results it can be concluded that the emissions of NO_x and PM of diesel vans tends to be significantly higher than that of passenger cars. Again typical differences would need to be established on a bigger sample. They amounted to 80 % higher for NO_x and to 2.5-4.5 times for PM, depending on driver profile. The NO_x increase would reflect in all environmental indicators that contain a NO_x-component.
- There is a suspicion that certain organic components (notably PAH) might score lower for a van. If true this might perhaps be attributed to a higher engine loading, but the effects observed do not allow any real trend to be confirmed, let alone any numerical indication.

10.1.4 Indirect emissions from the energy chain

Indirect emissions, associated with the well-to-tank (WTT) energy chain of petrol, diesel, LPG and CNG vehicles have been assessed based on available data for CO, NMHC, NO_x, SO_2, PM, CO_2, CH_4, N_2O, formaldehyde, acetaldehyde, 1,3 butadiene, and benzene. Using the same formula's as applied to the exhaust emissions, these indirect emissions have been translated into upper level estimates of the impact potentials, which can be compared to the impact potentials resulting from the direct emissions. If these upper limits are found to be a significant fraction of the impact values calculated for the direct emissions, they may be considered to have an influence on the overall comparison between the four fuels. In such instances a closer examination of the quantities and locations of the emissions and their possible contribution to various health and ecological effects should be carried out. This, however, was beyond the scope of this assessment.

Given the uncertainties related to the assessment of indirect emissions, the comparisons presented here should be considered as indicative. The comparisons are based on the average driver situation.

Emissions related to human health effects:

- The indirect emissions of CO, benzene and aldehydes are relatively small compared to the direct emissions for all fuels, with the exception of the CO-emission of diesel. For this fuel the direct and indirect CO-emissions are about equal, but both are relatively small. For these components the WTT-emissions therefore do not influence the outcome of the comparison between the different fuels.
- The indirect emissions of NO_x are comparable to the direct emissions in the case of petrol and LPG, but are much smaller than the direct emissions in the case of diesel and CNG. For this component the WTT-emissions therefore do somewhat influence the outcome of the comparison between petrol, LPG and CNG in the sense that they increase the advantage for CNG. The overall benefits of petrol, LPG and CNG relative to diesel, however, are not significantly affected by the WTT-emissions.
- If all indirect emissions are considered to contribute to the ozone formation potential, the resulting TOFP-value for the indirect emissions is found to be about half of the direct value for petrol and LPG. For diesel and CNG the indirect TOFP-values are a lower fraction of the direct TOFP-values. Including the full indirect TOFP-potential would therefore slightly reduce the advantage of petrol and LPG relative to diesel, and would give CNG a slight benefit compared to petrol and LPG. However, as ozone formation is a local phenomenon, strongly dependent on local meteorological, geographical and air quality characteristics, the contribution of the indirect emissions to ozone formation will in practice be much smaller than the upper limit estimated here.
- Both for primary PM and for secondary PM the emissions in the fuel chains of petrol and LPG are of the same order of magnitude as the direct emissions. For CNG the indirect emissions of primary and secondary PM are negligible. Including indirect emissions in the comparison increases the advantage of CNG compared to petrol and LPG. The comparison between these three fuels and diesel, with high direct emissions, is not significantly affected by the indirect emissions of primary and secondary PM.
- For petrol and diesel the indirect emissions of 1,3 butadiene are relatively high, both in absolute terms and compared to the direct emissions. For LPG and CNG the indirect emissions are much smaller and therefore insignificant compared to the direct emissions. Including the indirect emissions thus reduces the advantage of diesel compared to petrol and LPG, and increases the advantage of LPG and CNG relative to petrol and diesel.

Ecological effects:

- As for petrol, diesel and LPG the indirect emissions of both NO_x and SO_2 are relatively high, the estimated upper limit for the acidification potential resulting from the indirect emissions is of the same order of magnitude as the potential due to direct emissions. Including the total indirect acidification potential, the advantages of petrol, LPG and CNG relative to diesel would be significantly reduced. In the comparison between petrol, LPG and CNG the indirect emissions increase the advantage of CNG.
- Consequently the score of CNG on acidification, as expressed in the table above on ecological effects for the average driver, would be positively affected by including the upper limit estimates for indirect emissions and acidification in the comparison and the resulting impact potentials. For smog (TOFP) the scores would remain unchanged.

Climatic effects:

- The total greenhouse gas emissions comprise the direct and indirect emissions of CO_2, CH_4 and N_2O, all expressed in grams CO_2-equivalents using the respective global warming potentials. Petrol and, to a lesser extent, diesel and LPG have higher indirect CO_2-emissions than CNG (more than 10% of the value for the direct emissions). CNG, on the other hand, has somewhat higher indirect methane emissions from the energy chain (expressed in CO_2-equivalents about 4% of the total greenhouse gas emissions).
- Based on the vehicle data measured in this project and the indirect emission data selected for this study, it can be concluded that the well-to-wheel (WTW) greenhouse gas emissions from diesel and LPG vehicles are both some 16% lower than the greenhouse gas emissions from comparable petrol vehicles. The WTW greenhouse gas emissions from CNG-vehicles, running on Dutch natural gas from the low pressure grid, are 25% lower than those of petrol. Compared to the evaluation of the direct emissions, including the indirect emissions thus increases the relative advantage of diesel and LPG compared to petrol, and even more strongly increases the relative advantage of CNG compared to petrol.
- Comparison with data on other natural gas mixes (e.g. EU-mix with significant share of imports from Russia or a future 100% import mix) shows that the WTW greenhouse gas emission benefit of CNG-vehicles would be reduced if in the future significant shares of Russian gas would be consumed. As this is largely a consequence of the technical state of the pipelines and other equipment used, appropriate “chain management” is considered of paramount importance if natural gas is to maintain its greenhouse gas emission benefits over the longer term. On the other hand, future filling stations connected to the high pressure grid could improve the WTW greenhouse gas emission benefit compared to the present situation due to the lower energy requirement for compression.
- Taking into account the above presented direct greenhouse warming potentials resulting from indirect emissions would not affect the score on climatic effects as displayed in the table above for the average driver.

10.1.5 *Comparison with the 1993 project*

Comparing the results from the 2003 project with those of the 1993 project, the following aspects are the most obvious:

- The real-world emissions of SI engines do not seem to show any reduction for CO and THC, and only a modest reduction for NO_x. It should be noted, however, that the cold start of the 1993 project was made at about 22 ºC, and that of the 2003 project at 9 ºC. This is certain to have had a significant effect, but its magnitude is not really known. A rough estimate on the basis of other testdata would seem to indicate, however, that in reality the real-world emissions have decreased by about a third for CO and by about half for HC and NO_x.
- The real-world emission of diesel engines showed significant reductions for CO and THC (but in practice these components are not critical), a good reduction for PM, but no reduction for NO_x. This can be attributed to the general use of an oxidation catalysts and a shift in calibration that favours the reduction of PM at the expense of NO_x.
- Evaluation of the organic components showed a remarkable behaviour of PAH, which seems to constitute a bigger share of THC. This was noted for all four fuels,

though in the case of the gaseous fuels that may have been caused by the cold start on petrol.

