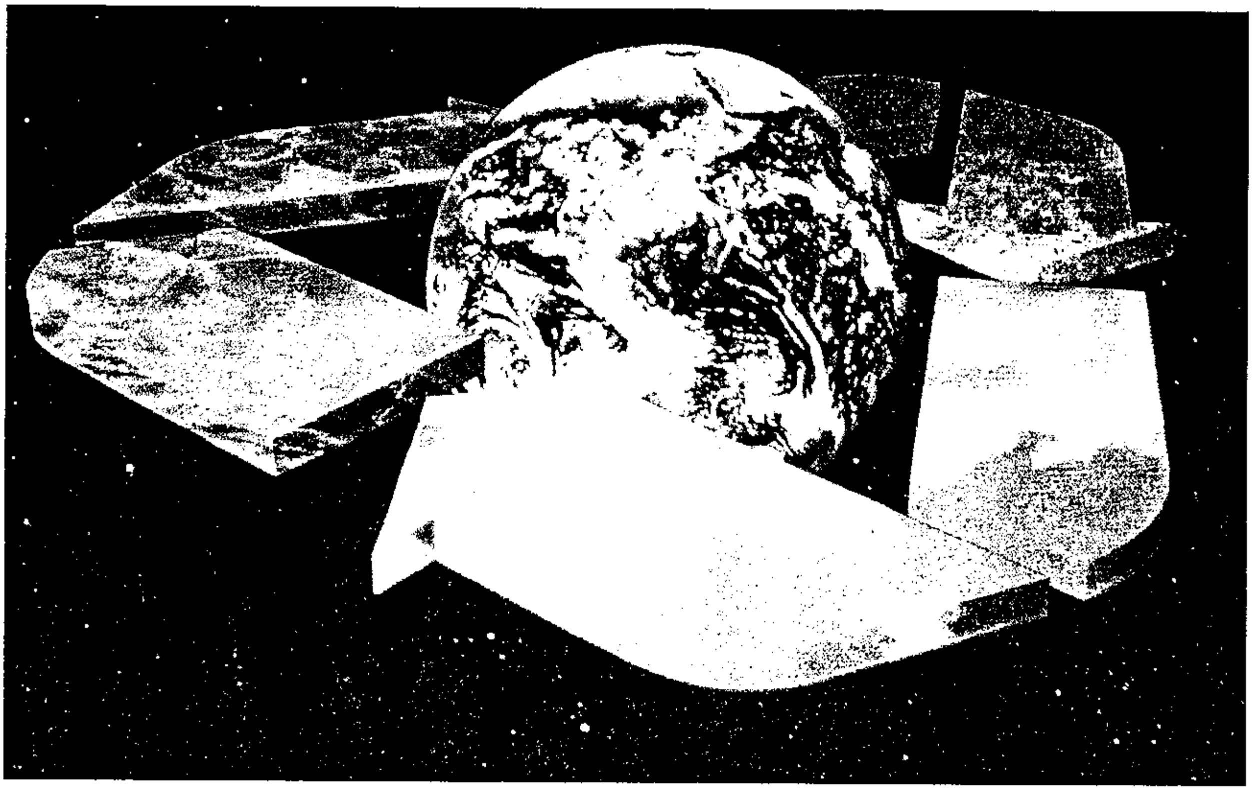
Ecotraffic

RESEARCH & DEVELOPMENT AB

CONSULTANTS IN ENVIRONMENT,
MOTOR FUELS AND TRANSPORTATION



CANCER RISK RANKING OF HD VEHICLES

Comparison between diesel fuel and CNG using different unit risk factors

Ecotraffic

E-mail eco@ecotraffic.se

Ecotraffic R&D AB

Karlavägen 18 • Box 5671 • S-114 86 Stockholm • Phone +46-8-614 50 56 • Fax +46-8-614 50 08
Ecotraffic Norge AS • P.O. Box 1404 Vika • N-0115 Oslo, Norway • Phone +47-23 11 47 40 • Fax +47-23 11 47 41

lingskapaciteten genom hydrering och svavelutvinning har byggts ut vid alla raffinaderier. De framtida kraven torde dock leda till att ytterligare avsvavlingskapacitet behövs och detta kommer sannolikt i sin tur leda till att mer väte behöver produceras än vad som kan erhållas från reformeringssteget. I första hand kan då etan i raffinaderigaser och butan tas i anspråk. Alternativt kan förgasning av vakuumrestolja vara källa för väteframställning.

