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Swedish Experiences from Low Emission City Buses: Impact on Health and Environment

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ABSTRACT

Several field trials on city buses[1] running on alternative fuels have been conducted in Sweden during the last decade. Reformulated diesel fuel and aftertreatment devices are measures that have been taken on diesel fueled buses to reduce the emissions. The primary scope of this paper was to compare the impact on environment and health from various fuels and technology for low emission buses. During the last decade, the emissions from gasoline fueled passenger cars have decreased considerably. Since cars compete with buses, it was also of interest to compare the environmental impact of these vehicle categories.

The vehicles mentioned above have been subjected to emission tests in projects funded by various Swedish government programs. By using available emission test data, emission factors (regulated and unregulated) have been established for each option. In the comparison between buses and cars, corrections have been made for climate, deterioration and driving pattern. The impact from the emission components on health and environment has been calculated using weighting factors for each compound. Acidification, eutrophication, ozone forming potential, cancer risk, greenhouse gases and several other effects have been evaluated.

The analysis showed considerable improvement for the diesel buses by reformulating the diesel fuel and by fitting aftertreatment devices. Particulate emissions and its effects are probably the most severe emission component from the diesel engines. Particulate filters are the only commercially available solution to that problem today. The NO_X emissions can be reduced by about 50% by using an EGR system.

Some of the alternative fueled buses had a positive impact regarding several of the effects investigated, e.g. acidification and local NO_2 emissions. In other cases (e.g. ozone forming potential), the difference between the best options was small. The cancer risk index is largely dependent on the unit risk factors, which are not fully developed yet, but the overall result in this case did not vary much between the risk factors evaluated. Clean diesel fuel with a particulate trap and CNG/biogas were the options with the lowest cancer risk index. The impact on the greenhouse gas emissions was the most significant advantage for the biofuels.

The comparison between gasoline fueled cars and buses showed an environmental and health advantage for the buses in all aspects but NO_X emissions and acidification. The significant impact of cold starts on cars was the major cause of the outcome of this comparison.

[1] The designation "city buses" is used throughout this paper, as it is quite common in Sweden and Europe. In the U.S., "transit buses" is used frequently instead.

It is expected that future development on engines and aftertreatment devices will diminish the advantage of the alternative fuels in city buses regarding many of the effects. On the contrary, the impact on greenhouse gases from some biofuel options will be more pronounced in the future.

INTRODUCTION

During the past years, the focus on emissions from heavy-duty vehicles has increased. One reason for this change in priority is that the emissions from light-duty vehicles have decreased considerably due to the introduction of the tree-way catalyst emission control system (TWC). No similar breakthrough has been achieved yet for the emission control on heavy-duty diesel engines.

A specific concern in Europe is that the growth of the European Union and the increase in integration of the economy might considerably increase the road transportation of heavy goods [1][2].

In major populated areas, city buses contribute significantly to the air pollution from traffic. Furthermore, public transportation should substitute passenger cars and therefore, the significantly reduced emission level from cars is an additional driving force to reduce the emissions from city buses. In this respect, it is also of interest to compare the emissions from both vehicle categories. In assessments of this kind, special consideration has to be taken regarding the driving pattern of these vehicles such as, e.g. cold start effects.

Background

The background to the work reported here has essentially been the need to provide some answers to questions on two specific issues.

First, a comparison of various fuels and aftertreatment technologies for city buses has been of interest. An investigation was carried out for the Traffic Office in the city of Gothenburg in 1999 and later this work was updated and published in a SAE paper in June 2000 [2]. An extension of the analysis of cancer risk index, including an assessment of the scope for generalization of the results for the conditions in the USA, was carried out for BP in the fall of 2000 [3].

Second, it is fundamental to compare city buses with passenger cars due to the desired substitution of the latter by the former. A comparison of various fuels for passenger cars was made in a project for the Swedish Governmental Authority in 1999 [4]. These data and the previously mentioned work on city buses [2] were used as input for an analysis, taking into account differences in driving pattern and cold starts, in order to make a more thorough comparison. This work was carried out in a project for the Swedish National Road Administration (SNRA), the Swedish Public Transport Association (SLTF) and Västtrafik[3] (VT), a company responsible for the public transportation in west Sweden. The report (in Swedish) was recently published by SNRA [5].

This paper summarizes the methodology and findings in the studies previously mentioned in this section.

Emission control of heavy-duty vehicles in Sweden

The emission control on heavy-duty city buses started in Sweden during mid 80´s through voluntary measures by the manufacturers, partly due to the customer demand from the municipalities. More than a decade ago, bus engines having an emission level below the Euro I emission limits were introduced, al-

[2] Numbers in brackets designate references at the end of the paper.
[3] Västtrafic is responsible for the public transportation in the region of Western Sweden (Gothenburg Area).

though this directive was not introduced until 1992. Similarly, engines with an emission level below Euro II were introduced already in the beginning of the 90´s. Retrofitting of aftertreatment devices was also initiated during that period. Oxidation catalysts were used initially and later, particulate filters were introduced as an after-market solution. A program for environmental zones in the three greater cities in Sweden (Stockholm, Gothenburg and Malmö) was introduced in July 1996. According to this regulation, which is not harmonized with EU, vehicles of a certain age have to be retrofitted with approved aftertreatment devices to be allowed into the environmental zones. This incentive has also spurred the use of aftertreatment devices. In 1999, Euro III buses were introduced and it is expected that bus engines fulfilling Euro IV, V and EEV[4] will be introduced soon. Retrofit kits with particulate filters and EGR that upgrade engines from Euro II to Euro IV are available on the market.

Reformulation of the diesel fuel is another area of considerable improvement. The Swedish Environmental Class 1 (EC1) diesel fuel specification is a considerably improved diesel fuel quality regarding potential health effects [6, 7, 8]. The use of this fuel is also a prerequisite of some of the aftertreatment devices mentioned above (i.e. particulate traps).

Field trials on alternative fuels for heavy-duty vehicles are being conducted in several major cities in Sweden. Most of the governmental support for these activities has been provided through the biofuels program of the Swedish Transport and Communications Research Board (KFB). An overview of this program and some of its results has been presented elsewhere [9, 10]. The majority of the field trials on alternative fuels have been conducted on ethanol (neat or blended with diesel fuel), natural gas and biogas. The tests on biofuels have been supported by KFB, whereas the activities on other alternative fuels have received support from various other governmental authorities.

Emission control of light-duty vehicles in Sweden

From 1989[5] until mid 1990´s, emission limits corresponding to U.S.-1987 (according to the U.S. FTP-75 driving cycle) was used in Sweden for light-duty vehicles. Starting with the model year 1993, a scheme for environmental classes was introduced. Environmental Class 3 (C3)[6] was the base level (U.S.-1987) and Environmental Class 2 (C2) and Environmental Class 1 corresponded to the U.S.-1994 and Californian TLEV limits respectively. The environmental classification system has subsequently been revised several times and today, it is based on the limits in the European Regulations (Euro III and IV).

Scope of this paper

The scope of this paper was twofold:

- To update and summarize the previously mentioned papers on heavy-duty buses [2, 3]
- To summarize the findings from recent studies comparing passengers cars and city buses [5]

In assessments of this kind, it is not easy to quantify the *absolute* impact on health and environment. Instead, an assessment of the *relative change* of these effects has been made in order to provide a basis for comparisons between different options. It should also be stressed that the aim in the previous studies cited above was to use a rather simple methodology in the evaluation of these effects. A very important condition in the evaluations was that the comparisons should be as technology neutral as possible. In general, not every available technology can be used for all engine/fuel options. However, the objective should be

[4] EEV: Enhanced Environmentally Friendly Vehicles.
[5] These emission limits were introduced already in 1987 as a voluntary measure.
[6] The environmental classes for cars and engines for heavy-duty vehicles should not be confused with the environmental classes for fuels.

to make the comparisons using the same technology for all options, *whenever* this technology is applicable. For example, it should be possible to compare engine/fuels *with* catalytic aftertreatment devices for all options. Since not all the tests evaluated here were planned with the intention to provide the basis for technology neutral comparisons, it was not possible to completely fulfil this criterion. Showing data for options *with and without* a certain technology does provide supplementary information. For example, additional data for options *without* aftertreatment are also shown in some cases to illustrate the impact of these devices.

Generalizing the results

It should be stressed that generalization of the data provided in this paper is not trivial. The vehicle technology used on various markets is different (e.g. USA vs. Sweden). Furthermore, the driving cycles, fuel specifications and ambient conditions are not similar. For example, the driving pattern in general and cold start effects in particular can both have a considerable impact on the results.

The study carried out for BP highlighted some of the similarities and differences between heavy-duty engines and fuels in USA and Sweden [3]. The comparison between passenger cars and city buses showed that the cold start and ambient temperature at the cold start has a considerable impact on the emissions from gasoline fueled cars [5]. For example, a comparison for a specific country or region that has a hotter climate would be more favorable for the cars than the results shown here. In summary, a generalization should not be made unless the most influential factors are taken into consideration.

METHODOLOGY

Data collection

The majority of the emission data used in this study have been collected from the emission evaluations of vehicles participating in field trials in Sweden (publications are referred to later). Most of the emission testing has been carried out at the emission test facilities of MTC, a subsidiary of the Swedish Motor Vehicle Inspection Co. For the light-duty vehicles, complementary data generated at the VTT Institute in Finland have also been used in addition to the data from MTC. For the newest cars (model year 2000[7]), certification data has been used extensively. The data used for the city buses in the previously published SAE Paper [2] have been amended with the newest test data. It should be mentioned that data from two test series that have not been officially published are included in the database.

In comparison to the SAE Paper on city buses [2] previously published, some comments should be made about new data and the reassessment that was made of some of the earlier data. Additional data was available only for CNG buses. Since the emission level for these buses was comparatively high, the data were only used for the "average" level, i.e. not for the "best" case. Due to the supplementary new data, the NO_X emission increased somewhat, but CO_2 and fuel consumption decreased marginally. CO and HC/NMHC emissions were virtually unaffected. A reassessment of PAC (Polycyclic Aromatic Compounds) emissions was made for some of the diesel engine test data, since the compounds analyzed was not exactly the same as in all the other tests. Similarly, the impact of the particulate filter was reduced marginally in one of the diesel fuel cases in comparison to the earlier evaluation. The corrections made had very little impact on the evaluated effects on health and environment and did not change any of the conclusions.

7 The denotation "model year 2000" is not fully correct since some cars representing model year 2001 have also been included. Data for cars fulfilling Euro III (2000/2001) and a small fraction of cars fulfilling Euro IV (2005/2006) was the basis for the assessment. As the evaluation was made in late 2000, additional data should be available today.

The complementary data were obtained through a literature survey. This survey has also provided data for the weighting factors for each emission component or fuel used in the calculation of the effects on health and environment.

Timeframe

The engine technology for the buses is representative of mid 1990 technology level (Euro II). Euro III diesel buses were not included, nor the latest technology for ethanol or methane. In both cases, this was due to lack of data. The EGR technology evaluated is somewhat newer but an application on Euro III engines was not considered. In general, a technology level, which is approximately comparative, can be found for all fuels for city buses.

Cars of model year 1993/1994 and 2000 (Euro III) were used in the comparison between buses and cars. In the first case, the availability of data on unregulated emissions and in-use deterioration was the best. Furthermore, the technology level of these cars is roughly comparative to the buses investigated. The model year 2000 represents technology that is more advanced and in this case, the availability of independent data is scarce. Therefore, certification data has been used and consequently it has to be recognized that the data of lifecycle emissions in this case has to be considered as an estimate.

Corrections

In order to improve the comparison between fuels and between the two categories of vehicles, some corrections have been made.

Emission deterioration

The reduction efficiency of catalytic aftertreatment is generally reduced with increasing mileage of the vehicle.

The deterioration of catalysts and particulate filters for the diesel-fueled buses was taken into account by reducing the efficiency of these devices compared to the actual measurement data. It was anticipated that the deterioration of the engine would be small for a diesel engine. In comparison to the case for the diesel-fueled engines, there are limited data for catalyst efficiency for the ethanol engines and no available data for the methane-fueled engines. Therefore, no correction for the anticipated decrease in catalyst efficiency with time has been carried out, which might lead to that the emissions from these fuels are somewhat underestimated. There was not enough data available to quantify the deterioration of spark-ignited methane-fueled engines, although test data indicate that these engines (e.g. air-fuel control system) could be more prone to deterioration than diesel engines.

For the deterioration of passenger cars, in-use emission data was evaluated to determine the deterioration factors. A mileage of 80 000 km was set to represent the average lifecycle emissions of the cars. A deterioration factor very similar to the model year 1993/1994 was anticipated for the model year 2000. Since the emission level is considerably lower for the newer cars, the deterioration in absolute numbers is significantly lower for the newer cars.

Cold start and ambient temperature effects

The cold start and ambient temperature has been taken into account in the comparison between the two categories of vehicles. For the buses, a drive cycle simulation using the program Advisor® from NREL was used to estimate the cold start effect. Cold start test data has been used to estimate the impact of cold start and ambient temperature for the cars. An ambient temperature of +7°C, which corresponds to the yearly average temperature in Sweden, was used for both vehicle categories.

Fuels for city buses

The fuels of interest to compare for city buses were:

- Reformulated diesel fuel (in some cases in comparison to current European specification diesel fuel)
- Ethanol with ignition improver
- Methane, i.e. natural gas (CNG) and biogas (CBG[8])

Reformulated diesel fuel

Reformulated diesel fuel was introduced in Sweden a decade ago according to a classification system by the Swedish EPA (SEPA). The classification system comprises three different classes from 1 to 3. The Environmental Class 1 fuel (EC1) is the "cleanest" fuel (<10 ppm S and very low PAH), EC3 is the diesel fuel quality corresponding to the current EU specification and EC2 is somewhat in between. The specifications for these fuels were agreed upon in discussions between the Swedish government, the oil industry and the automotive industry. The basis for these specifications was the results from an extensive test series [6 – 8]. The environmentally classified fuels are promoted by tax incentives and the current difference in tax between EC1 and EC3 is 42 öre per liter (about 19 U.S. c/gallon, or about 17 % of the fuel price without taxes). Due to the relatively high tax incentive, and the fact that the incremental cost of producing the EC1 fuel is considerably less than the tax incentive, the market share of EC1 is currently more than 90 %. One of the main reasons for introducing the EC1 fuel was the impact on the emission components potentially causing adverse health effects.

Ethanol

Ethanol has been domestically produced from spent sulfite liquor for decades in Sweden. There has been several production sites of this kind in operation but currently only one is in operation and it has a capacity of 10 000 ton per year. A plant for producing ethanol from grain, using biomass as process fuel, was completed in the beginning of 2001 and its capacity is 50 000 m^3/year. The domestic production of ethanol and the option to produce this fuel from (relatively) low-cost biomass[9] (tree residues from forestry and forest industry) has been two of the primary driving forces for using ethanol as a fuel in Sweden. It is also anticipated that the cost of producing ethanol from cellulosic material will decrease considerably in the future. The Swedish National Energy Administration (STEM) is supporting R&D activities in this area. For 6 years (from 1992 to 1998), KFB has been supporting research, development and demonstration of vehicles running on neat ethanol and ethanol blends. In this study, ethanol produced from tree residues has been used for the calculations of the fuel cycle emissions. The activities regarding methanol have been relatively few in Sweden during the last decade. The author's company is currently working in the area of methanol production and has published reports with the results from several projects [11, 12]. These projects have been funded by the EU and STEM. Currently, no domestically produced non-fossil methanol is available in Sweden.

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[8] CBG: Compressed BioGas, in analogy to CNG:

[9] The designation "low-cost" biomass should be considered in respect to the relatively high-cost (excluding tax and subsidiaries) for other types of biomass (e.g. grain, oil plants, etc.). It should be noted that fossil feedstock, such as e.g. natural gas and coal could be much cheaper per energy unit than "low-cost" biomass in many cases.