10.2 Recommendations

The following recommendations can be made:

- It is felt that the manufacturers of LPG and CNG vehicles might do well to apply a different (cold) start strategy (starting on LPG/CNG instead of on petrol), since this would seem a relatively easy way to take much more advantage of the favourable characteristics of gaseous fuels for the local situation.
- It is recommended to further investigate the PAH situation, to find the likely cause of the remarkable behaviour.
- The total evaporative HC-emissions can be quite considerable compared to the HC emissions from the exhaust. Including the evaporative emissions in the comparison between the four fuels can significantly influence the outcome of the comparison, especially between diesel and the other three fuels. It is therefore recommended to further study the evaporative HC-emissions of the different vehicles types. The study should not only quantify the evaporative HC-emissions of the different vehicle types but also examine the composition of these emissions (e.g. benzene content).
- It is recommended that the emission behaviour of SI engines is monitored for the coming model years, to check if the inclusion of the –7 ºC test in the type approval procedure does actually improve the emission performance under real-world driving circumstances at real-world ambient temperatures.

11 References

[1] Rijkeboer, R.C. and Hendriksen, P.: “Regulated and unregulated exhaust gas components from Light Duty vehicles on petrol, diesel LPG and CNG”.
TNO report 93.OR.VM.029/1/PHE/RR. Delft October 1993.

[2] Van de Burgwal, H.C., P. Hendriksen and D.A.C.M. Bremmers: “Environmental and human health effects of exhaust gases from passenger cars”.
TNO report 02.OR.AT.014.1/HvdB. Delft September 2002.

[3] André, M: “Construction de cycles de conduite représentatifs pour la mesure des émissions de polluants des véhicules”
INRETS report LEN 9808. Bron, France, February 1998

[4] Joumard, R.: “Detailed ARTEMIS 300 description”.
INRETS report LTE 0104. Bron, France, July 2001.

[5] de Haan, P. and Keller, M.: “Real-world driving cycles for emission measurements: ARTEMIS and Swiss cycles”.
INFRAS report B 7014b2-04, March 2001.

[6] IARC: http://monographs.iarc.fr/monoeval/grlist.html

[7] RIVM: “Milieu in cijfers, MilieuCompendium”
www.rivm.nl/milieuennatuurcompendium/nl/i-nl-0079-04.html

[8] Taakgroep Verkeer en Vervoer (CBS, RIVM, RIZA en TNO): “Methoden voor de berekening van de emissies door mobiele bronnen in Nederland”
Rapportagereeks MilieuMonitor Nr. 4, January 2002

[9] Tillemans F.W.A., ECN, personal communications

[10] Tillemans F.W.A., Ouden A.C.B. den, "Brandstofcelbussen en distributievrachtwagens in de stedelijke omgeving; een analyse van het milieupotentieel"
ECN-C-03-009, 2003

[11] J. Winebrake, D. He, and M. Wang, “Fuel-Cycle Emissions for Conventional and Alternative-Fuel Vehicles: An Assessment of Air Toxics”, Argonne ANL/ESD-44, August 2000

[12] “GM Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems – A European Study”, L-B-Systemtechnik GmbH, September 2002

[13] Kroon, P., “Milieuvergelijking van auto’s op aardgas, benzine en LPG bij bi-fuel motoren”, ECN-cx-92-093, ECN, June 1992

A Vehicle specifications

Table 16: Specifications of the passenger cars

No.	*Passenger cars*	*Fuel*	*Engine Type*	*Power*	*Inertia*	*Mileage*
				[kW]	[kg]	[km]
1	Renault Scenic Bi-fuel	LPG	1.6l 16V 4 cyl.	76	1470	6110
2	Renault Scenic petrol	petrol	1.6l 16V 4 cyl.	79	1360	5490
3	Renault Scenic DCi	diesel	1.9l 8V 4 cyl.	75	1360	13583
4	Opel Astra Bi-fuel*	LPG	1.6l 8V 4 cyl.	62	1360	6056
5	Opel Astra Bi-fuel*	petrol	1.6l 8V 4 cyl.	62	1250	6056
6	Opel Astra DTi	diesel	1.7l 8V 4 cyl.	55	1360	12665
7	Opel Astra CNG	CNG	1.6l 16V 4 cyl.	71	1360	5100
8	Opel Vectra Bi-fuel*	LPG	1.8l 16V 4 cyl.	90	1590	16499
9	Opel Vectra Bi-fuel*	petrol	1.8l 16V 4 cyl.	90	1470	16499
10	Opel Vectra DTi	diesel	2.0l 16V 4 cyl.	74	1470	18901
11	Peugeot 406 Bi-fuel	LPG	1.8l 16V 4 cyl.	80	1360	13950
12	Peugeot 406 petrol	petrol	1.8l 16V 4 cyl.	80	1360	5050
13	Peugeot 406 HDi	diesel	2.0l 8V 4 cyl.	80	1470	10400
14	Volvo V40 Bi-fuel	LPG	1.8l 16V 4 cyl.	88	1470	22795
15	Volvo V40 petrol	petrol	1.8l 16V 4 cyl.	90	1360	22842
16	Volvo V40 D	diesel	1.9l 8V 4 cyl.	85	1470	20849
17	Volvo V70 Bi-fuel	LPG	2.4l 20V 5 cyl.	103	1700	6250
18	Volvo V70 petrol**	petrol	2.4l 20V 5 cyl.	103	1700	20402
19	Volvo V70 D5	diesel	2.4l 20V 5 cyl.	120	1700	17119
20	Volvo V70 CNG	CNG	2.4l 20V 5 cyl.	103	1700	5050
21	Ford Focus Bi-fuel	LPG	1.8l 16V 4 cyl.	84	1360	7677
22	Ford Focus Petrol	petrol	1.8l 16V 4 cyl.	84	1360	27512
23	Ford Focus TDCi	diesel	1.8l 8V 4 cyl.	84	1360	13867
24	Fiat Multipla CNG	CNG	1.6l 16V 4 cyl.	76	1700	17464

* measurements on petrol and LPG done with the same vehicle

** all vehicles including the vans are Euro 3, with exception of the V70 on petrol, which is Euro 4

Table 17: Some important specifications of the passenger cars averaged.

Averages per fuel	*Average Power*	*Average Inertia*	*Average Mileage*
	[kW]	[kg]	[km]
Petrol	84	1409	14800
Diesel	82	1456	15300
LPG	83	1473	11300
CNG	83	1549	9200

Table 18: Specifications of the vans

No.	*Vans*	*Fuel*	*Engine Type*	*Power*	*Inertia*	*Mileage*
				[kW]	[kg]	[km]
1	Ford Transit Bi-fuel*	LPG	2.3l 16V 4 cyl.	103	1930	5953
2	Ford Transit Bi-fuel*	petrol	2.3l 16V 4 cyl.	107	1930	5953
3	Ford Transit TDCi	diesel	2.4l 16V 4 cyl.	92	1930	10270

* measurements on petrol and LPG done with the same vehicle

B Detailed emission results

Emissions and emission profiles: Business driver.