En osäker faktor är vilket krav på högsta aromathalt [illegible] att ställas i framtiden.

4 Förändring av råoljor och raffinaderistruktur

CANCER RISK RANKING OF HD VEHICLES

Comparison between different fuels and unit risk factors

Memorandum for BP Amoco

Ecotraffic ERD^3 AB

Peter Ahlvik
Åke Brandberg

August 2000

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Fel! Hittar inga figurförteckningsposter.

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1 INTRODUCTION AND BACKGROUND

Some 15 years ago, the focus on the emissions from diesel vehicles, heavy-duty vehicles in particular, started to increase in Sweden. The role of fuel formulation was identified as an important factor. Not only the sulfur content of the fuel was of interest, but also other fuel properties that could have an impact on some harmful unregulated emission components was of interest. For example, the Swedish EPA (SEPA) set a target of reducing the cancer risk from vehicle exhaust by 90%. The role of sulfur regarding the ability to use aftertreatment devices was also identified early on in this process (although the aftertreatment devices were at a very early stage of development at that time). Emission testing was carried out at the emission laboratory of the SEPA in Studsvik[1] and by the motor and oil industry. These tests finally led to the introduction of reformulated diesel fuel in Sweden almost a decade ago according to a classification system by the SEPA. 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 the extensive test series mentioned above.

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 EC 2 is somewhat in between. 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 US 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.

Emission tests on diesel fueled vehicles, with and without aftertreatment devices, have also been carried out after the introduction of the reformulated fuels. Extensive tests on alternative fuels have also been carried out in order to quantify the impact of these fuels in comparison to the conventional fuels. Already some 10 years ago it was quite clear that reformulated diesel fuel and the use of aftertreatment devices could significantly reduce the harmful emissions. A glance at the results from the alternative fuels tested at that time also showed that the benefit of these fuels in this respect was somewhat questionable regarding several unregulated emission components (although one should note that an advantage in NO_X and greenhouse gas emissions for the biofuels still was clear). However, this information has not been passed on to the public in Sweden and it has not even been fully recognized by the scientific community. The reason for this might be twofold. First, no summary and evaluation has been made of all the test results generated during the last decade in an attempt to compare all the results on a neutral basis. Second, the comparisons that have been made often have compared diesel vehicles *without aftertreatment* with alternatively fueled vehicles *with aftertreatment*. In some cases, "ordinary" diesel fuel (of EU

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[1] This lab was later taken over by the Swedish Motor Vehicle Inspection Co. and moved to another location (Haninge outside Stockholm) in new facilities. An agreement for contract research with funding from SEPA was signed between these two parties and the department "Motortestcenter" of the Swedish Motor Vehicle Inspection Co. carried out the actual research work. Later this department was organized as an independent subsidiary under the name MTC AB.

specification) – and not the "best available" EC1 fuel – has been used in these comparisons. The SAE Paper that the authors of this memorandum presented at the SAE Fuel & Lube Meeting in Paris is taking care of these two issues [1][2]. Whether the results from this paper also could be applied to the situation in California (using e.g. correction factors, etc.) is an issue that is beyond the scope of this memorandum but some comments will nevertheless be made to highlight some issues of interest in this respect.

After the presentation of the SAE Paper mentioned above, Ecotraffic has been commissioned by BP/Amoco/ARCO to carry out the evaluation that has been summarized in this memorandum. The work carried out comprise some calculations using various unit risk factors for cancer, a summary of the methodology for sampling and analysis of unregulated emissions and the compilation of information in order to provide some more insight about the fuel qualities tested in various Swedish project.

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[2] Numbers in brackets designate references at the end of the memorandum.