Methane

Methane is currently used in Sweden by several vehicle fleets. Natural gas is available on the West Coast and in the southern parts of Sweden. However, the pipeline grid for natural gas currently supplies energy for only a small proportion of the consumption in Sweden. Since natural gas is a fossil fuel, biogas has been of primary interest for governmental support. Biogas from sludge and waste is produced in several cities in Sweden. There are also several plants for preparation of biogas (upgrading) for vehicle use. A specification for biogas to be used in this application has been issued in order to meet the quality demands. If biogas is to be produced on a larger scale, the production from lucerne or similar crops has the greatest potential. Therefore, this feedstock has been used as the basis for the calculations of the fuel cycle emissions.

It should be noted that the variation in the data for emissions from methane-fuelled buses tends to be great. Therefore, the results for this fuel have been divided into two different cases. The BAT (Best Available Technology) case is the average of the four best test results. Therefore, it represents kind of an ideal case for the timeframe studied. Hence, the denotation BAT was used. The "average" case was calculated as the arithmetic average of all test data, except extreme outliers (i.e. high-emitters) that were omitted from the averaging.

Other alternative fuels

Several other fuels are used or tested for heavy-duty vehicles in Sweden, such as RME, DME and LPG (propane). However, in general, the environmental impact of these fuels is small (RME) in comparison to diesel fuel, or else the use is currently insignificant (DME and LPG), and therefore, the available data is limited. Methanol could be of interest in the future but currently no HD vehicles fuelled by this fuel are in use in Sweden. Due to the conditions cited, the fuels mentioned above have been neglected in this study.

Fuels in the comparison between city buses and cars

Gasoline is used by more than 95 % of the passenger cars in Sweden so the choice of reference fuel for this vehicle category was obvious. Although other fuel options were investigated in a previous study [4], these were excluded in the comparison between buses and cars. For the buses, diesel fuel and ethanol were used. Methane was excluded from the assessment due to lack of input data for the analysis of cold start emissions. However, since the impact of cold start was later determined to be very small for diesel fuel and ethanol, an approximation could be used for methane as well without introducing too much error.

Engine and aftertreatment technology for city buses

The diesel engine chosen as the "reference" (base level) for this study was a Euro II city bus engine from Scania. Engines meeting this limit were actually introduced several years before the Euro II directive was applied. Therefore, these engines, with some alterations of the specifications, have been in use for almost the whole of the past decade. Emission tests from vehicles with these engines, and in addition, some additional information from tests on other vehicles, have been used as the input data for diesel engines [13 – 26]. Euro III diesel fueled buses were not included in the study due to lack of independent test data.

Aftertreatment technology

The aftertreatment devices used for bus engines in Sweden are oxidation catalysts and particulate filters. These devices have been extensively investigated concerning their emission characteristics [14, 18, 19, 22, 25 and 26]. The currently mostly used diesel particulate filter (DPF) system in Sweden is the CRT™ trap by Johnson Matthey. The main feature of this trap is that it is continuously regenerating. In Table 1, the emission reduction specified by the environmental zone requirements in Sweden is listed. "Type A" device is a catalyst and "type B" is a particulate trap. The assumed reduction efficiency used in this study for the same emission components is also listed in this Table.

Test data often indicate significantly greater reduction efficiency than the requirements for the environmental zone decree. On the other hand, some deterioration should be taken into account to obtain the emission level during the lifetime of the vehicle. To consider this deterioration, the reduction potential has been somewhat reduced in comparison to the test data. The small difference in NO_X reduction efficiency between the catalyst and the DPF is due to the difference in catalyst formulation. The catalyst and the DPF improve the NO_X/PM trade-off.

Table 1. Retrofit emission reduction requirements and the reduction assumed in this study

	HC	**NO_X**	**PM**	**Noise**
Type A	60 %	No incr.	20 %	No incr.
Type B	60 %	No incr.	80 %	No incr.
	Reduction efficiency used in this study			
Ox catalyst	88 %	1 %	15 %	–
Trap	92 %	4 %	90 %	–

For the unregulated emissions, the corresponding reduction efficiency has been derived from test data. In this case, the reduction efficiency, in most cases, has been less than for the HC emissions. It has not been fully explained why the reduction efficiency varies that much between different HC species. For example, the reduction efficiency for the oxidation catalyst (considering some deterioration) was 65 % for ethene and 50 % for formaldehyde. The reduction efficiency for the PAC (Polycyclic Aromatic Compounds) emissions (particulate bound and semivolatile) has been high in the tests conducted. In the previous assessment of the emission data, a level of 80 % was chosen for the catalyst and 86 % for the particulate filter respectively, using the same methodology (deterioration) as described above [2]. As mentioned earlier, a reassessment of the PAC emissions from the diesel engines (with and without aftertreatment) was made in this study. This reassessment was carried out since the analyzed species of PAC emissions differed in one test series [18, 19] from all the other test data. The test series mentioned differed from the other tests due to that some 2-ring PAH compounds were also included, whereas the other data included only 3-ring PAC emission components. After the correction was made, the difference between PAC emissions from the two engine families (Scania and Volvo) evaluated decreased. Without aftertreatment, the PAC emissions in the test mentioned were 88 µg/km, which was very close to the level of 76 µg/km for the other tests. The engine that had the higher level also used a somewhat older technology (early 1990´s), which makes the difference comprehensible. As part of the reassessment, the reduction efficiency of the catalyst and the particulate filter on PAC was decreased somewhat, i.e. to 78 % and 82 % respectively.

EGR system

A special after-market solution for reducing the emissions, which has now been commercially introduced in Sweden, is an exhaust gas recirculation (EGR) system that incorporates a diesel particulate filter (CRT™ in the particular version evaluated here). The EGR system is called DNO_X™ (designated DPF+EGR in this study) and it has been developed by the Swedish Consultant Company STT. An overview of the system and its impact on emissions is described in a report from STT [27]. The system utilizes filtered and cooled EGR, which is fed to the inlet duct of the compressor. Thus, the system should be classified as a low-pressure EGR system. The system will be used both as a retrofit solution and in OEM installations on new vehicles. The emission data for the DPF+EGR has been derived from the previously mentioned report (tests at MTC) [27], taking some assumed deterioration into account. The system is now offered as an OEM option for Euro III engines further reducing the emissions in comparison to the standards. These engines have lower emissions that the (older) Euro II engines evaluated here but they were not included in the study due to lack of independent test data.

Ethanol

The ethanol engine chosen for this study was a compression ignition (CI) engine (Diesel cycle) [28 – 36]. Most of the ethanol buses in service in Sweden are manufactured by Scania. The majority of these buses also use an oxidation catalyst, and therefore, only this configuration was evaluated. The Scania ethanol engine evaluated is an 11-liter 6-cylinder heavy-duty CI engine using ethanol with ignition improver and an increased compression ratio (24:1) to obtain compression ignition of the fuel. This engine has recently been replaced by a 9-liter engine using similar technology. The ignition improver used initially by ethanol engines was Avocet™ (an organic nitrate) but during the last years, Beraid™ (polyethylene glycol) has replaced the former. The emission performance of these ignition improvers has been shown roughly similar [30]. It should also be noted that the DPF+EGR system described above could be used on ethanol engines as well. In fact, EGR was initially evaluated on an ethanol engine [35, 36]. A research program has been initiated at the Luleå University of Technology to further investigate the potential of EGR on an ethanol engine, possibly in combination with a particulate trap. However, since this system currently is not commercially available, it has not been included in the evaluation.

Methane

The methane (CNG and biogas) engine option chosen was a spark ignition (SI) lean-burn engine (Otto cycle) [37 – 42]. The difference in emission level between CNG and biogas is marginal and in most cases, these fuels are treated as the same fuel in this study. The majority of the methane-fueled buses in Sweden are manufactured by Volvo. However, some data used in this study originate from a converted Scania engine. An oxidation catalyst was anticipated in both cases. The Volvo engine is a 10-liter 6-cylinder SI engine and the converted Scania engine is of the same type. The latter engine was derived from the diesel engine described above. There are also some TWC engines available on the Swedish market but the limited emission data available and the low market penetration of these engines led to that these engines were of little interest in this study.

Driving cycle for city buses

The driving cycle chosen for the city buses was the Braunschweig city bus cycle, which is sometimes also called the “bus cycle” (Figure 1). This driving cycle is intended for a HD chassis dynamometer. There were several reasons for the choice of this driving cycle. One reason was that this driving cycle is transient (contrary to the 13-mode cycles) and, therefore, it represents city driving of buses reasonably well. Another reason was that most of the Swedish data for unregulated emissions from HD vehicles have been generated using this driving cycle. The Braunschweig driving cycle has been extensively used in the past at MTC. The test inertia used for the buses was 13 ton. The test procedures for these tests are described in the test reports from each project, and an example for reference is a report by Grägg [24].

Driving cycle for cars

The driving cycle chosen for passenger cars was primarily the new European driving cycle (NEDC). Since most of the data for in-use emission testing (until now) have been generated using the FTP-75 driving cycle, this cycle was chosen for assessing the deterioration factors. The single most important factor determining the emissions from gasoline fueled passenger cars is the cold start. Since this factor is dominating for shorter trips, no further correction was made for potential impacts of differences in driving pattern (e.g. city vs. highway driving).

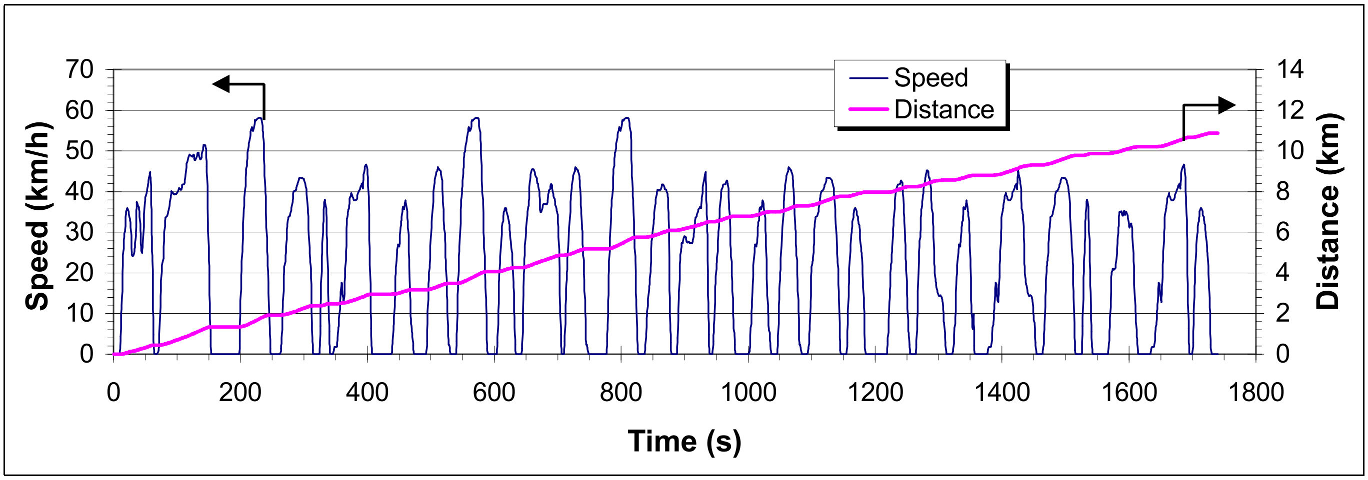

Figure 1. The Braunschweig city bus driving cycle for tests on chassis dynamometer

Calculation of effects

The calculation of the effects has been carried out for tail-pipe emissions only, i.e. atmospheric concentrations (due to dispersion atmosphere chemistry) have not been considered.

Investigated Effects

The effects of primary interest and the corresponding emission components are:

- Ozone (O_3) formation (NO_X and organic gases)
- Components influencing respiratory diseases (O_3, NO_2, particulate matter and organic gases)
- Cancer risk (numerous components)
- Vegetation injury (NO_X, SO_X and O_3)
- Visibility (particulate matter and droplets)
- Acidification (NO_X, SO_X and NH_3)
- Eutrophication (NO_X, and NH_3)
- Climate change (fossil CO_2, CH_4, N_2O, etc.)

Life Cycle Perspective

The effects mentioned above can be classified as local, regional and global effects. In order to obtain some life cycle perspective on the investigated effects, the fuel cycle emissions have also been included for the *regional* and the *global* effects. In those cases, the pollution from the vehicle and from the fuel cycle have been shown separately.

Data for the fuel cycle emissions have been collected from a previously published report by Johansson et al., "Life of Fuels" (LoF) [43]. Since this report was prepared some years ago, some of the data are old and could be somewhat improved by using new information. However, data on fuel production is still reasonably up-to-date. Furthermore, the impact from the fuel production on the effects analyzed here is generally small. Thus, the results from the mentioned report have been used extensively in this study. The emissions for vehicle production, scrapping, maintenance etc. are not included in the LoF report. However, it is anticipated that the difference between the investigated fuel/engine options is small in this respect.

Environmental impact and health effects

Regarding the calculation of the effects, some comments are made below about the calculation schemes and the methodology.

Ozone formation

Ozone formation in populated areas is generally limited by the VOC concentration. Based on the literature review, the following relative reactivity factors have been used (diesel=1). Most of the data taken into account originate from a paper by Newkirk and Bass [44]. A speciation of VOC emissions was used in that paper to calculate the reactivity of each fuel. The reactivity adjustment factors used in the evaluation in this paper are shown in table 2.

Table 2 shows that the Reactivity Adjustment Factor (RAF) values for the alternative fuels are considerably lower than for diesel fuel, in spite of the fact that Non-Methane Organic Gases (NMOG) is used instead of HC. It might be possible that biogas could have an even lower RAF than CNG but there are no data available to support that hypothesis. Since the RAF for diesel fuel is based on the results from U.S. diesel fuel [44], this could lead to an overestimation in comparison to EC1 fuel. It should also be noted that the RAF value for gasoline is lower than for diesel fuel, although this advantage for gasoline could be significantly lower if the comparison was made with EC1 diesel fuel.

Table 2. Reactivity adjustment factor (RAF)

Fuel type	RAF
Diesel fuel	1.00
Ethanol	0.31
CNG and biogas	0.28
Gasoline	0.62

Respiratory diseases

The assessment of ozone formation was covered in the previous section. Ozone was identified as an irritant component in a Swedish governmental investigation on environment and health and a long-term target for the reduction of ozone has been set (80 $\mu g/m^3$, hourly avg.) [45].

The NO_2 share of the NO_X emissions from diesel engines without catalytic aftertreatment is usually low, i.e. in the order of 5 %. However, most of the NO_X is converted to NO_2 in the atmosphere. Since NO_2 is the more harmful component, a high share of NO_2 in the exhaust is not desirable. It has been shown that some catalytic aftertreatment devices, such as the DPF evaluated in this study, could have a high proportion of NO_2 under some driving conditions [19, 22]. In this study, the total NO_X emissions have been used for comparison, although this might give an underestimation of the inhaled NO_2 in some cases. In order to obtain a proper comparison, a model of the dispersion and the atmosphere chemistry would have to be used instead and this was beyond the scope of this study.

Of the organic gases, the aldehydes are particularly irritant components and therefore these emissions are shown in addition to the other components described above.

Particulate matter has also been identified as a component causing respiratory diseases [45]. Several epidemiological studies have shown, by using statistical methods, that the daily mortality and morbidity correlate with increases in particulate air pollution. A paper by Pope et al. is one example of such results [46].