Table 19: Emission profile PAH

	Business driver			
[ug/km]	Petrol	Diesel	LPG	CNG
naphthalene	37.8	14.9	6.0	6.3
acenaphthylene	1.7	0.5	0.7	0.3
acenaphthene	1.0	1.6	0.0	0.0
fluorene	5.0	1.5	0.6	1.1
phenanthrene	4.0	2.9	1.4	2.2
anthracene	0.5	0.2	0.1	0.2
fluoranthene	0.8	0.7	0.3	1.3
pyrene	0.8	0.6	0.4	1.0
benzo[a]anthraceen	0.3	0.1	0.2	0.0
chrysene	0.5	0.3	0.3	0.3
benzo[b]fluoranthene	0.2	0.0	0.0	0.0
benzo[k]fluoranthene	0.2	0.2	0.0	0.0
benzo[a]pyrene	0.2	0.1	0.0	0.0
indeno[1,2,3-cd]pyrene	0.1	0.0	0.0	0.0
dibenzo[a,h]anthracene	0.0	0.0	0.0	0.0
benzo[g,h,i]perylene	0.2	0.1	0.0	0.0

Table 20: Emission profile aldehydes

	Business driver			
[ug/km]	Petrol	Diesel	LPG	CNG
formaldehyde	101	915	52.9	235
acetaldehyde	101	245	102	47.4
acrolein	6.4	13.3	2.9	2.5
aceton	100	135	26.5	0.0
propionaldehyde	9.0	40.6	12.9	21.7
crotonaldehyde	5.4	11.4	3.1	0.0
n-butyraldehyde	22.0	17.2	13.7	0.0
benzaldehyde	31.6	21.5	9.3	0.0
iso-valeraldehyde	0.0	0.0	0.0	0.0
n-valeraldehyde	7.3	10.4	7.1	0.0
o-tolualdehyde	1.9	0.0	0.0	0.0
m-tolualdehyde	10.9	8.5	0.9	0.0
p-tolualdehyde	8.3	7.1	7.5	0.0
hexanal	7.5	8.9	11.9	0.0
2,5-dimethylbenzaldehyde	0.0	0.0	0.0	0.0

Emissions and emission profiles: Business driver.

Table 21: Emission profile C_1 to C_{12}.

	Business driver			
[mg/km]	Petrol	Diesel	LPG	CNG
Methane	3.1	2.3	2.5	53
Ethane	0.12	0.10	0.16	0.35
Ethene	0.11	0.18	0.12	0.10
Propane	0.67	0.27	1.08	0.00
Propene	0.04	0.03	0.06	0.01
Acetylene	0.00	0.00	0.00	0.00
Isobutane	0.17	0.01	0.22	0.00
n-Butane	0.01	0.00	0.55	0.00
Isopentane	0.09	0.00	0.17	0.00
n-Pentane	0.01	0.00	0.02	0.00
Isobutene & 1-Butene	0.00	0.04	0.00	0.00
cis-2-Butene	0.01	0.00	0.01	0.00
trans-2-Butene	0.01	0.00	0.01	0.00
1,3-Butadiene	0.00	0.00	0.00	0.00
1-Pentene	0.00	0.00	0.00	0.00
trans-2-Pentene	0.00	0.00	0.00	0.00
cis-2-Pentene	0.00	0.00	0.00	0.05
Isoprene	0.00	0.00	0.00	0.00
n-hexane	0.17	0.00	0.00	0.00
2-methylpentane	0.08	0.01	0.02	0.01
n-heptane	0.03	0.01	0.03	0.00
n-oktane	0.01	0.02	0.00	0.00
2,2,4-trimethylpentane	0.20	0.01	0.03	0.00
benzene	0.36	0.17	0.11	0.05
toluene	0.67	0.09	0.13	0.06
ethylbenzene	0.08	0.03	0.01	0.03
p,m-xylene	0.21	0.04	0.05	0.07
o-xylene	0.08	0.03	0.02	0.03
1,2,3-trimethylbenzene	0.04	0.01	0.01	0.00
1,2,4-trimethylbenzene	0.18	0.04	0.00	0.00
1,3,5-trimethylbenzene	0.03	0.00	0.00	0.00

Emissions and emission profiles: Business driver.

Table 22: Ammonia emission

	Business driver			
[mg/km]	Petrol	Diesel	LPG	CNG
NH_3	17.6	0.5	55.2	36.4

Table 23: Sulphur dioxide emission (calculated)

	Business driver			
[mg/km]	Petrol	Diesel	LPG	CNG
SO_2	7.7	3.3	2.4	1.3

Table 24: Nitrous oxide emission

	Business driver			
[mg/km]	Petrol	Diesel	LPG	CNG
N_2O	2	6	2	<1

Table 25: Nitrogen oxides emission

	Business driver			
[g/km]	Petrol	Diesel	LPG	CNG
NO	0.06	0.30	0.04	0.02
NO_2	0.02	0.38	0.01	0.00

Table 26: Elementary and organic carbon emission

	Business driver			
[mg/km]	Petrol	Diesel	LPG	CNG
OC	1.1	10.4	0.0	0.0
EC	0.3	19.5	0.1	0.3

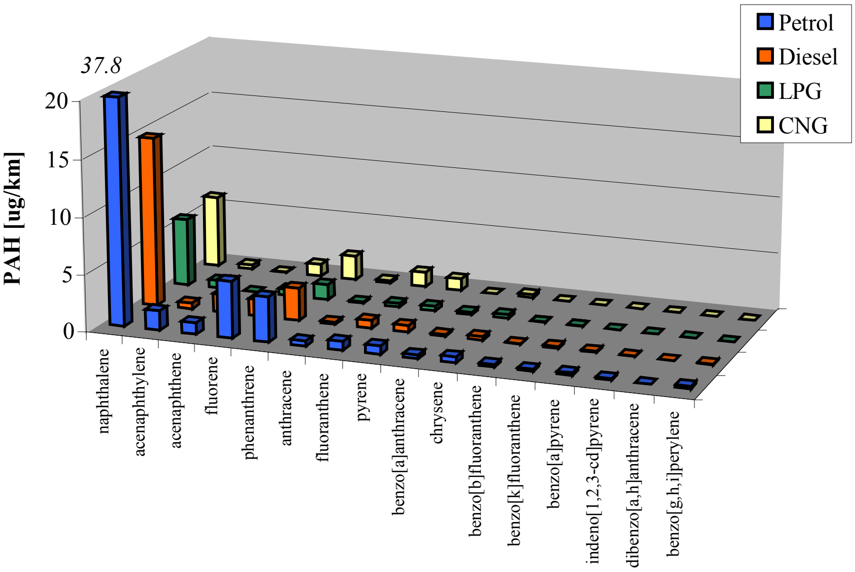
Table 27: Standard emissions

	Business driver			
[g/km]	Petrol	Diesel	LPG	CNG
CO	0.68	0.01	0.75	1.38
HC	0.01	0.01	0.01	0.05
NO_X	0.09	0.76	0.05	0.02
$HC+NO_X$	0.10	0.77	0.06	0.07
PM	0.005	0.043	0.005	0.002
CO_2	181.5	159.6	167.0	146.3

Table 28: Fuel consumption

	Business driver			
	Petrol	Diesel	LPG	CNG
	[l/100km]	[l/100km]	[l/100km]	[m^3/100km]
FC	7.68	6.00	10.27	8.27