2 METHODOLOGY

2.1 Testing, sampling and analysis

The emission test results that have been used in the evaluation of the health effects in the SAE Paper [1] by the authors of this memorandum all originate from the same emission test laboratory. This is the emission lab of MTC (formerly Motortestcenter, a department of the Swedish Motor Vehicle Inspection Co.). Some of the tests referred described later in this memorandum have been carried out at Volvo Truck Co. [4] and some were generated at the emission test facilities of SEPA [5]. Since the results in the references mentioned later [4 and 5] were generated on older engines (pre 1990), they have not been used in the evaluation in the SAE Paper by these authors [1]. However, regarding the effects of fuel properties and the possible parallels to the improvement that could be expected by the ARCO fuel, these reports are of great interest.

It should be pointed out that all the test results used in the evaluation in the mentioned SAE Paper have been generated on a chassis dynamometer using the Braunschweig city bus cycle. This test cycle is shown in Figure 1 below.

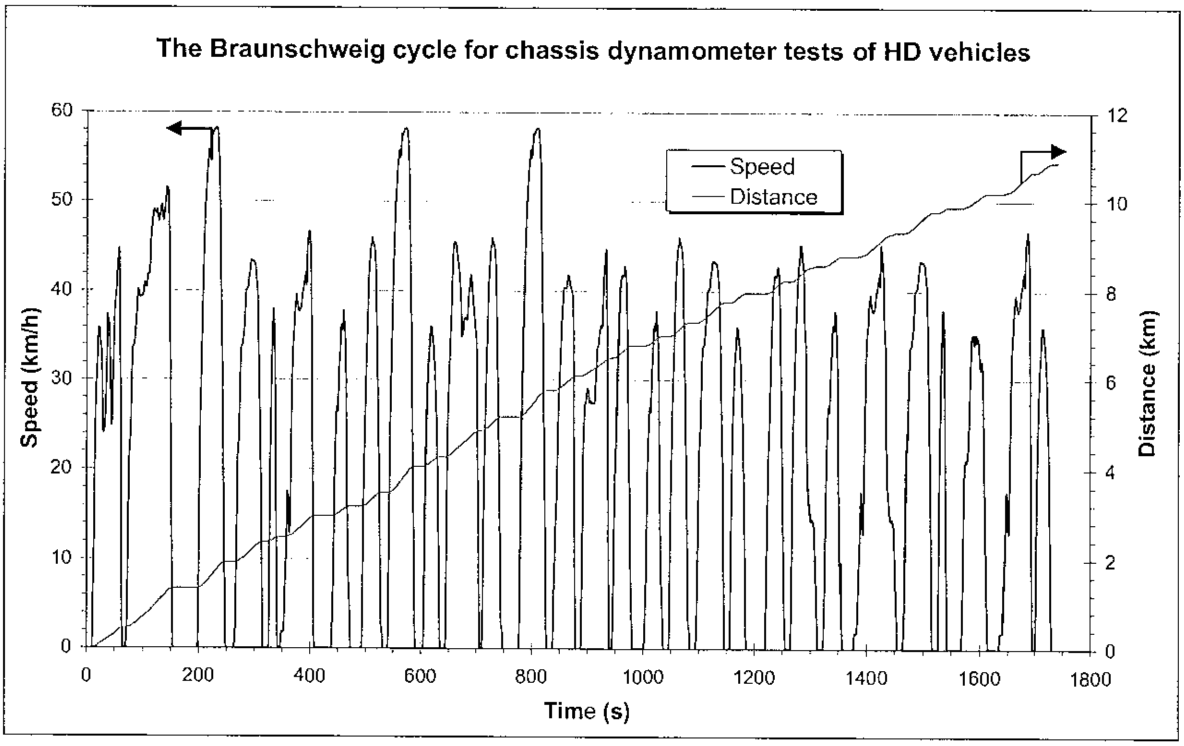

Figure 1: The Braunschweig city bus driving cycle

As can be seen in Figure 1, the Braunschweig cycle is of the transient type and it is characterised by frequent stops and subsequent accelerations. The test cycle is intended to represent city driving much better than the steady-state ECE R49 13-Mode driving cycle used until now in Europe[3]. Many other alternative chassis dynamometer test cycles are also available (such as the CBD cycle frequently used in the USA), but the most comprehensive emission data in Sweden (unregulated emissions in particular) have been generated using this driving cycle. Therefore, the choice of test cycle was obvious. All tests on the chassis dynamometer have been performed using the same vehicle inertia (approx. 13 metric tons) and other settings of the chassis dynamometer since all the buses tested have been of a similar size and load capacity.