Cancer risk

The cancer risk factors for various emission components from different sources vary significantly. It should be noted that the uncertainty regarding the data for cancer risk factor assessments is great. Therefore, the results for this effect also involve more uncertainty than the other investigated effects. Several sets of risk factors are also available from organizations such as, for example, U.S. EPA, CARB, CAPCOA and OEHHA of Cal. EPA [47 – 51]. A review draft version of the latest evaluation by EPA of cancer risk factors is available (July 2000), but the review has not been finalized yet [52].

In this study, the unit risk factors (URFs) by the Swedish researchers Törnqvist and Ehrenberg [53] have been used extensively as the basis for the evaluation of cancer risk. Some results with other unit risk factors are also shown. One of the features of the risk factors by Törnqvist and Ehrenberg is that they also consider other forms of cancer than lung cancer and other routes of uptake besides inhalation. Their risk estimates have been the basis for SEPA in setting the reduction targets of hazardous compounds in ambient air. The risk factors used in this study are listed in Table 3. The unit risk factors in Table 3 are expressed as the individual mortality risk at a lifetime (70 years) exposure of 1 $\mu g/m^3$ for each component.

It is obvious from the data in Table 3 that the URFs from various sources differ substantially. There are some similarities between the URFs by Törnqvist & Ehrenberg and EPA, since the same scientific sources have been used in both assessments. Differences can be noted for ethene, propene formaldehyde and PAC. Partly these differences are due to that Törnqvist and Ehrenberg also consider other forms of cancer than those in the two other studies.

Table 3. Unit risk factors for cancer (10^{-6})*

Component	Törnqvist & Ehrenberg	U.S. EPA 1990	OEHHA 1999
Particulates	70	70	300
Benzene	8	8	29
Ethene	50	(5)[a]	-[b]
Propene	10	(1)[a]	-[b]
1,3-Butadiene	300	300	170
Formaldehyde	100	10	6
Acetaldehyde	2	2	2.7
PAC	28 000[c]	4 000	1 100

Notes:

[a] EPA has not assigned any URFs for ethene and propene. The data shown in the table above have been calculated by Törnqvist and Ehrenberg assuming the same potency as 5% of the corresponding epoxides, hence the parenthesis.

[b] OEHHA has not assigned any URFs for ethene and propene.

[c] PAC in this case is defined as tri-aromatics+. These components are known to be the biologically most active components [6].

Ethene and propene are included by Törnqvist and Ehrenberg among the components due to the proven metabolism similarity to that of 1,3 butadiene [53]. The URF for ethene and propene, which are active through their monoepoxides, have been derived by the dosimetry-rad equivalence method, using γ-radiation as reference standard. EPA and OEHHA use no URFs for ethene and propene.

In this study, PAC is defined as the sum of 29 different compounds that has been analyzed in all data sets used in this study [14]. Most of the PACs are PAHs (Polycyclic Aromatic Hydrocarbons). It should be noted that PAC in the table only comprises tri+ aromatics. Two-ring and lighter compounds are not included, since the tri+ aromatics have been found more biologically active than the former. The major difference between the URF for PAC is due to that Törnqvist and Ehrenberg (besides taking other forms of cancer than lung cancer into account) also considers other routes of uptake than inhalation (food chain).

Particulate matter has a lower risk factor than PAC but the concentration in the exhaust is often significantly higher (as with diesel fuel). The risk estimate on particulate matter is based on the particulate mass.

The most recent work on risk assessment by the U.S. EPA is not included in Table 3 for two reasons. First, the work is not finalized yet. Second, the URFs are not given in the same form as in Table 3. It should also be noted that the risk assessment by OEHHA has not received the same acceptance by the scientific community as the assessments by EPA and its associated experts.

Acidification

The NO_X emissions are the main contributor to the acidification from heavy-duty vehicles in Sweden, since all fuels in use (except diesel fuel quality according to the European specification) have a very low sulfur content. The NO_X emissions from fuel production have been obtained from the LoF report [43], and the NO_X emissions from the vehicles have been collected from the compiled emission data, as described earlier.

The SO_X emissions have been calculated using the sulfur content of the fuels. In case of diesel fuel, the EC1 fuel has a limit of 10 ppm sulfur but since the industry average generally is much less than this limit, a level of 6 ppm has been used instead. This is considerably lower than the current European specification at 350 ppm. Ethanol is essentially sulfur-free and a level of 2 ppm sulfur has been anticipated for CNG and biogas. In all cases examined, the sulfur emissions from the vehicles were low in comparison to the sulfur emissions from the fuel production. Gasoline according to the Euro IV (2005) and Swedish EC1 gasoline fuel specification (<50 ppm S) was anticipated for the passenger cars.

The level of NH_3 is generally very low from the types of HD engines investigated here, and due to the limited data available, this compound has been neglected. For example, Almén found that the NH_3 emission from two tested diesel-fueled trucks was as low as 3 mg/km [17]. The NH_3 emissions from gasoline fueled cars might be considerably higher than from the buses but, since only limited data were available, this emission component was also omitted for the cars.

Climate change

Most of the greenhouse gas (GHG) emissions can be attributed to fossil CO_2. However, in some cases, such as for the methane emissions from CNG and biogas-fueled vehicles, other components could also be of significant importance. The data used in the calculations are shown in Table 4.

Table 4. Global warming potential (relative to CO_2)

Component (GHGs)	**Chem.**	**GWP**
Carbon dioxide	CO_2	1
Oxides of nitrogen	NO_X	7
Carbon monoxide	CO	3
Non-methane hydrocarbons	NMHC	11
Methane	CH_4	24,5
Nitrous oxide	N_2O	320

In total, six different emission components were used in the calculation of the total global warming potential (GWP). IPCC (Intergovernmental Panel on Climate Change) values for the GWP at a timeframe of 100 years were used for all components but NO_X and NMHC [54]. The same values as in the LoF report was used for these components. LoF used older IPCC data for the other components. Values for NO_X and NMHC (and HC) have not been included in later IPCC data, but we still used the older figures here. It was considered that the omission of these components would introduce even greater errors than using the old data. Speciation of HC/NMHC emissions and the use of GWP factors for each component could potentially improve the precision in the calculations but the limited data on speciated hydrocarbons available precludes this calculation.

RESULTS – BUSES

The results in the majority of the graphs shown in this chapter deal with several engine/fuel options. These are:

- Diesel engine fueled with EC1 diesel fuel
- Diesel engine with oxidation catalyst fueled with EC1 diesel fuel
- Diesel engine with DPF fueled with EC1 diesel fuel
- Diesel engine with EGR+DPF fueled with EC1 diesel fuel
- Ethanol-fueled diesel engine with oxidation catalyst
- Methane-fueled engine with oxidation catalyst, average emission results
- Methane-fueled engine with oxidation catalyst, average of the best emission results, hence the denotation "BAT" (Best Available Technology)

It should be noted that most Figures shown in this chapter are structured in a similar way. The basis for comparison is a diesel engine without a catalyst fueled with EC1 diesel fuel. To simplify the comparisons, indexes with the mentioned option as the base level (100), has been calculated for all the results. In the comparisons of regional and global effects, where fuel production is of importance, CNG and biogas have been shown separately. Note that there are rounding errors for some of the values shown in the Figures.

Ozone formation

In general, heavy-duty vehicles contribute less to ozone formation than gasoline-fueled light-duty vehicles do, due to the lower total emissions of reactive organic compounds. However, a relative comparison of this effect is still of interest for the buses investigated here. The ozone forming potential for the engine/fuel options is shown in Figure 2.

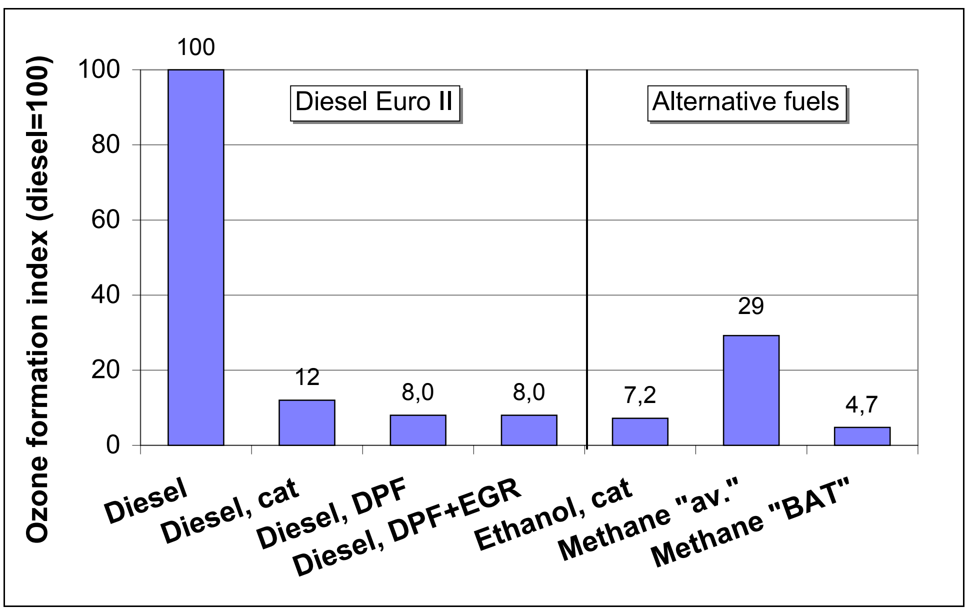

Figure 2. Ozone forming potential (buses)

The ozone forming potential from the conventional diesel engine without aftertreatment is significantly higher than from all other options. There are two reasons for this result. First, the RAF level for the HC emissions (as well as for NMHC) in diesel exhaust are higher than from any other fuel investigated. Second, the absence of catalytic aftertreatment results in relatively high HC emissions.

The diesel fuel options with aftertreatment and ethanol has significantly lower ozone forming potential (about one order of magnitude) in comparison to the base case. The reason why ethanol is not significantly better than the diesel options with aftertreatment is that the HC emissions (according to FID data) are 2 – 2.5 times higher for ethanol than for diesel. In spite of the lower RAF for ethanol, the ozone forming potential is roughly similar to the previously mentioned diesel fuel options.

Methane-fueled engines often have high emissions of total hydrocarbons (THC), since they are SI engines. Although most of the THC emission is composed of methane for CNG and biogas, the NMHC emissions also tend to increase if the THC emissions increase. Due to the great variation of the air-fuel ratio, from test to test and from vehicle to vehicle, for the gaseous-fueled engines, there is also a great variation of the NMHC emissions. The results for methane should be interpreted so that it is obvious that this fuel has a great potential for low ozone formation but this potential cannot be fully exploited unless the air-fuel control is improved. Provided that biogas has lower NMHC emissions than CNG (and possibly also a lower RAF), the ozone forming potential should be somewhat lower for this fuel than for CNG.

Respiratory diseases

The results for the emission components chosen (NO_X, PM and aldehydes) as and indication of the impact on respiratory diseases are shown below. The result for ozone, which also is an important compound in this respect, was shown above.

NO_X emissions

The NO_X emissions are shown in Figure 3. It should be noted that the transient Braunschweig driving cycle chosen as the basis for comparison gives different results in comparison to steady state driving cycles.

As already mentioned, there are significant differences in the NO_X emissions from the various engine/fuel options. Conventional aftertreatment devices for diesel engines have little effect on the NO_X emissions as shown in Figure 3. The EGR system, in its present development state, can reduce the NO_X emissions by some 50 % in the Braunschweig test cycle. Ethanol reduces the NO_X emissions by approximately 40 %. The greatest impact on the NO_X emissions can be obtained with the lean-burn methane engine, although the variability in the measurements raises some questions about the long-term stability of the control system.

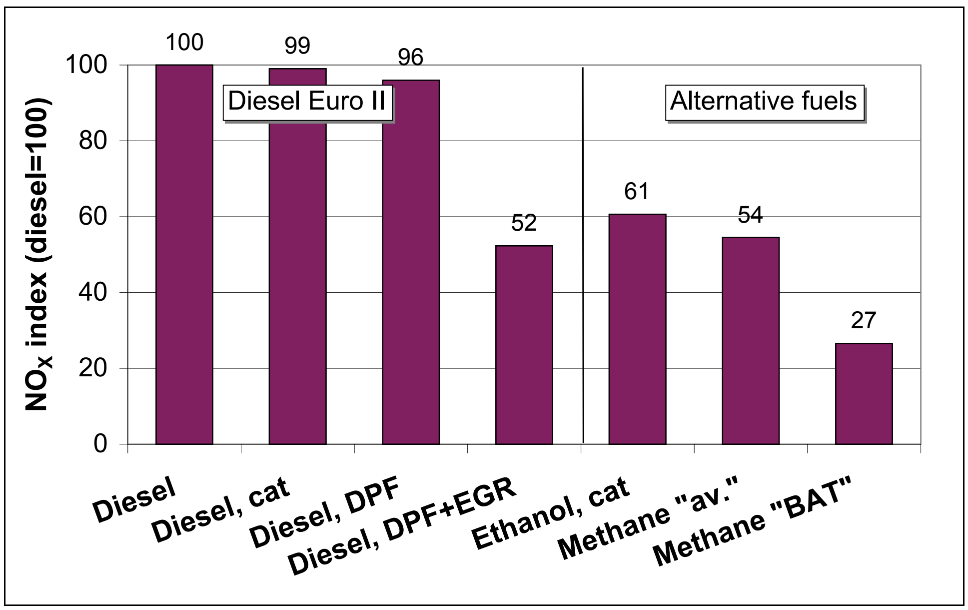

Figure 3. NO_X emissions (buses)

Particulate emissions

The particulate emissions are shown in Figure 4. It should be noted that the evaluation of these emissions is on mass basis. The use of particulate number emissions, area or volume might give different results. However, there are presently not sufficient data available to support a different method of assessment of the particulate emissions.

As expected, Figure 4 shows that the diesel engine options, without aftertreatment and with an oxidation catalyst, have the highest particulate emissions of all investigated options. The impact of the oxidation catalyst, at about 15 %, is rather low.

The two options with particulate filter reduce the particulate emissions by at least 90 %, although some anticipated deterioration is taken into account. In practice, particulate filters have been shown to maintain the filtration capacity very well over time. The anticipated deterioration should instead be interpreted as a certain failure rate of the systems in operation. The small difference between the DPF and the EGR+DPF systems is probably due to that the origin of the data are from different engine types and/or due to a difference in DPF efficiency. It is anticipated that the particulate level (engine-out and tail pipe) should be higher with EGR than without EGR. It should also be noted that the particulate level in both cases, at less than 0.02 g/km (0.017 and 0.020 respectively), is very low and the difference is on the same order of magnitude as the measurement scatter.