Emissions and emission profiles: Business driver



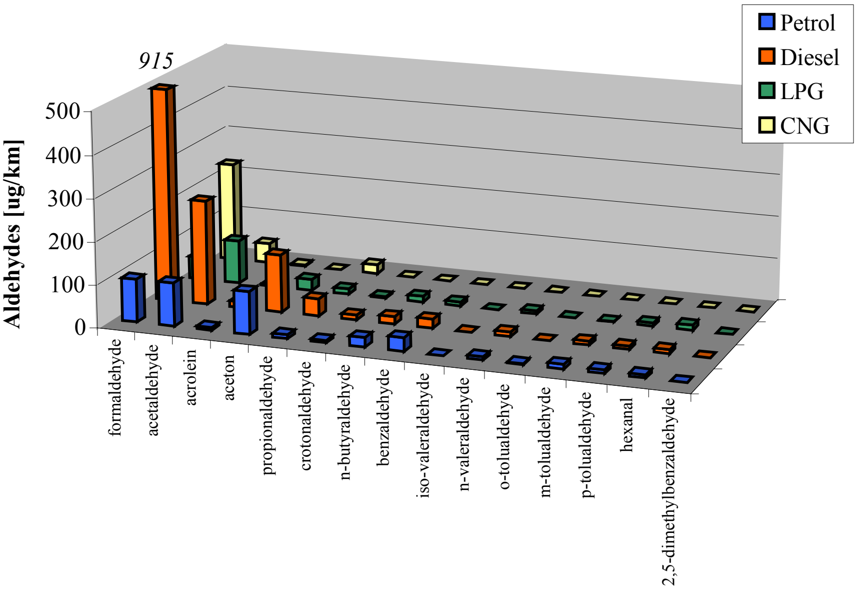


Figure 39: PAH and aldehydes emission profile

Emissions and emission profiles: Business driver

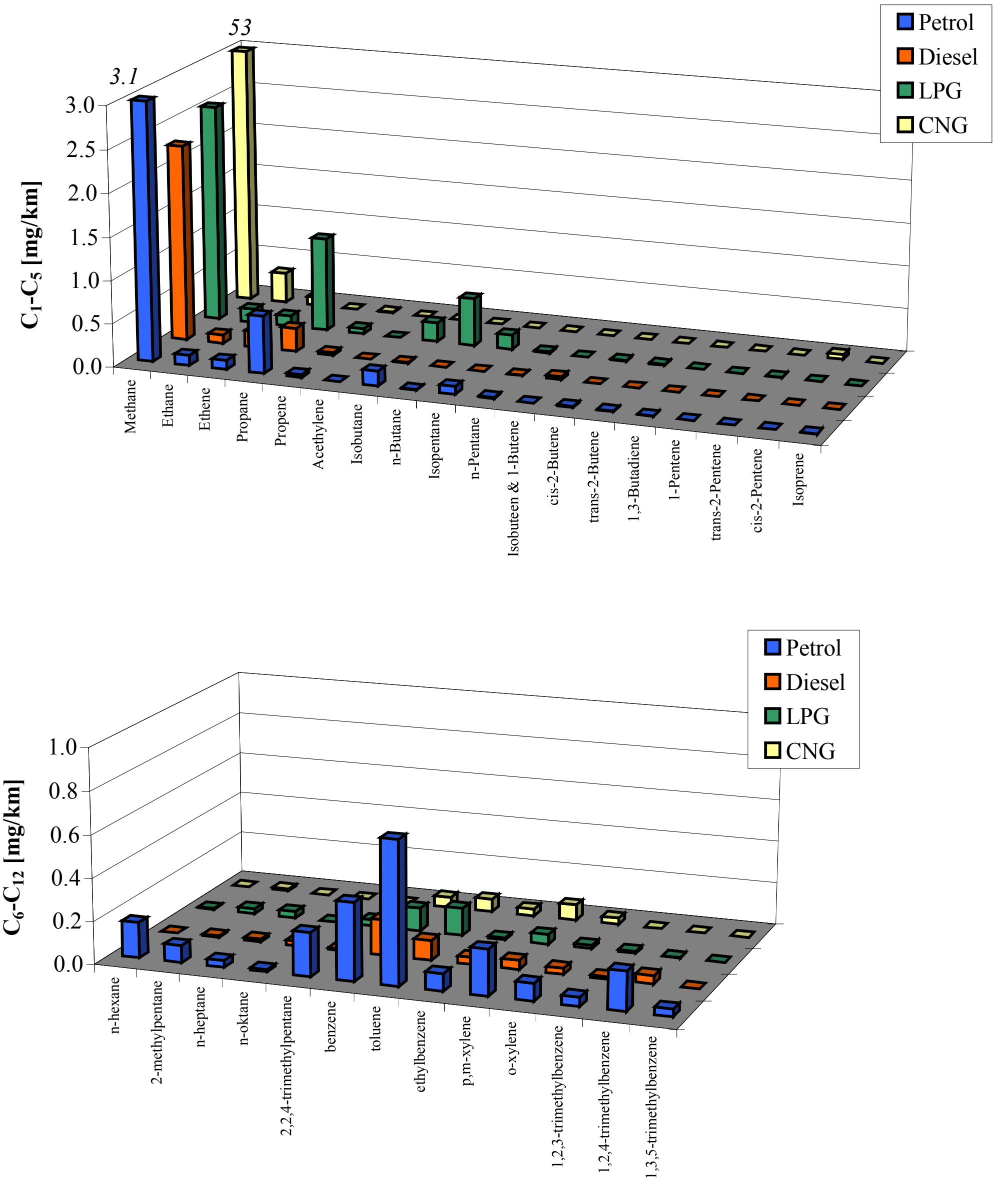


Figure 40: C_1-C_{12} emission profile

Emissions and emission profiles: Local driver.

Table 29: Emission profile PAH

	Local driver			
[ug/km]	Petrol	Diesel	LPG	CNG
naphthalene	2537	64	1677	739
acenaphthylene	52	2.5	41	18.1
acenaphthene	59	0.3	18.8	10.3
fluorene	3.8	1.8	4.6	4.6
phenanthrene	8.1	6.4	4.0	3.3
anthracene	1.7	1.5	1.1	0.3
fluoranthene	5.4	5.2	3.3	2.6
pyrene	5.8	6.4	2.7	1.4
benzo[a]anthracene	3.1	1.5	0.6	0.1
chrysene	4.1	2.3	1.8	0.7
benzo[b]fluoranthene	3.2	1.6	1.5	0.3
benzo[k]fluoranthene	3.7	1.8	1.6	0.1
benzo[a]pyrene	3.0	2.4	0.4	0.1
indeno[1,2,3-cd]pyrene	3.3	1.8	1.2	0.1
dibenzo[a,h]anthracene	0.3	0.0	0.1	0.0
benzo[g,h,i]perylene	6.0	3.6	1.7	0.4

Table 30: Emission profile aldehydes

	Local driver			
[ug/km]	Petrol	Diesel	LPG	CNG
formaldehyde	1919	13357	1194	1150
acetaldehyde	1250	4160	710	434
acrolein	249	351	160	70
aceton	2163	2001	527	342
propionaldehyde	265	353	154	134
crotonaldehyde	20.9	34.0	31.9	0.0
n-butyraldehyde	367	244	195	89
benzaldehyde	473	14.3	279	215
iso-valeraldehyde	0.0	0.0	0.0	0.0
n-valeraldehyde	10.3	54.3	0.0	0.0
o-tolualdehyde	0.0	0.0	19.4	0.0
m-tolualdehyde	14.3	33.9	27.8	49.9
p-tolualdehyde	0.0	0.0	2.6	0.0
hexanal	0.0	0.0	0.0	0.0
2,5-dimethylbenzaldehyde	0.0	0.0	0.0	0.0

Emissions and emission profiles: Local driver.

Table 31: Emission profile C_1 to C_{12}.