The sampling of the emissions have been carried out in the diluted exhaust from a full-flow dilution tunnel similar to the specification for engine dynamometer tests in Federal Register and the EU directives). For PAC analysis and biological testing (i.e. Ames and TCDD receptor affinity), sampling filters with a diameter much larger (> 200 mm) than the normal 70 mm have been used in order to increase the sampling volume. Sampling of the semivolatile phase has been carried out using polyurethane foam plug (PUF) in series with the particulate filter. The sampling and testing procedures have been described in more detail elsewhere, (e.g. in Westerholm and Egebäck [5]).

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[3] It is replaced by the new 13-Mode European Steady-state Cycle (ESC) and the European Transient Cycle (ETC).

3 CANCER RISK RANKINGS

3.1 Unit risk factors derived from Törnqvist and Ehrenberg

The relative cancer risk estimations in our recent SAE Paper have been made with unit risk factors (URF) used by the Swedish researchers Törnqvist and Ehrenberg as basis for estimates of cancer cases in Sweden caused by polluted air [2]. Some reconsiderations have been discussed later but no alteration was done. There are no official URFs in Swedish regulations.

3.1.1 Particulate matter (PM)

The URF of $7\cdot10^{-5}$ (individual lifetime, 70 years, risk of cancer death at exposure of 1 $\mu g/m^3$) is the same as used by US EPA.

3.1.2 Benzene

The URF of $0.8\cdot10^{-5}$ is the same as used by US EPA.

3.1.3 Ethene, Propene

The URF of $5\cdot10^{-5}$ for ethene and $1\cdot10^{-5}$ for propene respectively, active through their monoepoxides, have been derived by the the dosimetry-rad equivalence method, using γ-radiation as reference standard [20]. The lower value for propene was estimated on basis of more rapid de-toxification. Whereas EPA's risk factor might be applicable to leukemia risk, the adopted factor also includes solid tumors expected to appear after longer latency times. Later validation studies might indicate a true value to be lower, may be one-half of the adopted, but still several times EPA's value.

3.1.4 1,3-Butadiene

The URF $30\cdot10^{-5}$ is the same as used by US EPA and is accepted as provisional awaiting measurements of doses of the genotoxic metabolites. In particular, information on levels of diepoxybutane is required. This bifunctional, cross-linking alkylator demonstrates a 10-100-fold higher genotoxic potency than monoepoxides.

3.1.5 Aldehydes

For formaldehyde, the EPA-value takes into consideration only nasopharyngeal cancer. A likely value to cover cancer at all sites may be about 10 times higher, URF $10\cdot10^{-5}$, but a lower value of 3 has been considered although not used. For acetaldehyde, the URF $0.2\cdot10^{-5}$ is the same as used by US EPA.

3.1.6 Polycyclic aromatic compounds (PAC)

For PAH the unit risk used by US EPA is restricted to risk for lung cancer. In order to take initiation of cancer in other organs as well into consideration, the adopted URF-value, $2800\cdot10^{-5}$, is seven times higher than US EPA's value.

3.2 Rankings with OEHHA and EPA URFs

Using the emission data from the recent SAE Paper by these two authors, a recalculation of the relative cancer risk has been carried out with various sets of unit risk factors. The investigated cases are the following:

- URFs derived from a report by Törnqvist and Ehrenberg ("base" case)
- URFs by EPA, 1990
- URFs by OEHHA, 1999. PM factor for diesel used for all fuels in addition to the factors for the volatile compounds. This case has been called OEHHA case #0
- URFs by OEHHA, 1999. Only the PM factor has been used for diesel fuel (other components have been excluded). All factors but PM have been used for the alternative fuels. This case has been called OEHHA case #1
- URFs by by OEHHA, 1999. All factors but PM have been used for all fuels. This case has been called OEHHA case #2.