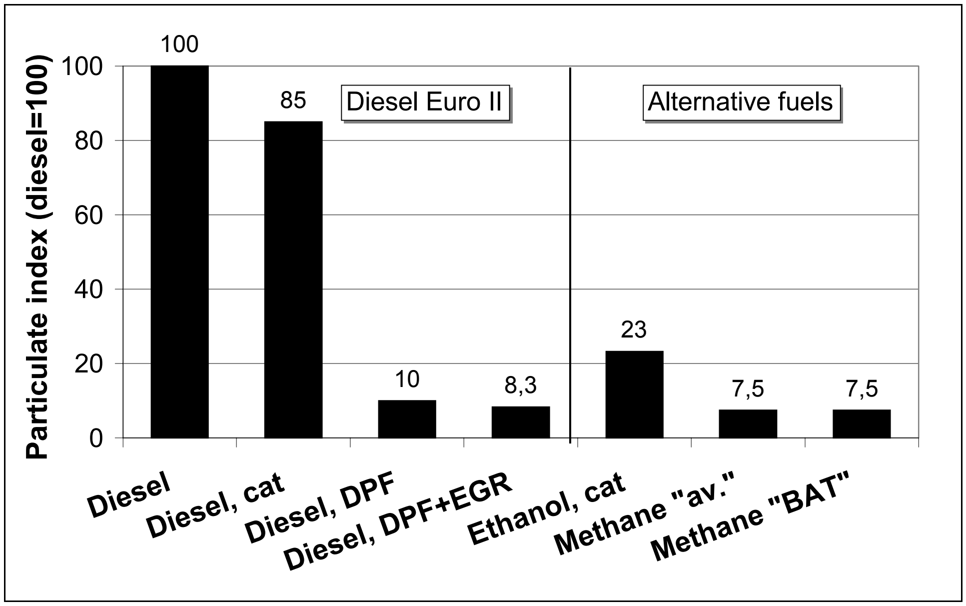

Figure 4. Particulate emissions (buses)

The ethanol engine has significantly lower particulate emissions than the diesel-fueled options without particulate filter. A certain share of the particulate emissions originates from the engine lubrication oil. Since an ethanol engine for a heavy-duty truck from another engine manufacturer has showed somewhat lower particulate emissions than the bus engine used in the calculations here, the oil derived particulate emissions could also be dependant on engine hardware. Comparisons of the emission results from the two mentioned engines [28 – 33 and 34] indicate that this might be the case. It is also likely that some of the particulate emissions could be derived from the fuel. The ignition improver contains very heavy molecules that could condense on the sampling filter and, possibly, produce soot emissions under certain operating conditions. Tests using EGR on an ethanol engine has shown significantly increased particulate emissions [36] that due to the blackness of the sample filters most certainly could be attributed to soot emissions. It is likely that these soot emissions originate from engine operation at very low air-fuel ratios (during transients) and it is conceivable that the same phenomenon – although less in magnitude – could occur for an ethanol engine without EGR.

The methane-fueled engines have very low particulate emissions. This could be anticipated, since a lean-burn SI engine uses premixed charge where the air and fuel has been mixed to a molecular level. These operating conditions are known to produce negligible soot emissions. The air-fuel preparation for gaseous fuels also enhances the premixing process in comparison to liquid fuels. Furthermore, there is little evidence that variability in the transient air-fuel control would increase the particulate emissions, although this could happen to a certain extent if the relative air-fuel ratio is significantly below the stoichiometric level. The bulk of the particulate emissions from the methane engines presumably originate from the engine lubrication oil.

Aldehyde emissions

The aldehyde emissions are shown in Figure 5. Only formaldehyde and acetaldehyde are shown since the data on higher aldehydes, as well as on ketones, are relatively few. The sum of the two aldehydes mentioned is shown without applying any weighting factor for each of them. However, it is known that formaldehyde is the more irritating of these two aldehydes. For example, the occupational health limits in Sweden for formaldehyde (0.6 mg/m^3) is almost two orders of magnitude less than for acetaldehyde (45 mg/m^3) [55].

The diesel-fueled engine has relatively high aldehyde emissions without after-treatment. Surprisingly, the oxidation catalyst has relatively small impact on the aldehyde emissions. On the other hand, the DPF has much higher efficiency in oxidizing the aldehydes resulting in the lowest aldehyde emissions of all options. The difference in catalyst formulation between the oxidation catalyst and the DPF and the larger catalyst volume for the latter could be the explanation to the mentioned difference.

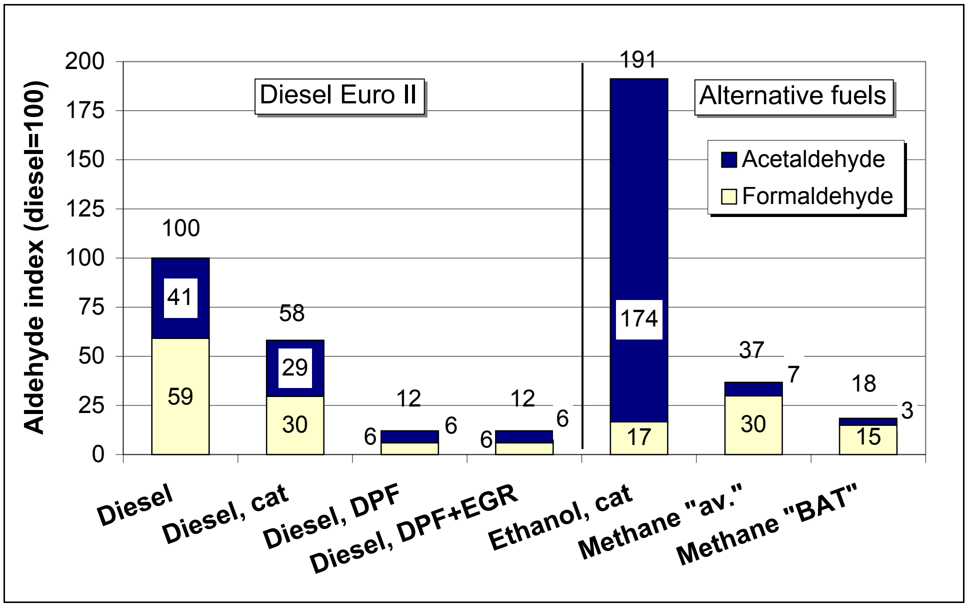

Figure 5. Aldehydes (buses)

Ethanol has the highest total aldehyde emissions of all engine/fuel options. However, acetaldehyde comprises most of the aldehydes and the formaldehyde emissions are actually lower than from diesel fuel with catalyst, which is on the same level as the best methane alternative. Acetaldehyde is more difficult to oxidize than formaldehyde and this is one explanation to the high level of aldehyde emissions from ethanol engines. Another explanation is that the HC emissions (by FID) are higher than for diesel fuel. Another problem experienced with ethanol-fueled city buses in Sweden is the bad smell of the exhaust. This smell is mainly attributable to acetic acid but the aldehydes could also be of some importance in this respect. The problem with a catalyst working at low temperature is that the oxidation of acetaldehyde (and probably unburned ethanol to some extent) at these operating conditions tends to *increase* the level of acetic acid. In some cases, the smell from a bus without catalyst has been considered less annoying than when a catalyst has been used.

The aldehydes from methane mainly consist of formaldehyde. This is comprehensible since formaldehyde is an intermediate product of the oxidation of methane to CO_2 and H_2O. There is some evidence in the literature that the formaldehyde emissions from CNG engines without catalyst could be rather high [44]. In general, formaldehyde is relatively easy to oxidize and therefore, a catalyst reduces these emissions considerably. In summary, reducing the level of unburned fuel and maximizing the catalyst efficiency for formaldehyde oxidation would be the methodology to achieve low aldehyde emissions from methane-fueled engines.

Cancer risk

The cancer risk index is probably one of the most uncertain results. It should be stressed (once again) that the unit risk factors for the individual emission components vary from source to source and therefore the results for this effect is less accurate than the other investigated effects.

Unit risk factors by Törnqvist and Ehrenberg

In Figure 6, the results for cancer risk using the unit risk factors derived from the paper by Törnqvist and Ehrenberg are shown.

As expected, the total cancer risk index is highest for diesel fuel without any aftertreatment (Figure 6). The particulate emissions comprise more than 50 % of the total cancer risk index in this case. 1,3-butadiene accounts for the greatest share of the contribution from the alkenes. The reason why the PAC emissions do not contribute more is the use of the low PAH EC1 fuel. Using an oxidation catalyst significantly reduces the volatile components and the catalyst has a small effect on the particulate emissions as well. The most significant reduction of the cancer risk from diesel fuel is obtained by using the DPF. 1,3-butadiene accounts for most of the contribution from the volatile organic components. The reason for the small differences in the PAC emissions between the two options with DPF is only due to the fact that two different engines have been used in the two cases. As mentioned before, a correction was made for the PAC emissions for the diesel options with aftertreatment in comparison to the previous evaluation [2] but this had very little impact on the results. Similarly, the decrease in particulate reduction efficiency for the diesel with DPF+EGR was negligible. It would be somewhat difficult to hypothesize about the effects of a different type of DPFs but the impact on particulates (mass) could be anticipated to be reasonably similar for other types of DPFs. The impact of the catalyst formulation is also important and a DPF without catalyst cannot give as favorable results for the volatile emission components.

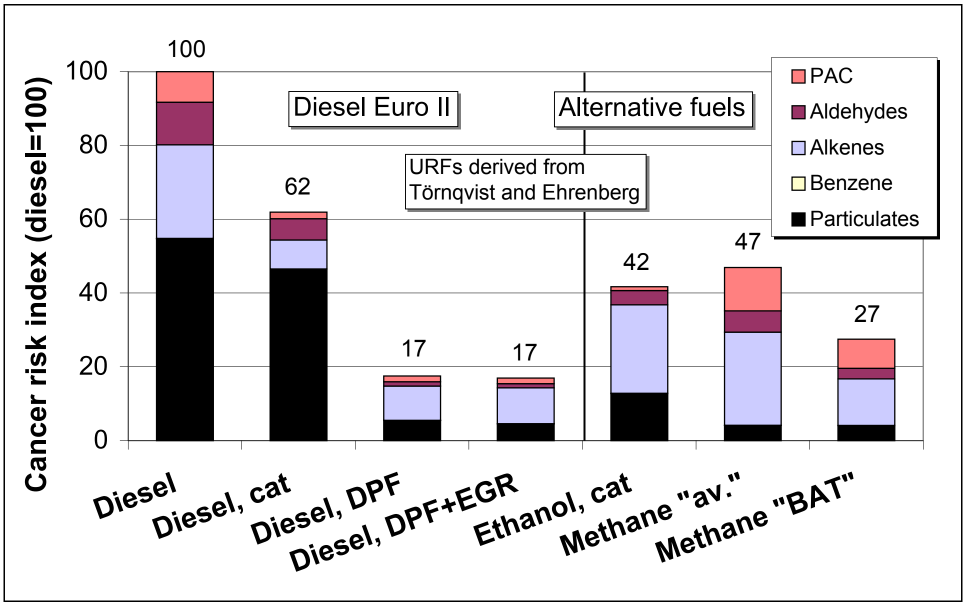

Figure 6. Cancer risk index, URFs by T & E (buses)

Ethanol has a lower cancer risk index than diesel fuel with an oxidation catalyst (in both cases). The particulate emissions are lower from ethanol but the alkenes, mainly ethene, but also 1,3-butadiene to some extent, are higher than from diesel fuel. Due to the relatively high emissions of alkenes and the condition that the ethanol engine has no particulate filter, the cancer risk is higher than from diesel fuel with DPF.

The cancer risk index is lower for methane than for diesel fuel without aftertreatment and diesel with an oxidation catalyst. Particulate and aldehyde emissions are lower from methane but, on the other hand, 1,3-butadiene and PAC emissions are higher. The significantly higher PAC emissions from methane in comparison to diesel fuel were not expected, since CNG and biogas contain no PAH. Probably PAC formed from the engine lubrication oil could be one source of the PAC emissions. The pyrene emission is the

PAC compound that is highest of all these components. This also explains the relatively high emissions of 1-nitropyrene, a very potent carcinogen.

It is interesting to note that the contribution to the cancer risk from benzene emissions is negligible for all assessed engine/fuel options.

Unit risk factors by U.S. EPA (1990) and OEHHA (1999)

Using the emission data as above, a recalculation of the relative cancer risk using various sets of unit risk factors was carried out in the study for BP [3]. The investigated cases besides the case shown above (URFs by Törnqvist and Ehrenberg, "base case") were the following:

- URFs by EPA, 1990
- URFs by OEHHA, 1999. URF for diesel particulate used for the PM emissions from fuels, in addition to the factors for the volatile compounds. This case was denoted "OEHHA case #0".
- URFs by OEHHA, 1999. Only the URF for diesel particulate was used for diesel fuel (other components were excluded). All factors but PM was used for the alternative fuels. This case was denoted "OEHHA case #1".
- URFs by by OEHHA, 1999. URFs for all components except PM was used for all fuels. This case was denoted "OEHHA case #2".
- URFs by OEHHA, 1999. This case is similar to OEHHA case #1 above but with the following modifications. The URF for diesel particulate is at the lowest level within the range provided by OEHHA and the level for 1,3-butadiene is at its highest level. This case was denoted "OEHHA case #3".

Figure 7 shows the same results as above but with the URFs that were derived by EPA in 1990.

The results in Figure 7 (using the URFs from 1990 by EPA) show very similar results for most of the fuel/engine options in comparison to the previous case. However, it should be noted that the contribution of the individual compounds is different in both cases. The greatest relative difference is for diesel with a catalyst and for the two methane cases. The index for diesel with catalyst is 69 with the EPA factors vs. 62 with the factors by Törnqvist and Ehrenberg. Methane "av." drops from 47 to 38 and methane "BAT" drops from 27 to 22.

The results for the case denoted "OEHHA case #0" are shown in Figure 8.

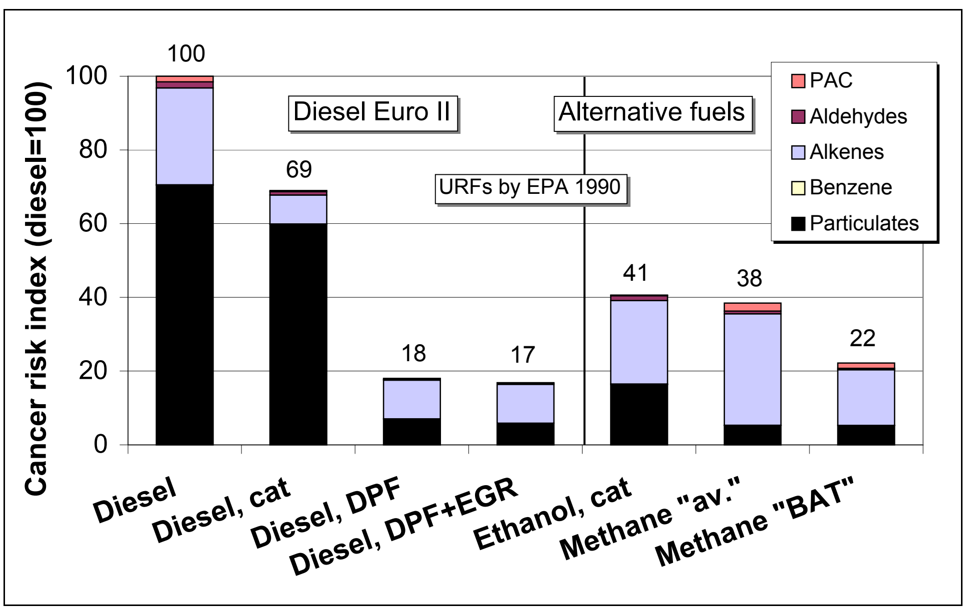

Figure 7. Cancer risk index, URFs by EPA -90 (buses)

The results in the OEHHA case #0 are considerably different compared to the previous cases (Figure 8). The domination of the particulate emissions is striking. This is due to the very high URF for "diesel exhaust", or diesel particulate matter, in comparison to the other components (and in comparison to the URF for PM by EPA).

It may be argued that the URF for diesel PM includes all other emission compounds and therefore, the level in Figure 8 are overestimated for all engine/fuel options. Furthermore, it is not known whether the PM from other fuels does have a similar unit risk factor as diesel particulate. Different composition of the adsorbed volatile organic matter, a shift in particle size distribution and total number of particles, etc. could have a significant influence on the cancer risk although these possible effects remain to be quantified. So far, not much information is available to support a hypothesis regarding this matter. Besides particulate matter, 1,3-butadiene is the emission component with the highest contribution to the total cancer risk index (for all fuels). It should be noted that EPA is about to reassess the URF of 1,3-butadiene (a considerably lower value than previously has been suggested) and this could have a significant impact on the results.