	Local driver			
[mg/km]	Petrol	Diesel	LPG	CNG
Methane	34.4	12.2	28.1	169
Ethane	1.88	0.51	2.54	2.96
Ethene	13.1	7.07	10.3	3.89
Propane	0.00	0.23	13.4	0.00
Propene	4.64	1.06	3.79	1.67
Acetylene	3.80	1.23	3.56	1.07
Isobutane	0.17	0.02	0.76	0.16
n-Butane	0.64	0.20	5.64	0.44
Isopentane	11.2	0.06	3.14	1.12
n-Pentane	0.84	0.04	0.67	0.32
Isobutene & 1-Butene	2.31	0.10	1.00	0.74
cis-2-Butene	0.62	0.06	0.39	0.19
trans-2-Butene	0.52	0.05	0.38	0.12
1,3-Butadiene	0.31	0.05	0.22	0.05
1-Pentene	0.26	0.01	0.11	0.03
trans-2-Pentene	0.48	0.01	0.22	0.09
cis-2-Pentene	0.41	0.00	0.17	0.09
Isoprene	0.55	0.00	0.22	0.03
n-hexane	4.94	0.08	4.08	5.29
2-methylpentane	13.6	0.13	7.79	7.88
n-heptane	5.81	0.06	3.70	1.13
n-oktane	4.73	0.09	2.16	0.74
2,2,4-trimethylpentane	37.4	0.06	10.0	10.6
benzene	25.4	3.14	12.8	6.62
toluene	95.6	0.77	49.4	28.5
ethylbenzene	17.1	0.07	16.2	8.11
p,m-xylene	42.9	0.38	38.4	20.2
o-xylene	18.5	0.11	17.0	8.88
1,2,3-trimethylbenzene	14.1	0.00	7.18	3.24
1,2,4-trimethylbenzene	38.0	0.20	21.8	11.1
1,3,5-trimethylbenzene	14.5	0.00	8.72	3.87

Emissions and emission profiles: Local driver.

Table 32: Ammonia emission

	Local driver			
[mg/km]	Petrol	Diesel	LPG	CNG
NH_3	14.2	2.5	29.3	24.3

Table 33: Sulphur dioxide emission (calculated)

	Local driver			
[mg/km]	Petrol	Diesel	LPG	CNG
SO_2	14.7	5.8	4.4	2.4

Table 34: Nitrous oxide emission

	Local driver			
[mg/km]	Petrol	Diesel	LPG	CNG
N_2O	8	11	7	3

Table 35: Nitrogen oxides emission

	Local driver			
[g/km]	Petrol	Diesel	LPG	CNG
NO	0.10	0.47	0.11	0.10
NO_2	0.01	0.32	0.01	0.02

Table 36: Elementary and organic carbon emission

	Local driver			
[mg/km]	Petrol	Diesel	LPG	CNG
OC	2.6	11.3	1.2	0.0
EC	5.2	58.2	2.6	0.1

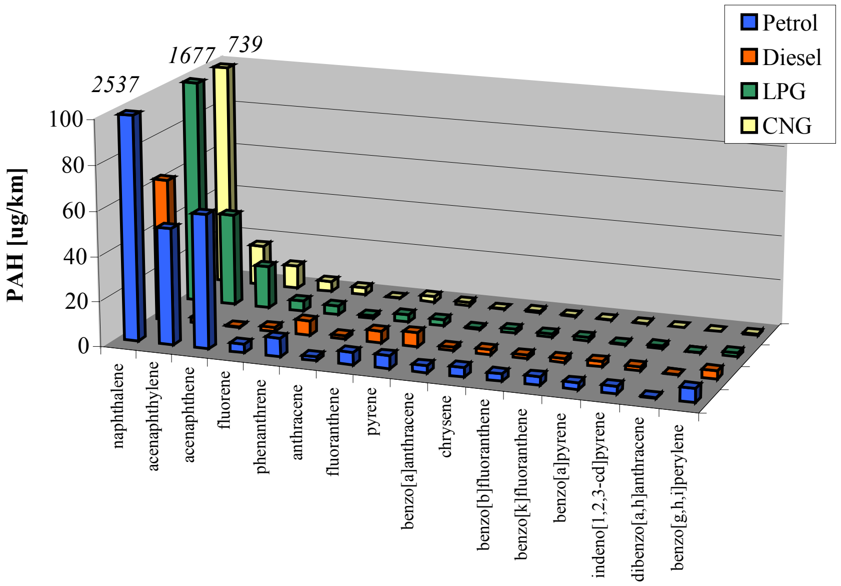
Table 37: Standard emissions

	Local driver			
[g/km]	Petrol	Diesel	LPG	CNG
CO	5.03	0.54	4.24	2.42
HC	0.70	0.06	0.50	0.36
NO_X	0.17	1.03	0.19	0.18
$HC+NO_X$	0.87	1.09	0.69	0.53
PM	0.008	0.062	0.005	0.004
CO_2	336.9	279.9	297.6	273.0

Table 38 Fuel consumption

	Local driver			
	Petrol	Diesel	LPG	CNG
	[l/100km]	[l/100km]	[l/100km]	[m^3/100km]
FC	14.56	10.52	18.81	15.48

Emissions and emission profiles: Local driver



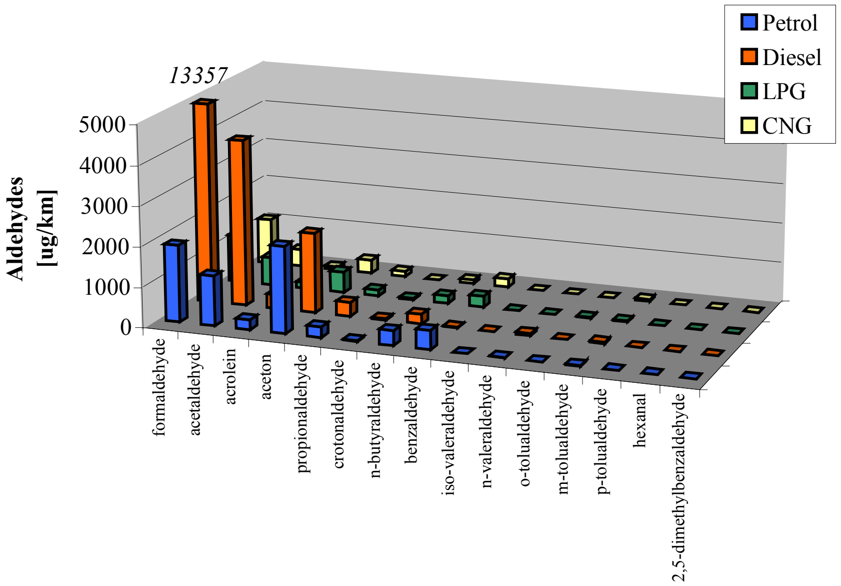


Figure 41: PAH and aldehydes emission profile

Emissions and emission profiles: Local driver

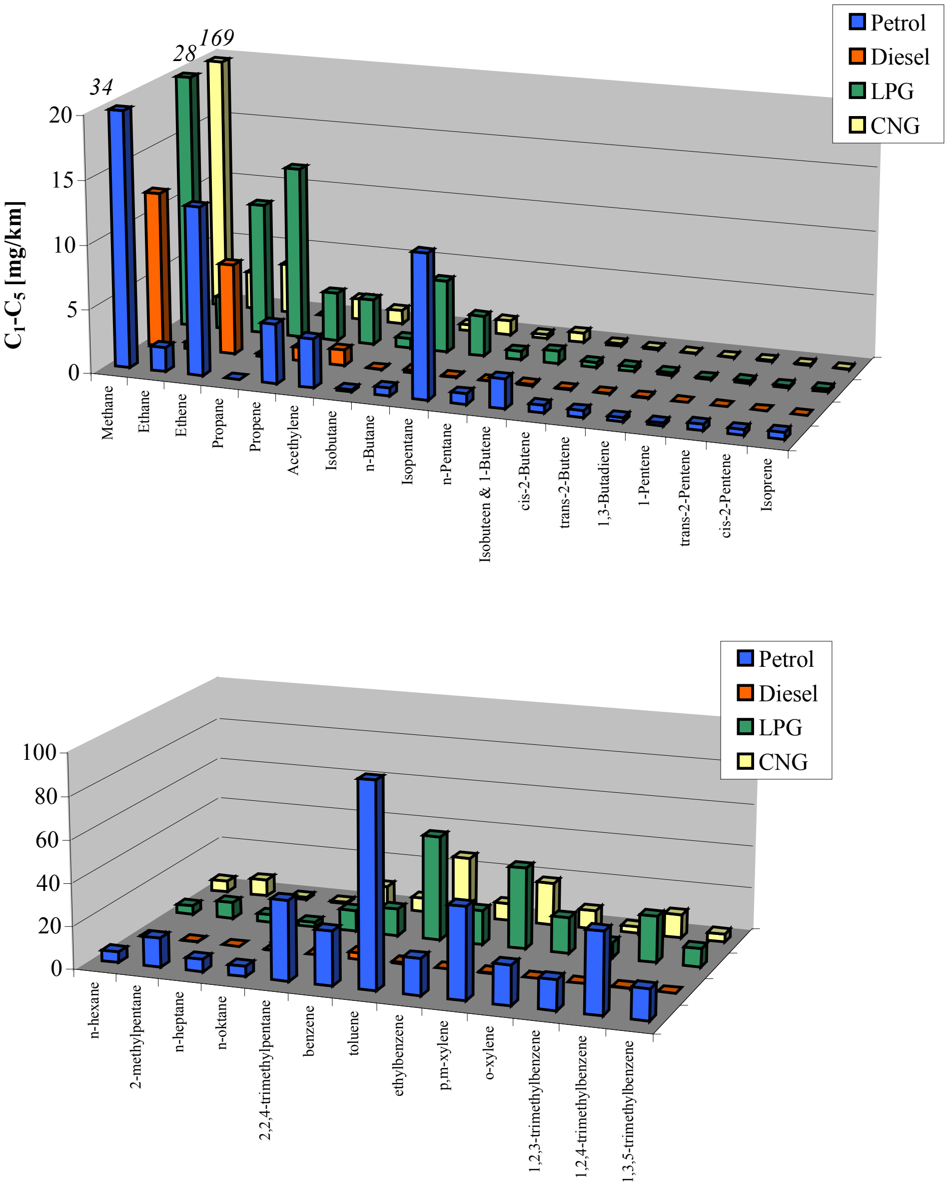


Figure 42: C_1-C_{12} emission profile

Emissions and emission profiles: Average driver.

Table 39: Emission profile PAH

	Average driver			
[ug/km]	Petrol	Diesel	LPG	CNG
naphthalene	420	19	252	140
acenaphthylene	10.3	0.9	6.6	3.6
acenaphthene	11.7	1.4	2.6	1.9
fluorene	4.6	1.6	1.1	1.7
phenanthrene	4.9	3.7	1.0	2.4
anthracene	0.7	0.4	0.2	0.2
fluoranthene	1.5	1.8	0.4	1.6
pyrene	1.5	2.0	0.8	1.1
benzo[a]anthracene	0.6	0.5	0.3	0.0
chrysene	1.0	0.8	0.6	0.4
benzo[b]fluoranthene	0.6	0.4	0.3	0.1
benzo[k]fluoranthene	0.6	0.6	0.2	0.0
benzo[a]pyrene	0.5	0.7	0.1	0.0
indeno[1,2,3-cd]pyrene	0.5	0.5	0.2	0.0
dibenzo[a,h]anthracene	0.0	0.0	0.0	0.0
benzo[g,h,i]perylene	0.8	1.0	0.4	0.1

Table 40: Emission profile aldehydes

	Average driver			
[ug/km]	Petrol	Diesel	LPG	CNG
formaldehyde	432	3181	261	401
acetaldehyde	312	959	215	117
acrolein	51	75	32	14.9
aceton	468	465	118	61
propionaldehyde	56	98	39	41
crotonaldehyde	8.3	15.5	8.5	0.0
n-butyraldehyde	84	58	46	15
benzaldehyde	112	20	59	39
iso-valeraldehyde	0.0	0.0	0.0	0.0
n-valeraldehyde	8.0	18.5	5.9	0.0
o-tolualdehyde	1.6	0.0	3.6	0.0
m-tolualdehyde	11.7	13.2	5.8	9.2
p-tolualdehyde	6.9	5.9	6.2	0.0
hexanal	6.2	7.4	9.9	0.0
2,5-dimethylbenzaldehyde	0.0	0.0	0.0	0.0

Emissions and emission profiles: Average driver.

Table 41: Emission profile C_1 to C_{12}

	Average driver			
[mg/km]	Petrol	Diesel	LPG	CNG
Methane	8.8	4.0	7.2	74
Ethane	0.44	0.17	0.59	0.84
Ethene	2.50	1.44	1.99	0.80
Propane	0.55	0.26	3.31	0.00
Propene	0.88	0.22	0.75	0.31
Acetylene	0.70	0.23	0.65	0.20
Isobutane	0.17	0.01	0.32	0.03
n-Butane	0.12	0.04	1.48	0.07
Isopentane	2.14	0.01	0.72	0.20
n-Pentane	0.16	0.01	0.14	0.06
Isobutene & 1-Butene	0.42	0.05	0.18	0.13
cis-2-Butene	0.12	0.01	0.08	0.04
trans-2-Butene	0.10	0.01	0.08	0.02
1,3-Butadiene	0.06	0.01	0.04	0.01
1-Pentene	0.05	0.00	0.02	0.01
trans-2-Pentene	0.09	0.00	0.04	0.02
cis-2-Pentene	0.08	0.00	0.03	0.06
Isoprene	0.10	0.00	0.04	0.01
n-hexane	1.04	0.01	0.75	0.97
2-methylpentane	2.56	0.03	1.45	1.44
n-heptane	1.09	0.02	0.70	0.20
n-oktane	0.88	0.03	0.40	0.14
2,2,4-trimethylpentane	7.03	0.01	1.86	1.94
benzene	4.96	0.70	2.44	1.25
toluene	18.1	0.22	9.16	5.25
ethylbenzene	3.21	0.04	2.98	1.51
p,m-xylene	8.03	0.10	7.08	3.74
o-xylene	3.46	0.04	3.13	1.65
1,2,3-trimethylbenzene	2.62	0.01	1.32	0.59
1,2,4-trimethylbenzene	7.12	0.07	4.00	2.02
1,3,5-trimethylbenzene	2.68	0.00	1.60	0.71

Emissions and emission profiles: Average driver.

Table 42: Ammonia emission

	Average driver			
[mg/km]	Petrol	Diesel	LPG	CNG
NH_3	17.3	0.9	50.6	34.5

Table 43: Sulphur dioxide emission

	Average driver			
[mg/km]	Petrol	Diesel	LPG	CNG
SO_2	8.9	3.7	2.8	1.5

Table 44: Nitrous oxide emission

	Average driver			
[mg/km]	Petrol	Diesel	LPG	CNG
N_2O	3	7	3	1

Table 45: Nitrogen oxides emission

	Average driver			
[g/km]	Petrol	Diesel	LPG	CNG
NO	0.07	0.33	0.05	0.03
NO_2	0.02	0.37	0.01	0.00

Table 46: Elementary and organic carbon emission

	Average driver			
[mg/km]	Petrol	Diesel	LPG	CNG
OC	1.1	11.5	0.4	0.0
EC	0.6	26.1	0.2	0.3

Table 47: Standard emissions

	Average driver			
[g/km]	Petrol	Diesel	LPG	CNG
CO	1.48	0.10	1.39	1.58
HC	0.13	0.02	0.10	0.11
NO_X	0.10	0.80	0.07	0.04
$HC+NO_X$	0.24	0.83	0.18	0.15
PM	0.006	0.046	0.005	0.002
CO_2	208.1	180.5	189.3	168.6