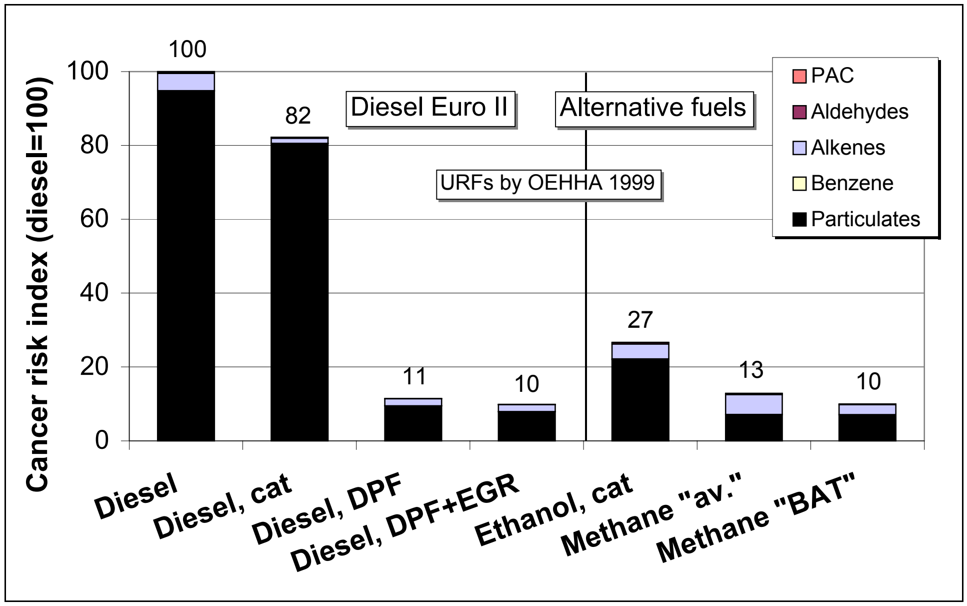

Figure 8. Cancer risk index, OEHHA case #0 (buses)

In OEHHA case #1 (Figure 9), the URF for diesel PM has been used for all options running on diesel fuel. Furthermore, the volatile organic compounds have been neglected using an assumption that the URF for diesel particulate actually incorporates the risk from the other non-particulate components. The URF for the particulate emissions from the alternative fuels has been set to zero, although a risk assessment of these combustion particles has not been carried out.

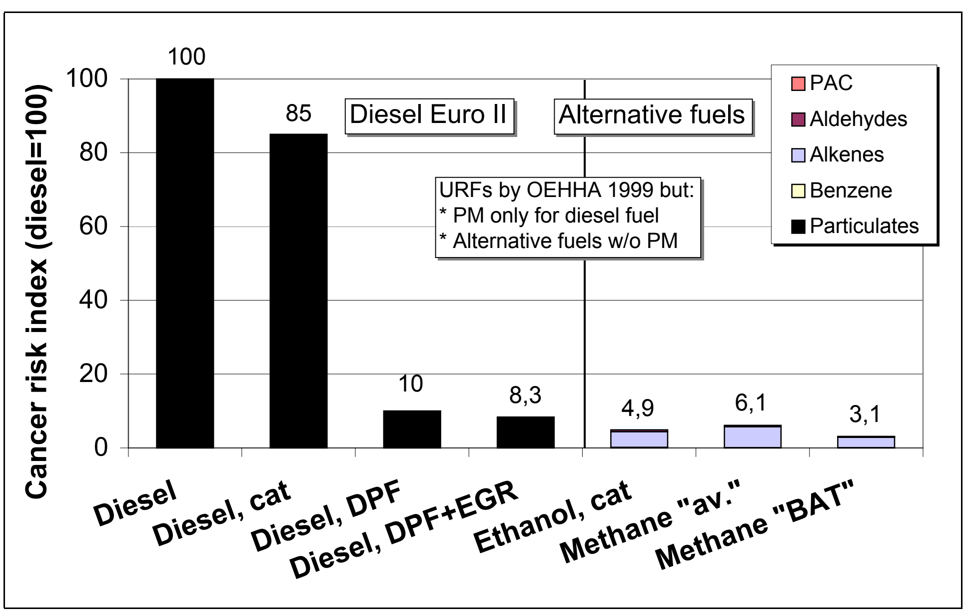

Figure 9. Cancer risk index, OEHHA case #1 (buses)

The relative cancer risk for all the diesel fuel options in Figure 9 is higher than for the alternative fuels. As expected, the relative impact of the DPF is greater than in the previous figures. Still the cancer risk index is 2 – 3 times higher for the diesel options using DPF than the alternative fuels. Methane with the best technology has the lowest cancer risk. As in the previous case (Figure 8), the question of how the particulate emissions from the alternative fuels should be treated remains to be taken into account. Reassessment of the URF for 1,3-butadiene – as previously mentioned – could significantly change the results in Figure 9.

Figure 10 shows the relative cancer risk for the engine/fuel options without the contribution from the particulate matter (in all cases).

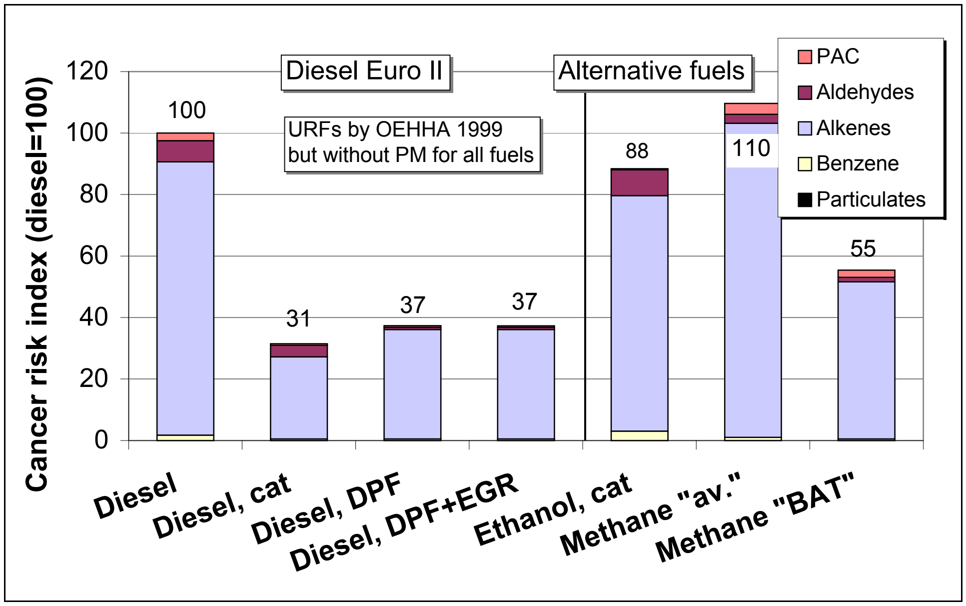

Figure 10. Cancer risk index, OEHHA case #2 (buses)

The total cancer risk index in Figure 10 is dominated by the 1,3-butadiene emissions for all engine/fuel options. In this case, the best diesel-fuelled options are somewhat better than the best methane option. The primary reason for this outcome is the lower emissions of 1,3-butadiene for the best diesel options. However, the other volatile components are also lower for the diesel-fuelled options. This appears to follow a general trend implying that the 1,3-butadiene emissions are lower for compression ignition (CI, or Diesel-cycle) engines than for spark ignition (SI, or Otto-cycle). The lower engine-out emissions of total HC and NMHC for the CI engine in comparison to the SI engine is most likely one contributing factor. Similar results were also noted in the comparison of the health effects from light-duty vehicles by these authors [4]. Consequently, this outcome could be an effect that is related to the engine type (CI vs. SI) and not that much attributable to the fuel composition. However, it should be noted that certain compounds in the fuel, such as e.g. olefines could have an impact on the 1,3-butadiene emissions. If the URF of 1,3-butadiene will be reassessed (yielding a significantly lower level), this would have a significant impact on the results.

As a simple way of showing the effects of a sensitivity analysis, a case similar to OEHHA case #1 (Figure 9) but with the following modifications, has been calculated. The URF for diesel particulate has been set to the lower bound within the range provided by OEHHA. Simultaneously, the range for 1,3-butadiene has been set at the higher bound. Figure 11 shows the results from this calculation.

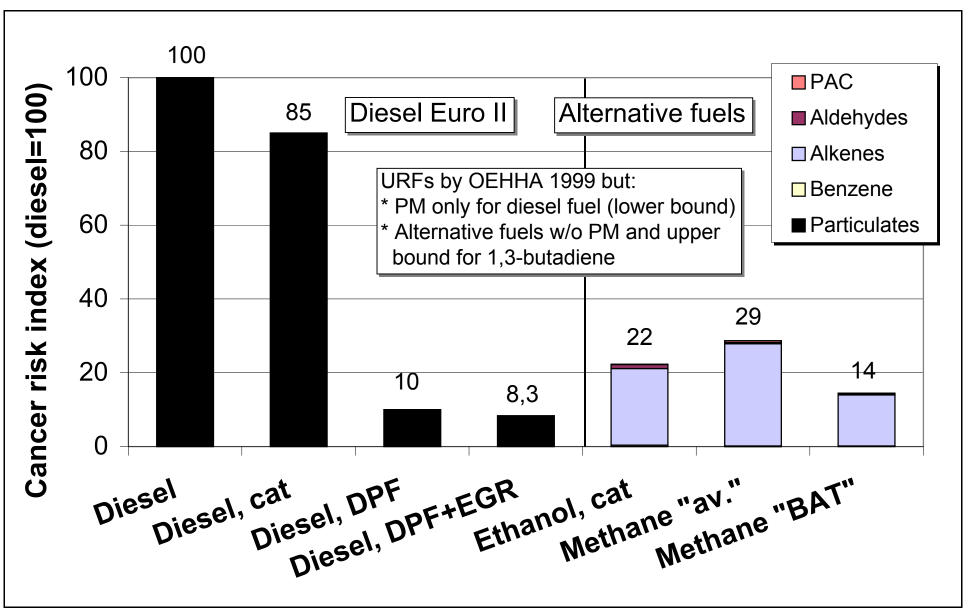

Figure 11. Cancer risk index, OEHHA case #3 (buses)

Since an identical URF has been used for diesel particulate in both the OEHHA case #1 and #3, the results in Figure 11 are similar to the results in Figure 9 (since the comparison is relative only). On the other hand, the small *advantage* for the alternative fuels in comparison to diesel with DPF in the Figure 9 (OEHHA case #1) is changed to a *disadvantage* in Figure 11. The use of an opposite choice of ranges for URFs for diesel particulate (higher bound) and 1,3-butadiene (lower bound) respectively, would change the comparison in favor of the alternative fuels.

The results from the calculations with different URFs clearly show the significant importance of the unit risk factors. If the whole range of uncertainties for all the individual URFs is taken into account, it is somewhat difficult to determine which option is the best option of all the engine/fuel alternatives investigated.

Acidification

The results for acidification are shown in Figure 12. The data for the contribution from fuel production and vehicle emissions have been shown separately.

In general, the acidification is dominated by the vehicle emissions, except for the biofuels where the contribution from the fuel production can be higher. For example, the production of ethanol (from tree residues) causes high NO_X emissions. The *conversion* step in the production is the largest contributor. However, it is likely that the production process used in the calculations could be significantly improved in this respect in the future. It should also be noted that the NO_X emissions attributable to cultivation and transport of the feedstock could also be significantly improved for the biofuels in the future. New engine and aftertreatment technology for the vehicles and the machinery used in cultivation and transportation would make this improvement possible. In all biofuel cases, an increased yield would also significantly decrease the acid emissions. This is particularly an issue in the ethanol case.

The vehicle emissions causing acidification comprise mainly of NO_X emissions, since the sulfur content in all fuels is very low. The conventional diesel engine has the highest NO_X emissions, hence also the highest acidification attributable to the vehicle. A catalyst or a particulate trap has little influence on the NO_X emissions. The EGR system can reduce the NO_X emissions by some 50 %. Methane has the lowest NO_X emissions of all fuels and, therefore, it has the lowest acidification potential.

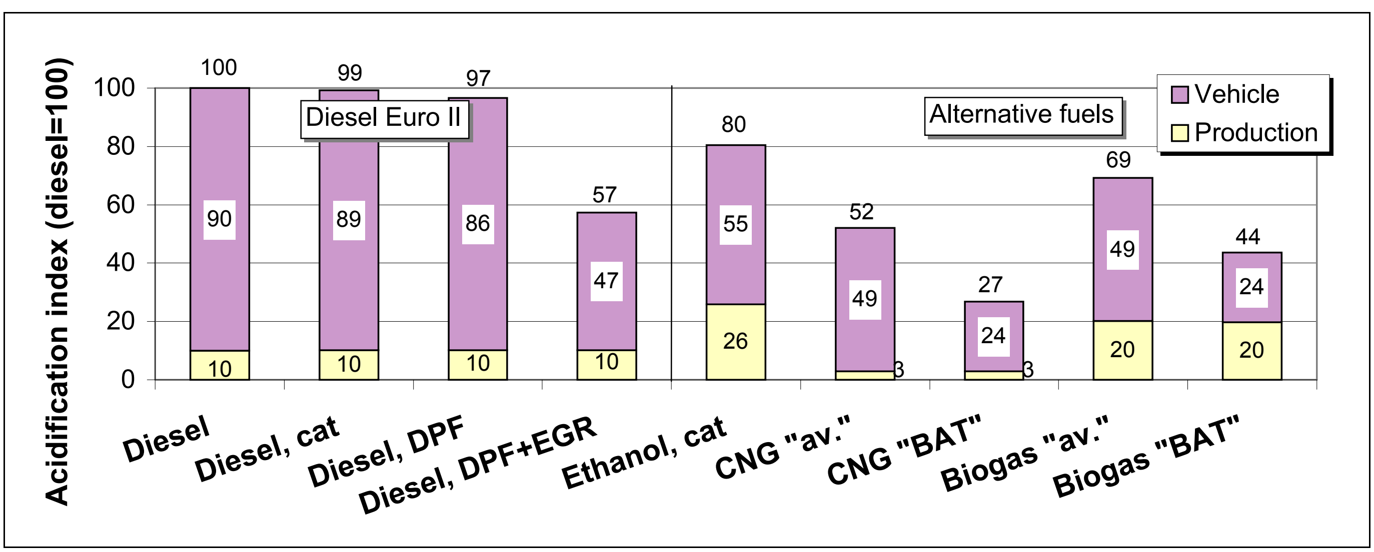

Figure 12. Acidification (buses)

Climate change

The results for the GHGs are shown in Figure 13. As in the previous case, regarding the acidification, CNG and biogas have been shown separately.

There is not much difference between the various diesel-fueled options. Using an oxidation catalyst and a particulate filter somewhat increases the exhaust backpressure, which increases the fuel consumption, and hence, the GHG emissions. On the other hand, the decrease in the emissions having higher GHG potential than CO_2 compensates for the former effect. Only the EGR-system shows a small decrease in GHG emissions due to a decrease of the NO_X emissions.

Ethanol has the lowest GHG emissions of all fuels. The cellulosic origin of the feedstock and the extensive use of biofuels in the production process are the reasons fore this favorable result. The ignition improver and the other blending components in the ethanol fuel are of fossil origin, which implies that there could still be a small improvement potential regarding the GHG emissions from the vehicle.

CNG has higher GHG emissions than diesel fuel both from fuel production and from the vehicle. The main reason for the difference in fuel production is the methane emissions. Methane has a lower carbon content than other fossil fuels and therefore, the higher GHG emissions from the vehicle might not be expected. SI engines generally have lower engine efficiency in comparison to CI engines. The difference is smallest at full load but increases at light load. Therefore, a driving cycle as the Braunschweig cycle always should give a greater difference in efficiency than an extreme high-load cycle as the ECE R49 cycle. The energy use of the best CNG alternative was 33 % higher than for the diesel engines. This eliminates the main advantage of the low-carbon methane fuel. There is also a great contribution from unburned methane and consequently, the total GHG emissions from CNG is higher than from diesel fuel. The increase in methane emissions is the main reason for the great difference between CNG “av.” and “BAT”.