Table 48: Fuel consumption

	Average driver			
	Petrol	Diesel	LPG	CNG
	[l/100km]	[l/100km]	[l/100km]	[m^3/100km]
FC	8.86	6.78	11.74	9.54

Emissions and emission profiles: Average driver

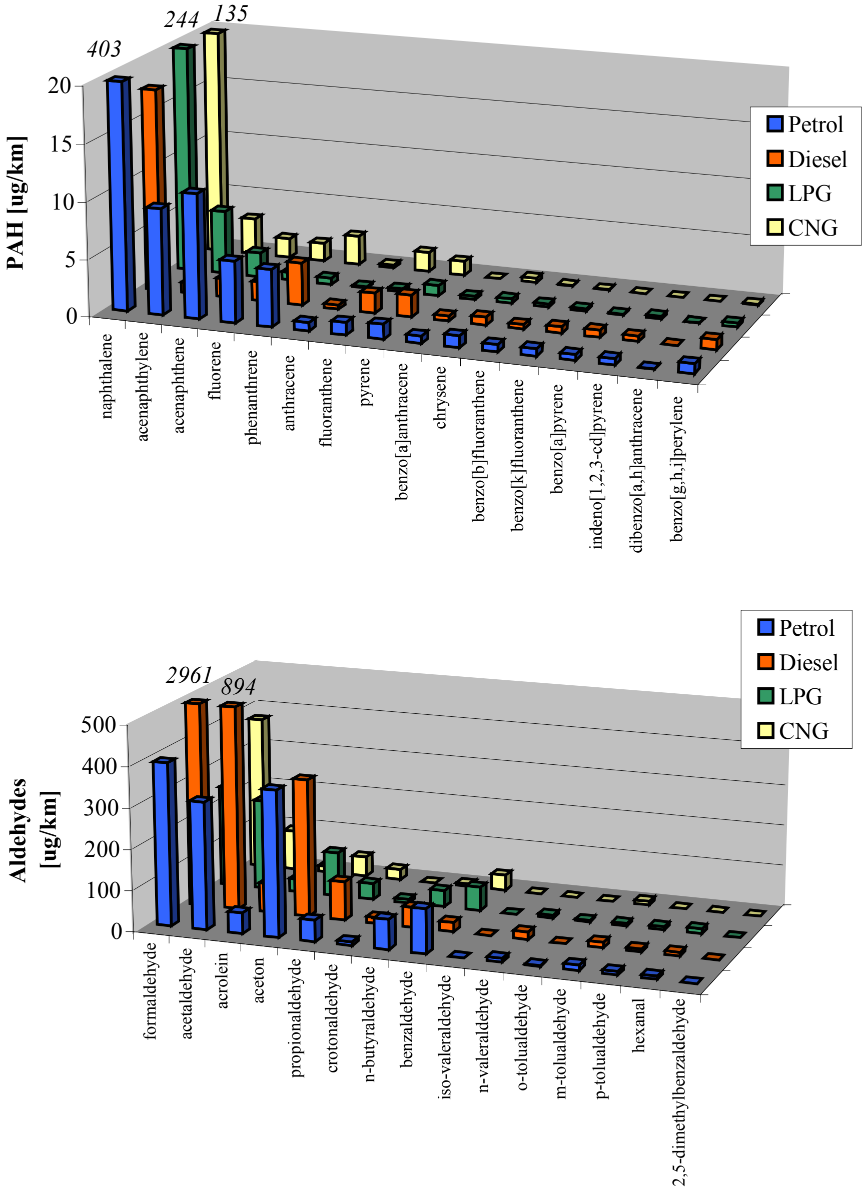


Figure 43: PAH and aldehydes emission profile

Emissions and emission profiles: Average driver

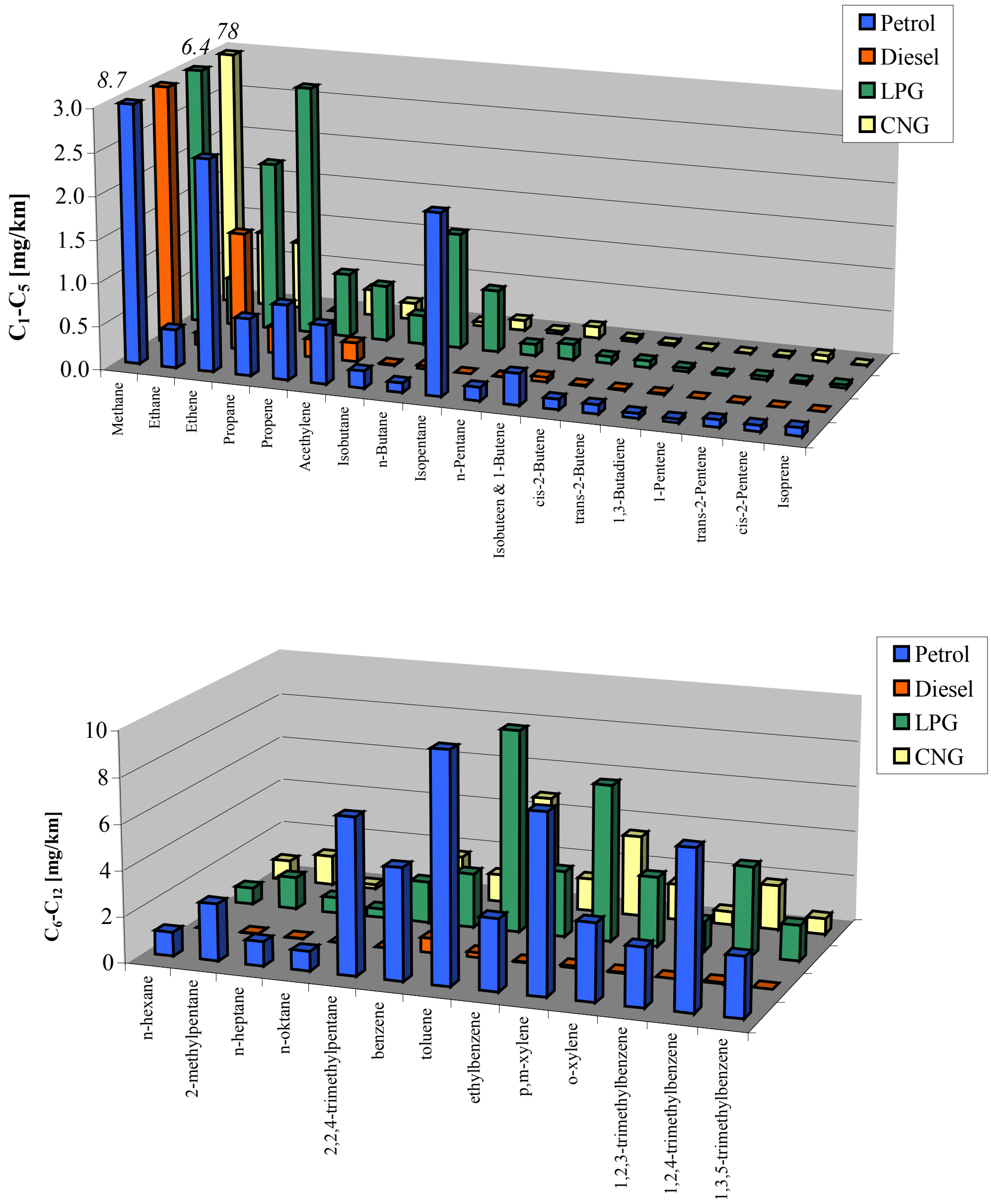


Figure 44: C_1-C_{12} emission profile

C Indicator values

Table 49: Health effect indicators, business driver

		Business driver			
		Petrol	Diesel	LPG	CNG
CO	[g/km]	0.68	0.01	0.75	1.38
NO_2	[g/km]	0.02	0.38	0.01	0.00
Primary PM	[g/km]	0.005	0.043	0.005	0.002
Secondary PM	[g/km]	0.079	0.586	0.062	0.028
SO_2	[mg/km]	8	3	2	1
PAH 2A	[ug/km]	0.6	0.2	0.2	0.0
PAH 2B	[ug/km]	0.5	0.2	0.0	0.0
Benz-a-pyrene	[ug/km]	0.2	0.1	0.0	0.0
1,3-butadiene	[mg/km]	0.00	0.00	0.00	0.00
Light aldehydes	[mg/km]	0.21	1.17	0.16	0.28
BTX	[mg/km]	1.25	0.30	0.28	0.18
Smog potent. POCP	[g/km ethene $_{eq}$)	0.03	0.00	0.03	0.06
Smog potent. TOFP	[g/km NMVOC $_{eq}$]	0.19	0.93	0.15	0.17

Table 50: Ecological effect indicators, business driver

		Business driver			
		Petrol	Diesel	LPG	CNG
Smog potent. TOFP	[g/km NMVOC $_{eq}$]	0.19	0.93	0.15	0.17
Acidification potent.	[gH^+/km]	0.003	0.017	0.004	0.003
Euthrophication potent.	[gNO_3^-/km]	0.003	0.016	0.004	0.003

Table 51: Climatic effect indicators, business driver

		Business driver			
		Petrol	Diesel	LPG	CNG
Direct GWP	[g/km $CO_{2\ eq}$]	182.2	161.3	167.6	147.5
EC-OC	[mg/km]	1.4	29.8	0.1	0.3
Ozone depletion	[mg/km]	2	6	2	0

Table 52: Health effect indicators, local driver

Health effect indicators		**Local driver**			
		Petrol	Diesel	LPG	CNG
CO	[g/km]	5.03	0.54	4.24	2.42
NO_2	[g/km]	0.01	0.32	0.01	0.02
Primary PM	[g/km]	0.008	0.062	0.005	0.004
Secondary PM	[g/km]	0.139	0.801	0.160	0.150
SO_2	[mg/km]	15	6	4	2
PAH 2A	[ug/km]	6.4	3.9	1.1	0.2
PAH 2B	[ug/km]	10.3	5.2	4.3	0.6
Benz-a-pyrene	[ug/km]	3.0	2.4	0.4	0.1
1,3-butadiene	[mg/km]	0.31	0.05	0.22	0.05
Light aldehydes	[mg/km]	3.42	17.9	2.06	1.65
BTX	[mg/km]	164	4.28	100.7	55.3
Smog potent. POCP	[g/km ethene $_{eq}$)	0.51	0.05	0.40	0.24
Smog potent. TOFP	[g/km NMVOC $_{eq}$]	1.07	1.34	0.91	0.59

Table 53: Ecological effect indicators, local driver

Ecological effect indicators		**Local driver**			
		Petrol	Diesel	LPG	CNG
Smog potent. TOFP	[g/km NMVOC $_{eq}$]	0.35	1.34	0.91	0.59
Acidification potent.	[gH^+/km]	0.005	0.023	0.006	0.005
Euthrophication potent.	[gNO_3^-/km]	0.004	0.023	0.006	0.005

Table 54: Climatic effect indicators, local driver

Climatic effect indicators		**Local driver**			
		Petrol	Diesel	LPG	CNG
Direct GWP	[g/km $CO_{2\ eq}$]	340.2	283.5	300.2	277.8
EC-OC	[mg/km]	7.8	69.5	3.8	0.1
Ozone depletion	[mg/km]	8	11	7	3

Table 55: Health effect indicators, average driver