The biogas options have somewhat higher GHG emissions than ethanol, although both are biofuels. The main concern in the fuel production cycle of biogas is the methane emissions. If the emissions of unburned fuel from the engine could be kept low, the contribution from the vehicle could also be lowered. The biogas fuel contains no fossil fuel components in contrast to the ethanol fuel.

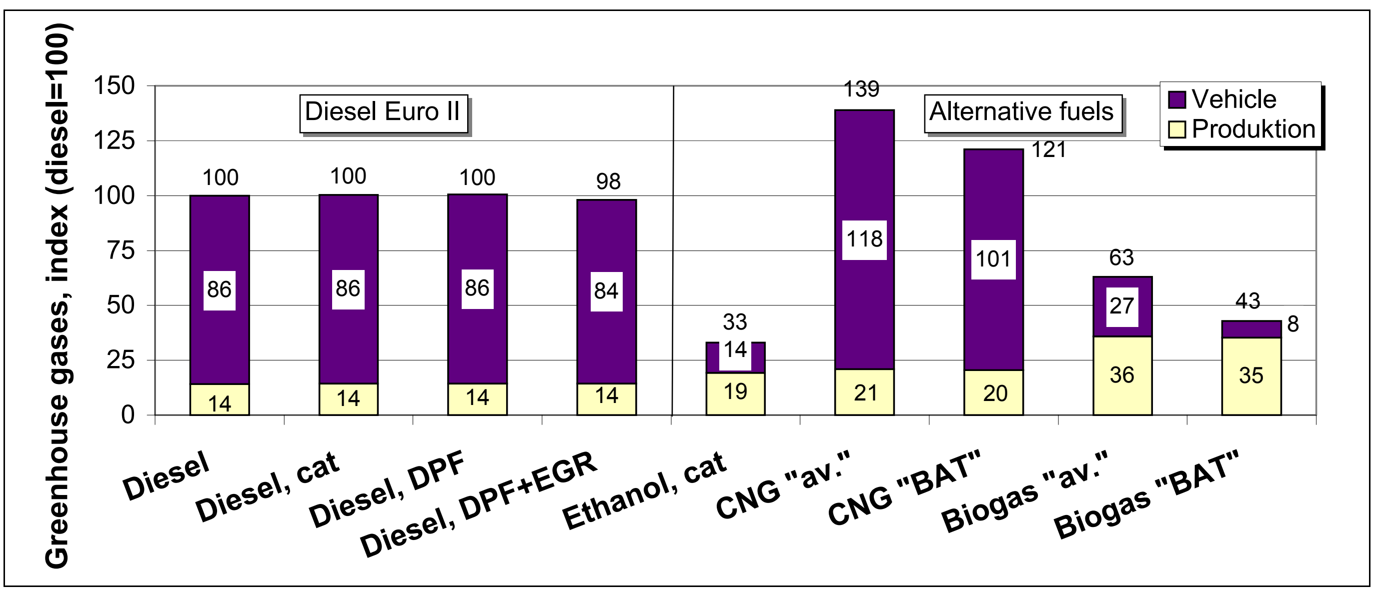

Figure 13. Greenhouse gases (GHG) (buses)

RESULTS – BUSES VS. CARS

Delimitation

First, it should be noted that the report [5] summarized here is considerably more extensive (70 pages) than this paper. Therefore, the summary in this paper might be somewhat too short to cover all aspects in sufficient detail. Consequently, only a selection of the most interesting results from the study mentioned is shown here.

Transport work

A comparison between emissions from cars and buses should be made using similar “transport work” (i.e. passenger-kilometers) for both cases. Since reliable data for an average on a national or regional level were not available, a case study was carried out instead.

Data from other studies on travel habits (bus and car) were used to establish the number of passengers for each vehicle category. From these data, four different cases were selected. First, a separation was made between daily average and travel to work. Second, two bus lines in Gothenburg, representing two different kinds of bus services were selected. The first line was “Line 64”, which is typical for driving from an area close to the city center to and from the downtown area. The other line “Green Express” is typical for a bus line to and from a suburb further away from the downtown area. This line has qualified for an environmental certificate from the Swedish Society for Nature Conservation (SNF), hence the name “Green Express”. The length of is 16 km for Line 64 and 64 km for Green Express. However, in both cases the distance from each terminal to the city center is approximately half of those distances, since the buses continue their trip to a similar terminal on the opposite side of the town. The average number of passengers for each category of vehicles is shown in Table 5.

It can be noted in Table 5 that the number of passengers is considerably higher for the Green Express in comparison to Line 64. The daily average is lower than during rush hours (work) in both cases. Passenger cars follow the opposite trend. Note that the daily average for line 64 is rather low but such numbers are often seen in Sweden. There were no data available to determine any difference in number of passengers for the cars travelling the same routes as the bus lines investigated.

Table 5. Average number of passengers

	No. of passengers	
Bus line / car	Daily average	Work
Line 64	15.0	20.2
Green Express	22.7	30.6
Passenger car[a]	1.92	1.39

Note:

[a] The figures for passenger cars include the driver.

Due to space limitations of this paper, only one case of the cases shown above is reported here. The case chosen is the daily average for Line 64. The other three alternatives are somewhat more favorable for the buses.

Corrections

Several corrections of the emission data were made to improve the comparisons. Driving pattern and cold start are two of the most important factors to take into consideration.

Emission deterioration

The methodology used for determining the emission deterioration was described earlier. No results from this evaluation are shown here due to space limitations.

Driving pattern

The fuel consumption was used as a parameter to assess whether the driving cycle was representative for the bus line to be evaluated. The fuel consumption for the buses at line 64 was 45 liters per 100 km. The range of fuel consumption for the various diesel bus alternatives tested according to the Braunschweig cycle was between 45.7 and 46 liter per 100 km. Due to the negligible difference in fuel consumption, no correction was made in this case (in contrary to the Green Express case). The average speed for Line 64 was 23.9 km/h, which is reasonably close to the average speed of 22.5 km/h in the Braunschweig cycle.

Cold start

As already mentioned in the methodology chapter, test data for cold start emissions at lower ambient temperatures were available for the passenger cars. The estimation of this effect was much more difficult for the buses, since there were very few data available in this case. Therefore, a calculation of the cold start impact was made using the simulation tool Advisor® from NREL. A validation of a simulation of a heavy-duty truck has been carried out by the author in a separate project for MTC [56]. An input menu of Advisor® is shown in Figure 14 as an example.

City buses in Sweden are generally only subjected to one cold start per day. Furthermore, this cold start is not particularly cold either, since some kind of heating device is generally used. An example of such a device is shown in Figure 15. In this case, the buses are supplied with hot water through a pipeline system[10]. The engine is heated to about 70°C with this system. Advisor® use no cold start correction above 75°C and consequently, the impact on engine emissions at 70°C is negligible. The important factor is the efficiency of the after-treatment devices. A temperature of +7°C, corresponding to the yearly average temperature in Sweden, was anticipated for the after-treatment devices, since the buses are mostly parked outside (the northern parts of Sweden is an exception in wintertime). It is also plausible to assume that

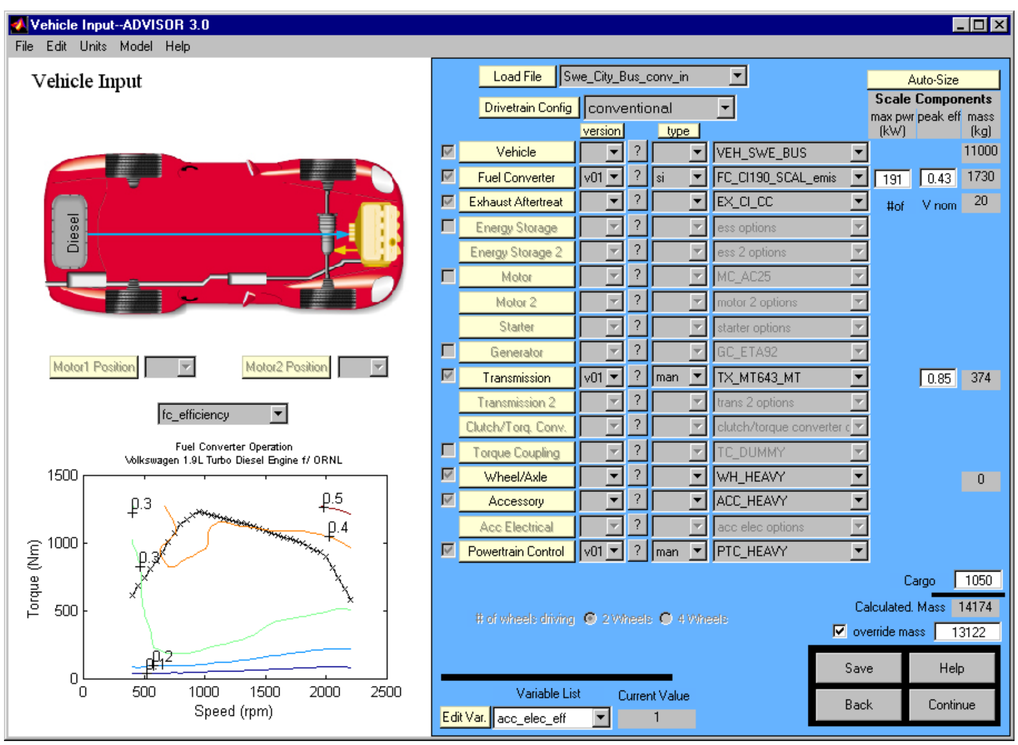

Figure 14. Input data menu for Advisor®

[10] Electric engine block heaters are used in some cases but the system shown is more common.

very little heat dissipates from the heated engine block to the aftertreatment devices during the preheating period.

Since emissions matrices from the particular bus engines evaluated were not available, a different approach was used instead. It was possible, by some adaptation of the available engine data, to obtain conversion efficiency for a *hot* Braunschweig cycle that was very close to the efficiency used in the previous study on city buses. A *cold* start Braunschweig cycle could then be simulated using the engine and aftertreatment temperatures mentioned earlier as "ambient" conditions. The somewhat lower conversion efficiency for the cold cycle was then used to estimate the cold start correction. A similar methodology was used for the impact of the stops, 4 and 7 minutes respectively, at the terminals at both ends of the line. The driver's instruction is to stop the engine at the terminal.

Figure 15. Preheating of buses

It could be anticipated that the impact of the cold start and terminal stop would be very small due to the long distance traveled per day for a city bus. This was also confirmed by the simulation since, for example, the CO and HC emissions increased by less than 1% (daily average) for the diesel engine with oxidation catalyst. However, if the engine would be left idling during the terminal stop – against the instructions – the impact on the emissions was considerable. When the engine is left idling, the aftertreatment device is cooled much faster than if the engine is shut off. This is due to that the exhaust temperature during idle is significantly lower than the light-off temperature of the catalyst. Consequently, the catalyst is cooled much faster if the engine is left idling. The impact on CO and HC emissions was 27% and 17% respectively in this case. However, since the driver should shut off the engine at the terminal stop, this impact was not taken into account.

Selection of results

Due to the space limitation, only a selection of the results from the bus and car comparison is shown. The results shown below are for the following emission components and effects:

- Ozone forming potential
- NO_X emissions
- Particulate emissions
- Cancer risk index

It should be noted that the car of model year 1993/1994 has been set as the reference level (gasoline = 100) for this comparison instead of the diesel bus, as in the former comparison. All the figures shown below are using the same transport work as the basis for the comparisons, i.e. emissions per passenger kilometer.

Ozone formation

The ozone forming potential is shown in Figure 16.

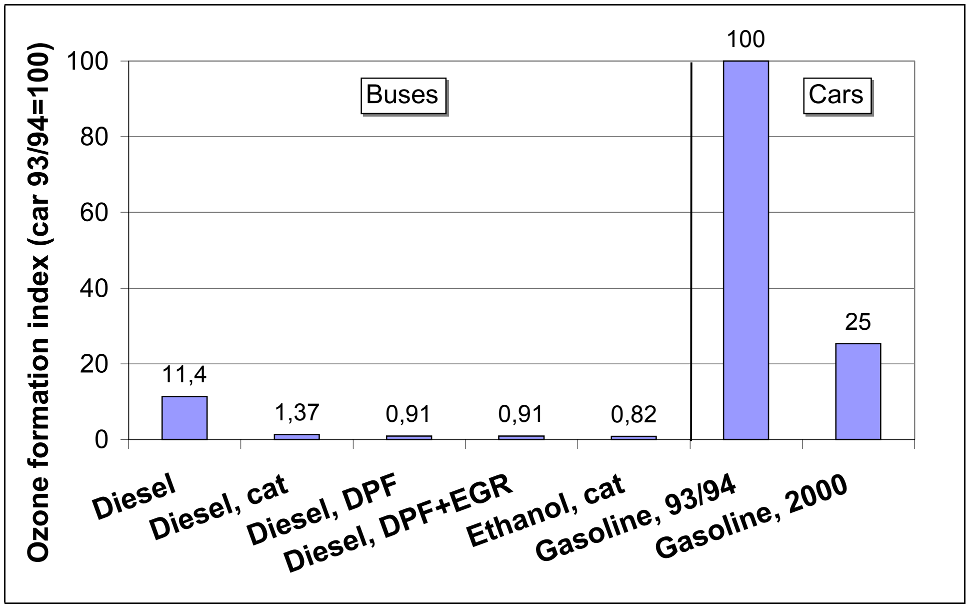

Figure 16. Ozone forming potential (buses vs. cars)

All bus options have a considerable advantage over the passenger cars in this respect. In general, buses have low HC emissions per vehicle kilometer. This advantage is further accentuated due to the "absence" of cold start effects and higher number of passengers in comparison to the cars. The impact of the cold start effect is also increased for the Line 64 (in comparison to the NEDC test cycle), since the trip length is so short in this case. The relatively low ozone forming potential of gasoline in comparison to diesel fuel cannot offset the mentioned effects.

NO_X emissions

As expected, the locally produced NO_X emissions are lower for the gasoline-fueled cars (Figure 17). The best bus option evaluated has about 50% higher level than the cars of model year 1993/1994. The improvement in this respect for the new cars is particularly remarkable and further reductions are feasible in the future. The greater number of passengers for the buses cannot compensate for the fact that the bus options evaluated do not have any catalytic reduction of the NO_X emissions, as in case with the cars. The reductions of NO_X emissions foreseen in future U.S. heavy-duty regulations are certainly necessary in view of the results shown here. Temperature does not have a significant impact on the NO_X emissions.

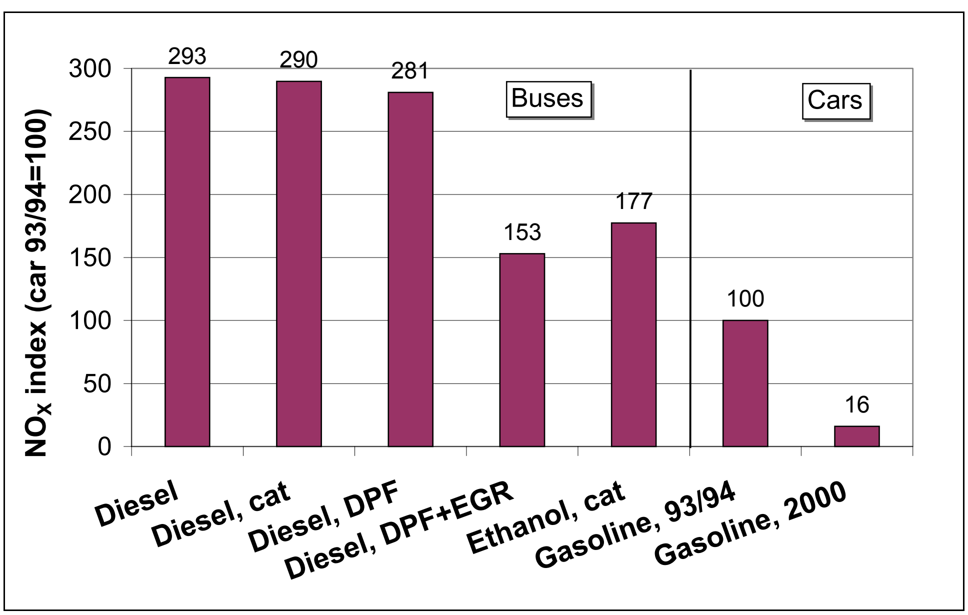

Figure 17. NO_X emissions (buses vs. cars)

Since the NO_X emissions are lower for the cars, they also have an advantage over the buses regarding the acidification (not shown here). However, this advantage is smaller due to the higher emissions in the fuel chain for gasoline compared to other fuels.

Particulate emissions

The results for the particulate emissions are shown in Figure 18. This is an emission component where an advantage for the gasoline-fueled cars might be expected. This is also the case when the comparison is made with diesel-fueled buses without a particulate trap. However, ethanol and the diesel options with a particulate trap have significantly lower particulate emissions than the gasoline-fueled cars.

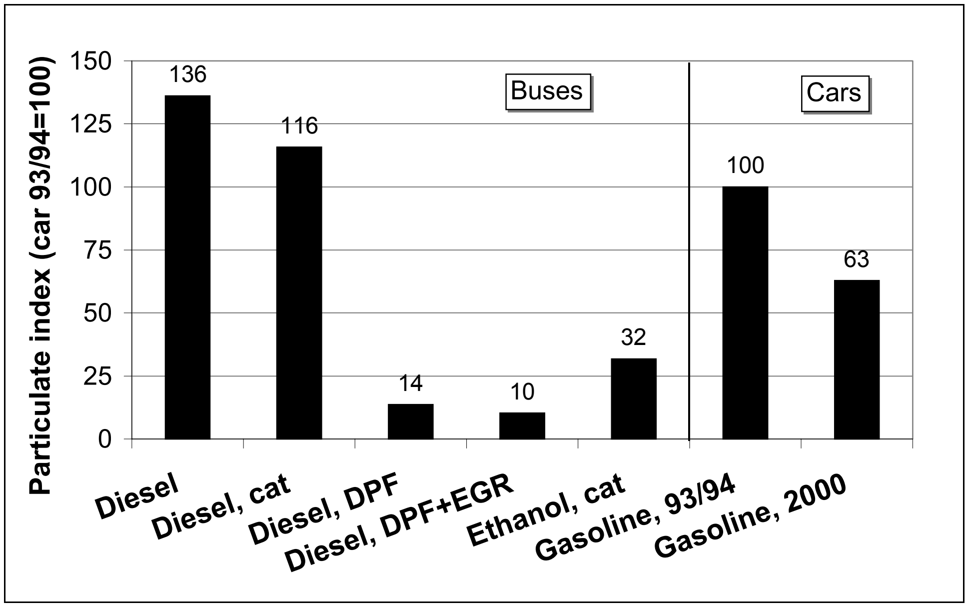

Figure 18. Particulate emissions (buses vs. cars)

The results for the particulate emissions need a more thorough explanation. It is known that the particulate emissions from gasoline-fueled cars are extremely low at ambient temperatures above +20°C. However, in the case evaluated here, the results are assessed for an average ambient temperature of +7°C. It has been shown that the particulate emissions for gasoline-fueled cars increase considerably at low ambient temperatures [57]. Consequently, the particulate emissions for the cars are higher at an average temperature of +7°C than at the "normal" test conditions. However, the results for a country with a hotter climate would be different from the results shown here. The limited data available on particulate size available do not indicate that the gasoline-fueled cars would have an advantage if the evaluation would consider the size distribution instead of the particle mass.

Cancer risk index

The cancer risk index has been evaluated in a similar way as before. These results are shown in Figure 19.

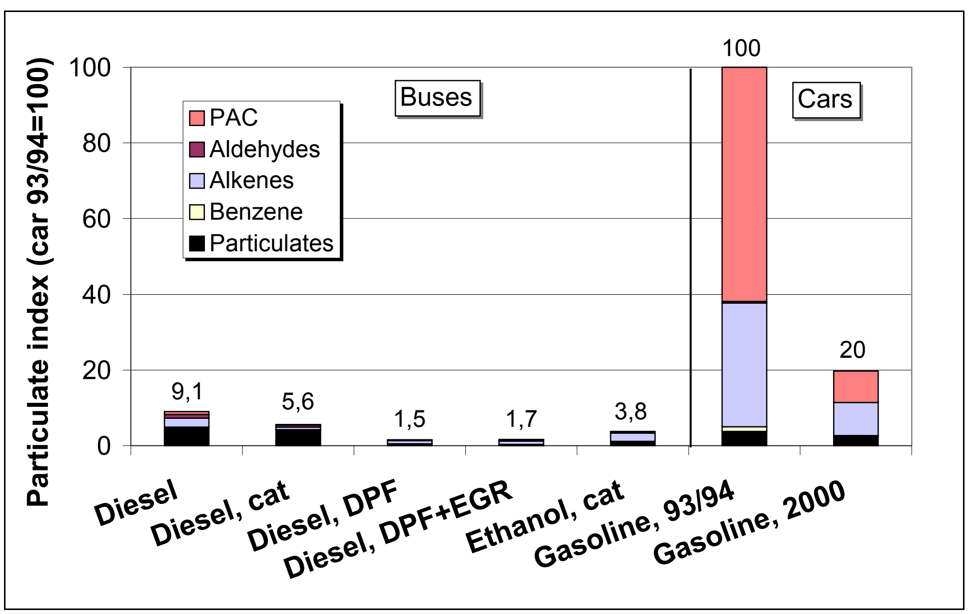

Figure 19. Cancer risk index, URFs by Törnqvist and Ehrenberg (buses vs. cars)

Figure 19 shows that the buses have a clear advantage over the gasoline-fueled passenger cars in this respect. The cancer risk index for the cars are dominated by PAC and the alkenes (primarily 1,3-butadiene). PAC emissions are generally low for gasoline-fueled passenger cars at ambient temperatures above +20°C. However, this is not the case at lower ambient temperatures, which has been shown in a previous paper by this author [58]. In that paper, it was shown that the PAC emissions during the first phase of the FTP-75 were very high at +5°C – some 50 times higher than comparable cars at +22°C. Reports published later have confirmed this trend.

In Figure 20, the results for the PAC emissions from three different cars are shown by using data from two recently published reports [59, 60]. Figure 20 shows the PAC emissions for two gasoline-fueled passenger cars and one diesel-fueled car at temperatures between –20 and +22°C. The Volvo car was certified to the Swedish Environmental Class 2 (C2, corresponding to U.S. 1994) and the Honda Civic was a Class 1 car (TLEV in California). The Golf diesel only met the Class 3 limits (U.S. 1987).

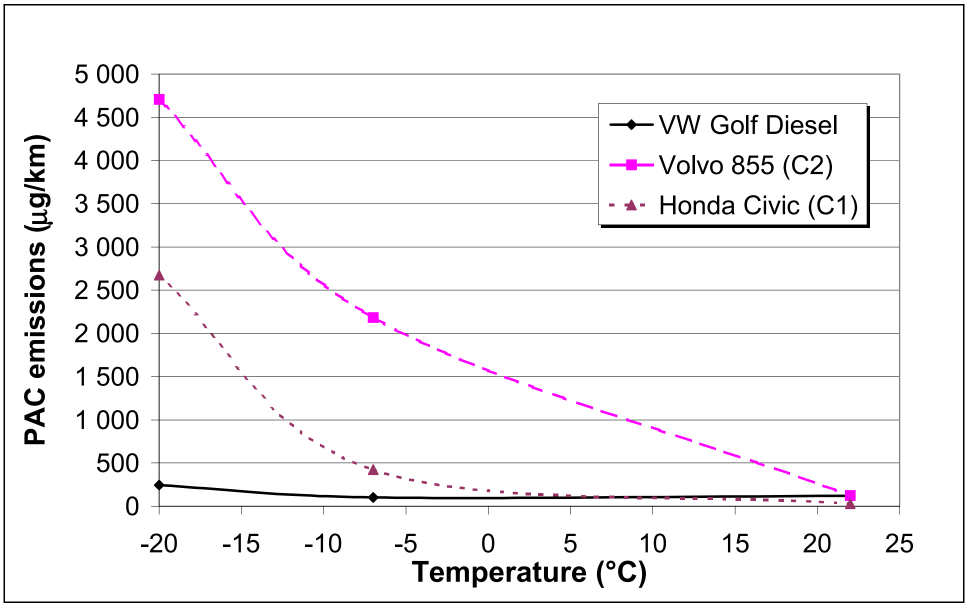

Figure 20. PAC emissions at various temperatures for three passenger cars

The results in Figure 20 clearly show that the PAC emissions for the gasoline-fueled cars increase considerably at low ambient temperatures. For example, the PAC emission levels (in µg per vehicle km) at the lowest temperature are more than two orders of magnitude higher than the best bus options evaluated. There is also a significant impact of new technology (TLEV). The PAC emissions for the diesel-fueled car are higher than the gasoline-fueled cars at +22°C but it is not affected as much by lower temperatures. It should be mentioned that additional data than those shown here have been used in the evaluation of PAC emissions from the cars.

Bearing in mind that the number of passengers is higher for the buses than for the cars – in addition to the cold start impact explained above – the results for cancer risk shown in Figure 19 are comprehensible. The results would be more favorable for the cars in a warmer climate.

Other effects not reported here

Besides the effects reported here, other effects were also evaluated. As expected, the buses showed a considerable advantage for climate gases and energy use. The advantage was not so clear for the aldehydes. In this case, only the diesel-fueled options with a particulate trap had a lower emission level than the model year 1993/1994 of the cars. The newest cars were on the same level as the best buses.

DISCUSSION

Diesel fuel quality and aftertreatment

In this study, Swedish EC1 diesel fuel was used as the reference, since this fuel represents the best available diesel fuel on the market. However, it is also of interest to elucidate some of the effects that could be obtained by using this improved fuel in contrast to the contemporary European fuel. The impact on the PAC emissions and the biological activity (in Ames and TCDD tests) are two of the main advantages of this fuel [8, 23]. One example of such results is the comparison of PAC emissions from a truck fueled with EC1 and EPEFE reference fuel reported by Grägg [21]. The same test cycle and analysis of PAC as previously described was used in this study. The results are shown in Figure 21, where the total PAC emissions are shown (sum of particulate associated and semivolatile PAC). Furthermore, the impact on 1-nitropyrene, a very potent carcinogen, is also shown.

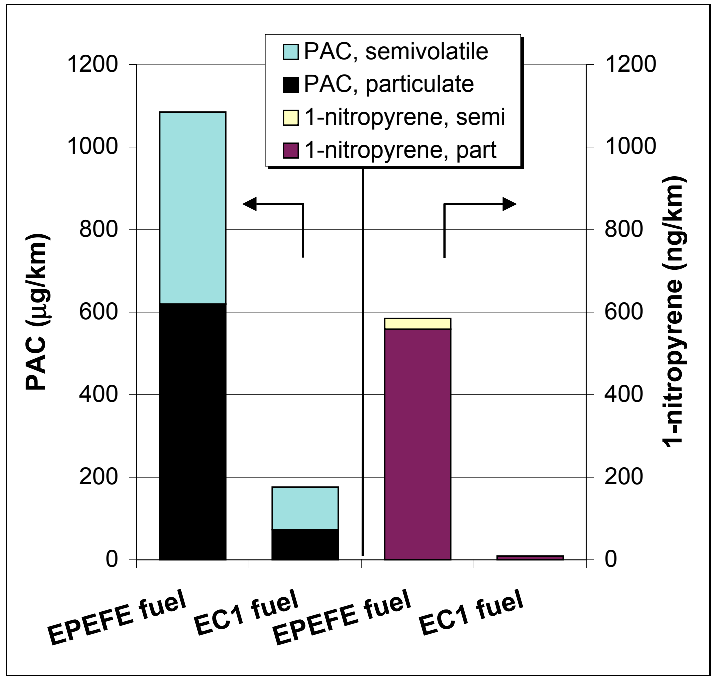

Figure 21. PAC and 1-nitropyrene emissions from two different diesel fuels qualities (HD truck)

The results in Figure 21 show that the EC1 fuel has a significant impact on the PAC emissions (84 % reduction). The impact on the 1-nitropyrene emissions is even more remarkable (i.e., a 99,5 % reduction).

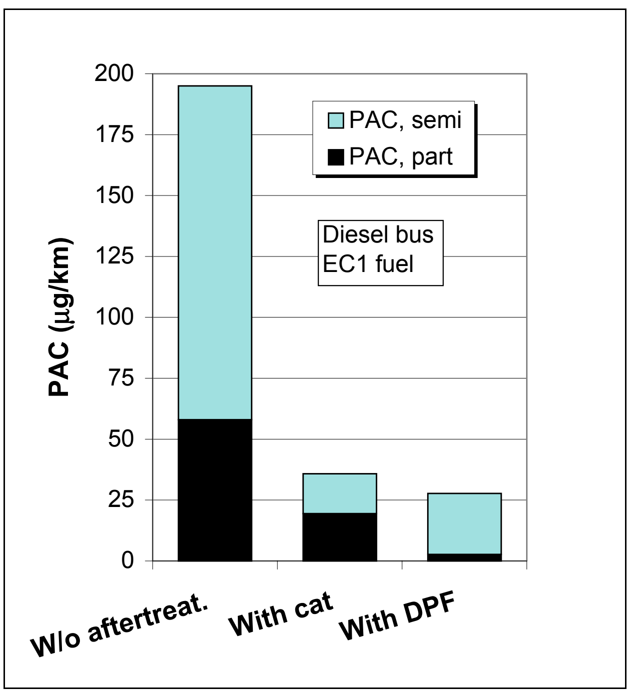

Figure 22. PAC emissions without after-treatment, with catalyst and with particulate filter (EC1 fuel)

An example of the impact from aftertreatment devices is shown in Figure 22 [18, 19]. The results have been generated on a city bus engine and, therefore, these results should not be directly compared with the former results. By coincidence, however, the level without a catalyst is very close to the level with EC1 fuel in the former Figure.

As can be seen in Figure 22, both the oxidation catalyst and the DPF significantly reduce the PAC emissions (82 and 86 % respectively). An interesting observation is that the considerable reduction of the particulate emissions by using the particulate filter seems to shift most of the PAC emissions to the semivolatile phase. In comparison to the results in Figure 21 with EPEFE fuel, a total reduction of PAC by up to 98 % seems possible by reformulating the fuel and using aftertreatment devices.

Ethanol

One of the principal problems of the contemporary ethanol-fueled diesel engines is that the HC emissions (by FID) are about two times higher than for diesel fuel. Bearing in mind that the FID-response for ethanol is lower than for diesel fuel, the level of total unburned organic components are even higher. Another indication that there are some fundamental problems with the combustion system of the ethanol engines is that the CO emissions (before catalyst) are significantly higher than for diesel fuel. Due to the lower energy content of the ethanol fuel, the fueling has to be increased in comparison to diesel fuel. This is usually achieved through increasing the nozzle hole size. In comparison to the diesel-fueled engine, this should lead to severe wall wetting, a problem that generally causes high smoke and particulate emissions in a diesel-fueled engine. Since ethanol generates little or no soot emissions, this potential combustion problem is not easily recognized. However, the higher levels of organic components in the exhaust gives a clue to that an improvement in this area also could improve the result for several of the effects investigated in this study. In summary, the ethanol-fueled diesel engine has not yet reached the same technical level as the diesel-fueled diesel engine in this respect.