Health effect indicators		**Average driver**			
		Petrol	Diesel	LPG	CNG
CO	[g/km]	1.48	0.10	1.39	1.58
NO_2	[g/km]	0.02	0.37	0.01	0.00
Primary PM	[g/km]	0.006	0.046	0.005	0.002
Secondary PM	[g/km]	0.090	0.622	0.079	0.048
SO_2	[mg/km]	9	4	3	1
PAH 2A	[ug/km]	1.2	1.1	0.4	0.0
PAH 2B	[ug/km]	1.8	1.5	0.8	0.1
Benz-a-pyrene	[ug/km]	0.5	0.7	0.1	0.0
1,3-butadiene	[mg/km]	0.06	0.01	0.04	0.01
Light aldehydes	[mg/km]	0.79	4.21	0.51	0.53
BTX	[mg/km]	31.1	1.03	18.7	10.3
Smog potent. POCP	[g/km ethene $_{eq}$)	0.12	0.01	0.10	0.09
Smog potent. TOFP	[g/km NMVOC $_{eq}$]	0.35	1.00	0.29	0.25

Table 56: Ecological effect indicators, average driver

Ecological effect indicators		**Average driver**			
		Petrol	Diesel	LPG	CNG
Smog potent. TOFP	[g/km NMVOC $_{eq}$]	0.93	1.00	0.29	0.25
Acidification potent.	[gH+/km]	0.004	0.018	0.005	0.003
Euthrophication potent.	[gNO_3^-/km]	0.003	0.018	0.005	0.003

Table 57: Climatic effect indicators, average driver

Climatic effect indicators		**Average driver**			
		Petrol	Diesel	LPG	CNG
Direct GWP	[g/km $CO_{2\ eq}$]	209.3	182.5	190.3	170.4
EC-OC	[mg/km]	1.7	37.6	0.6	0.3
Ozone depletion	[mg/km]	3	7	3	1

D Overall environmental performance with EETP rating methodology

The rating in the table below is established by giving a score ‘o’ to the average impact potential level of all fuels for the effect under consideration. Subsequently the results of the fuels are scored relatively to this average level on a scale between ‘--‘ and ‘++’. This approach allows the mutual comparison of the fuels for this particular driver profile.

Table 58: Overall environmental performance with the rating methodology as used in the European Emission Test Programme (Business driver)

Business driver

	Relevance	Petrol	Diesel	LPG	CNG
Health effects					
CO	low	o	++	o	-
NO_2	high	+	--	+	++
primary PM	high	+	--	+	++
secondary PM	high	+	--	+	++
PM size distribution	high	o	--	o	+
SO_2	low	--	o	o	+
PAH 2A	high	-	o	o	+
PAH 2B	medium	-	o	+	+
benz-a-pyrene	high	-	o	+	+
1,3-butadiene	high	o	o	o	o
light aldehydes	high	o	-	o	o
BTX	medium	o	o	o	o
smog potent. POCP	high	o	+	o	-
smog potent. TOFP	high	o	--	o	o
Ecological effects					
Smog potent. TOFP	high	o	--	o	o
Acidification potent.	medium	+	--	+	+
Euthrophication potent.	high	+	--	+	+
Climatic effects					
Direct GWP	high	--	o	o	++
EC-OC (GWP)	uncertain	+	--	++	++
Ozone depletion	low	o	--	o	++

--	Very high impact potential	(relative to average impact potential)
-	High impact potential	(relative to average impact potential)
0	Average impact potential	(average impact potential level of all fuels for the effect under consideration)
+	Low impact potential	(relative to average impact potential)
++	Very low impact potential	(relative to average impact potential)