It should be noted that an EGR system is more easily applicable on an ethanol engine than on a diesel-fueled engine. Results in this area have been very promising [35, 36]. It is likely that the impact of an EGR system could be greater with ethanol than with diesel fuel. The reason why this option has not been shown is that it is presently not commercial. A research program at the Luleå Technical University was started this year to investigate the impact of EGR and a particulate trap on an ethanol-fueled engine.

Methane

One of the findings in this study regarding the methane-fueled engines is that the air-fuel control in its present state (i.e. without feedback control), is not satisfactory. In this investigation, methane engines have been assumed to be of the lean-burn type. There are several reasons why this strategy has been preferred over the TWC system. Thermal stress and specific output are probably two of the most important factors. However, the current open-loop control system for the lean-burn engines has to be considerably improved to utilize the full potential of this option. If the engine runs too lean, the unburned THC/NMHC emissions are high and if the engine runs too rich, the NO_X emissions are high. On average, this increases both these emission components in relation to the potential, since the contemporary control system is not perfect. It should also be recognized that it is likely that a TWC engine could have significantly lower emissions than a lean-burn engine. An alternative development route to the lean-burn engine would be to try to solve the problems associated with the TWC technology.

Technology neutral comparisons

In the introduction section, the importance of technology neutral comparisons was pointed out. However, the comparisons made in the results section have shown all alternatives regardless if the comparison is neutral or not. Therefore, the basis for neutral comparisons needs to be discussed. First, a catalyst is, or will be, used on every new low-emission concept. Second, it is also likely that a particulate trap will be used on future low-emission diesel fuel fueled engines, unless a radical combustion system is developed that avoids soot formation. Particulate traps have not yet been discussed for alternatively fueled engines. However, if it will be verified that the emissions of nanoparticles (i.e. smaller than 50 nm) from these engines are on the same level as for diesel-fueled engines, then traps could be of interest also for these engines. Some findings in the literature have already indicated that this is the case [61, 62], but more research is needed to verify these findings. For the time being, the most technology neutral comparison is to compare engines using a catalyst. In the future, a particulate trap might be considered. Another way of comparing the various alternatives would be to make a rating according to the cost-effectiveness of reducing the emissions. A comparison according to this criterion would probably be the most relevant comparison but this evaluation was beyond the scope of this investigation.

FUTURE IMPROVEMENT POTENTIAL

Buses

There are many routes of possible short to medium-term improvements for the different bus options discussed in this paper. Some of them are discussed below.

EGR on diesel and ethanol

The impact of EGR on a diesel-fueled engine has previously been shown. Since EGR is still in its infancy for heavy-duty CI engines, it is likely that this technology has further development potential (temperature-controlled EGR, etc.). The results shown on the previously mentioned EGR system has showed that the system could decrease the NO_X emissions for an Euro II engine to the Euro IV level. It is likely that *at least* the same *relative* improvement in NO_X emissions could be obtained using EGR on an ethanol-fueled engine. The potential for EGR is far smaller on a lean-burn methane-fueled engine. The reason for this behavior is that the introduction of EGR decreases the possible dilution by air. Thus, the NO_X emissions will remain almost unchanged on a steady-state engine operating point. There could be some benefit of EGR in a transient driving cycle, since the air-fuel ratio is drastically reduced under some operating conditions, leading to high NO_X emissions. However, it should be realized that the problems of air-fuel control by introducing EGR would be even higher than for the contemporary engines.

Nozzle tip improvements on diesel and ethanol

A great improvement potential not often realized for diesel engines, whether fueled with diesel fuel or ethanol, would be the reduction of the HC emissions by reducing or eliminating the nozzle sac volume. This has been known for more than two decades [63]. The HC results in a report by Hedbom for a prototype Euro II diesel engine equipped with this technology showed HC emissions one order of magnitude lower than the data used in this study [22].

A recalculation of the data for NMHC emissions from the buses according to the new European Transient Cycle (ETC) using conversion factors derived from test results has been carried out to show the mentioned potential. These results are shown in Figure 23 along with the engine dynamometer test data in the ETC cycle from the previously mentioned report.

Although the data for the engine in Figure 23 were obtained without catalytic aftertreatment, NMHC emissions are on approximately the same level as diesel with catalyst and particulate trap. It is conceivable that the nozzle tip geometry (VCO nozzle) contributes most to the reduction of the HC/NMHC emissions but the combustion system and specific power (BMEP) of the engine do contribute as well.

Some European engine manufacturers have reduced the sac volume (mini-sac) somewhat during the last decade in comparison to the engines evaluated in this report (sac volume about 1 mm^3). However, the application of sacless nozzles on heavy-duty engines in Europe is certainly not as widespread as in the USA. Consequently, there still is a great improvement potential in this area.

By using a DPF on the previously mentioned engine, the HC levels were reduced to the same level as the background air (in spite of that this air is very clean at the emission laboratory site) [63]. It should be noted that there were several other technical features on this engine in comparison to the engines used as the base level here, but none of these changes presents any real technical problems to implement. Recent test data generated in other projects, such as e.g. the field test on low-sulfur diesel fuel and particulate traps in California 64, confirm that such extremely low HC and NMHC levels can be achieved also under real operating conditions.

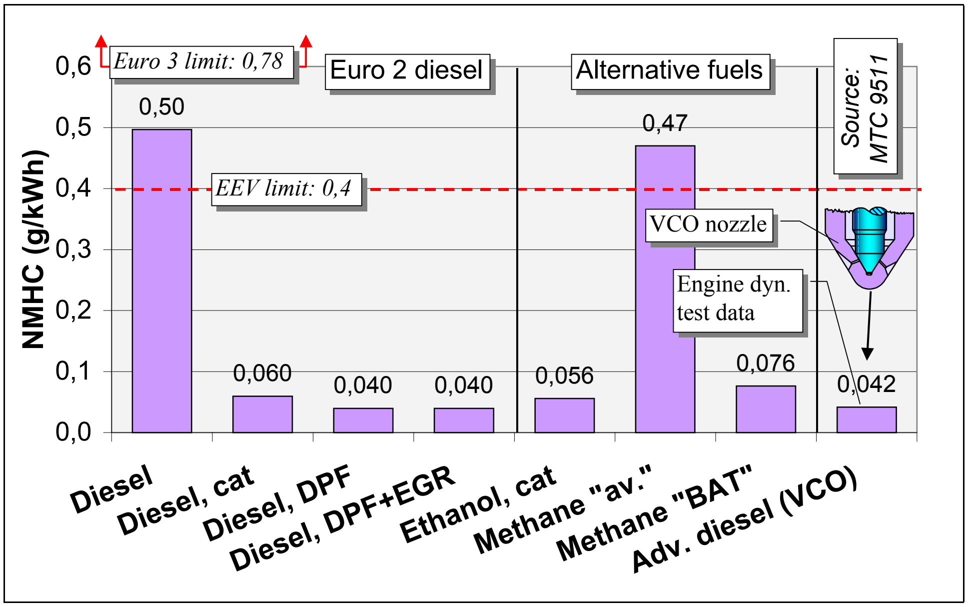

Figure 23. Impact of advanced technology on NMHC emissions (calculated data & test data)

A corresponding relative improvement of the level of unburned organic components as the diesel-fueled engine described above could also be expected on an ethanol-fueled engine, on the condition that the previously discussed problem of wall-wetting could be solved simultaneously.

Alcohol engines

The ethanol engines used in Sweden have so far used ignition improvers. The high cost (and fossil origin) of these components necessitates further development in this area. Solutions that do not rely on ignition improvers (e.g. glow plugs, spark plugs, etc.) also need to be investigated further.

Methanol has not been investigated in this study since there are no vehicles in operation using this fuel in Sweden. The renewed interest in methanol as a fuel for fuel cell vehicles also raises the question whether methanol should not be investigated for the use in heavy-duty CI engines as well.

Methane-fueled engines

The greatest short-term improvement potential for lean-burn methane engines would be to introduce and optimize a feedback control of the air-fuel ratio. Such systems have already been commercialized. This technology could decrease both the NO_X and the THC/NMHC emissions. It should also be noted that gaseous-fueled engines for the Swedish market (presumably) have been optimized for the ECE R49 cycle and not for transient operation (such as the Braunschweig cycle). Data from both test cycles is an indication that this has been the chosen strategy [38]. Further decrease of the crevice volumes around the combustion chamber and minimizing the valve overlap could also reduce the engine-out THC/NMHC emissions. A great development potential also lies in the optimization of the catalyst. In the future, with ever tightening emission regulations, it is likely that an advanced TWC system will be of considerable interest for methane engines. The drawback of TWC operation is an increase in fuel consumption and GHG emissions.

Utilization of the development potential on buses

In summarizing the development potential, it could be mentioned that if all technologically feasible measures were taken (regardless of fuel used) the impact of heavy-duty engines on environment and health could be considerably reduced.

Gasoline fueled cars

Since this paper does not focus on the development potential of passenger cars, this is not reported here. However, the conclusion on these vehicles would be the same as for the buses, i.e. there is still a great development potential not yet utilized. Since the cold start emissions at low ambient temperatures have a significant impact on the results, other methods than the conventional improvements of air-fuel preparation and aftertreatment devices could be considered as well. For example, systems that preheat the engine (e.g. a heat store) have been shown to have a significant impact on the cold start emissions.

SUMMARY AND CONCLUSIONS

Buses

An evaluation of several effects on environment and health has been carried out for city buses. The aim was to provide an overview of the relative impact from different engine/fuel combinations. The emissions according to the Braunschweig driving cycle was used as input data for the calculation of the effects. The methodology used in the calculations was intentionally simplistic. Diesel engine and Swedish EC1 fuel quality was the engine/fuel combination for the base case. The influences of aftertreatment devices (catalyst and DPF) are reported separately for the diesel fuel case. Ethanol and methane were the alternative fuels investigated. In summary, the findings in this paper are:

- Ozone formation is highest for diesel fuel without catalyst but the use of a catalyst or a particulate trap reduces ozone to essentially the same level as for ethanol or methane.
- NO_X emissions are highest for diesel fuel, lowest for methane and ethanol is in between. The use of EGR on a diesel-fueled engine reduces the NO_X emissions by about 50 %, but this technology could also be implemented on ethanol engines with similar results. The high share of NO_2 emissions for some aftertreatment concepts should be addressed.
- Particulate emissions are highest for diesel fuel and a particulate trap is the only contemporary available technology to decrease these emissions. Methane and diesel fuel with DPF have the lowest particulate emissions. Ethanol has a somewhat higher level.
- The aldehyde emissions are highest for the ethanol engine due to the high emissions of acetaldehyde. The oxidation catalyst has a lower activity on the aldehydes than on the HC emissions. Diesel fuel with a particulate trap has the lowest aldehyde emissions and methane is somewhat higher in this respect.
- The cancer risk index is highest for diesel fuel without aftertreatment. A catalyst reduces the impact of the volatile components but the contribution from the particulate emissions is not influenced very much. Ethanol and methane have lower cancer risk index than a diesel engine with oxidation catalyst. The lowest level is achieved with diesel fuel and a particulate filter.
- The evaluation of the cancer risk with other unit risk factors than those by Törnqvist and Ehrenberg showed relatively similar results for the older EPA unit risk factors. The results with the OEHHA factors and variations of these factors changed the results somewhat in favor of the alternative fuels although the difference between the best options was small. The results generated using various unit risk factors clearly have highlighted the need for more work in this area.

- Acidification is dominated by NO_X emissions from the engine for the fossil fuels, due to the low sulfur level in the fuel. Diesel fuel is highest and CNG is lowest in this respect. Diesel fuel with EGR and ethanol fuel is in between. Biogas has considerably higher emissions of acid components in the fuel production than CNG.
- The greenhouse gases (GHG) are on a similar level for all diesel fuel options. CNG has higher GHG emissions than diesel fuel, mainly due to lower engine efficiency and higher methane emissions. Biogas has lower total GHG emissions than diesel fuel and CNG but is somewhat hampered by the high methane emissions in the fuel production chain. Ethanol (being a biofuel) has the lowest GHG emissions of all fuels.
- Swedish EC1 diesel fuel considerably reduces the PAC and 1-nitropyrene emissions in comparison to current European diesel fuel. This should be taken into consideration in future diesel fuel specifications.
- The unburned organic components are higher from ethanol than from diesel fuel and this is a potential development area for the ethanol engines.
- The open-loop air-fuel control system used on contemporary methane engines must to be improved to utilize the full potential of this concept.
- Several areas of future improvements of the engine/fuel options investigated have been identified.

Buses vs. gasoline-fueled cars

The comparison between buses and cars showed that corrections must be introduced to properly compare the results of the two vehicle categories. Besides the number of passengers, driving pattern and cold start effects are two of the most important factors to consider. The latter factor is particularly important in cold climate conditions. The most important findings are:

- The Braunschweig cycle can be used to represent city driving of a bus in Swedish cities.
- Cold start effects on the buses could only be calculated using a simulation tool due to lack of experimental data. Cold start effects were negligible on the buses due to preheating of the engine and the long distance traveled per cold start.
- Idling of the buses at terminals could significantly increase CO, HC and particulate emissions for buses with aftertreatment devices. The driver's instructions are to avoid such idling and if this is done, the terminal stop has a negligible impact on the emissions.
- Ozone formation is a clear advantage for the buses.
- Contrary to some expectations, the particulate emissions are not much higher for diesel buses without particulate traps in comparison to gasoline-fueled cars. This is due to the increase in particulate emissions from the cars at low ambient temperatures. Diesel buses with traps and ethanol had a significant advantage over the cars.
- NO_X emissions are considerably higher for the buses than for the cars. Improvement in this area for the buses is certainly necessary.
- The cancer risk index showed a considerable advantage for the buses. Low PAC and 1,3-butadiene emissions due to the "absence" of cold start effects for the buses is the primary explanation for these results.
- The buses showed a clear advantage for the climate gases and energy use, whereas the results were not as clear for the aldehyde emissions.
- The results would have been more favorable for the cars if the evaluation had been carried out for a hot climate.

Overall conclusions

Overall conclusions drawn are:

- The analysis showed considerable improvements by reformulation of the diesel fuel and by fitting aftertreatment devices. Swedish EC1 fuel has a very low PAH content, which reduces the PAC emissions in the exhaust and, therefore, the cancer risk. This fuel is also required by several types of aftertreatment devices. DPF in combination with EGR has also a considerable impact on the evaluated effects.
- Some of the alternative fuels have a positive impact regarding several of the effects investigated, such as acidification. In other cases (e.g. ozone forming potential), the difference between the best options is small.
- The comparison between gasoline fueled cars and buses showed an environmental and health advantage for the buses in all aspects but NO_X emissions and acidification. The significant impact of cold starts on cars was the major cause of the outcome of this comparison.
- It is expected that continuing development of engines and aftertreatment devices will diminish the advantage of the alternative fuels regarding many of the effects investigated here.
- The impact on the GHG emissions from some biofuel options will be more pronounced in the future and this problem can only be solved by switching to a biofuel.

In the past, municipalities and bus operators usually have purchased low-emission vehicles by fuel type or (in best case) on demands specified for regulated emissions. However, they now look for specific effects as their intentions are to improve the air quality (priority can vary between locations). Therefore, an approach involving the calculation of effects would provide much more information for the selection of fuel, engine and aftertreatment options. This approach already has been introduced, to some extent, by the Traffic Office in Gothenburg. Our work has shown that a general overall comparison of this kind could be rather simple, provided that emission data are available. It is proposed that the methodology used here should be further developed and that more emission data are added when they are made available.

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