In all the cases mentioned above, the diesel-fueled bus without any aftertreatment has been used as the reference (base) case. A cancer risk index of 100 has been set for this option in each individual case mentioned above. Therefore, a direct comparison of the cancer risk index for the various options *between each case* should not be made. Comparisons should be made for each case only. It should be noted that the calculation of the cancer risk has been carried out on the emission components in the exhaust only, i.e. no secondary formed components or the possible "scavenging" by (rapid) oxidation of some of the emission components and similar effects have been taken into account. Since the calculation has not taken the dispersion and atmospheric chemistry into account, no absolute values of cancer cases for the population can be calculated. Instead, the purpose of this comparison was to make a relative comparison only of the *potential* cancer risk from the exhaust.

In Figure 2, the relative cancer risk has been shown using the URFs derived from Törnqvist and Ehrenberg. In comparison to the results in the SAE Paper, the individual contribution from ethene, propene, formaldehyde and acetaldehyde has been shown instead of lumping the alkenes and the aldehydes together as in the mentioned paper. For specific comments regarding the results in Figure 2, please refer to the SAE paper [1].

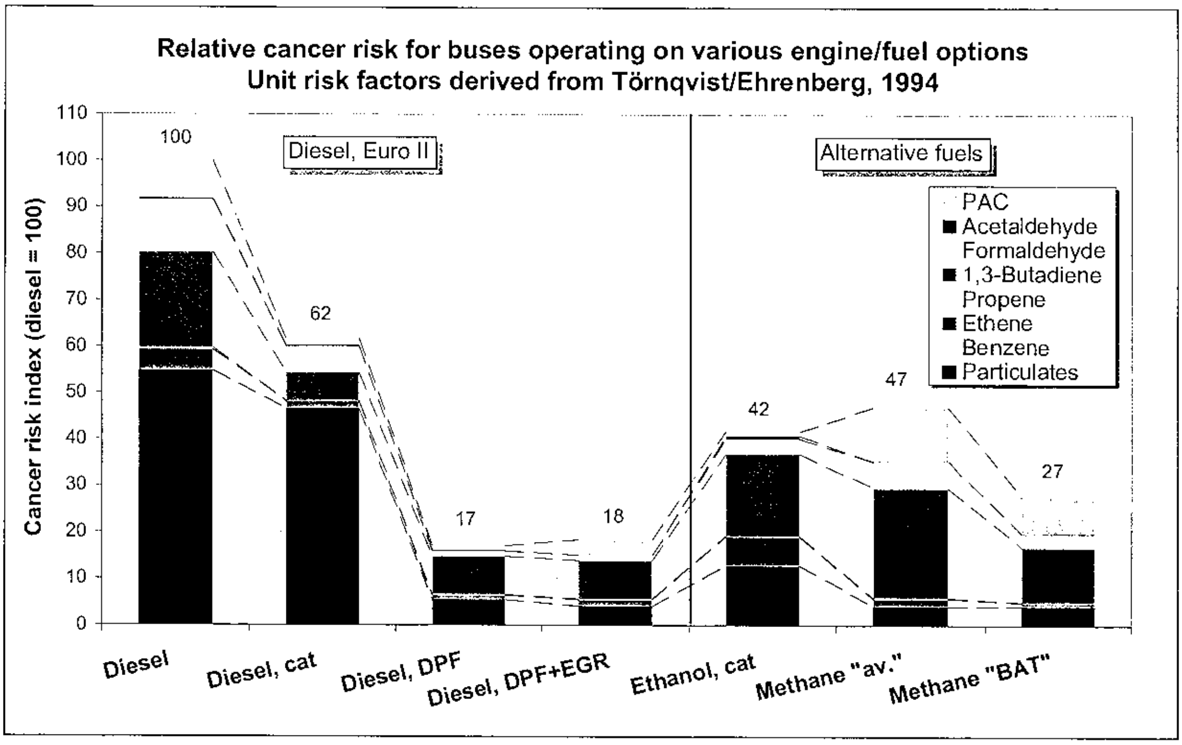

Figure 2: Cancer risk ranking, URFs derived from Törnqvist/Ehrenberg (as in ref. #1)

Figure 3, shows the same results as above but using the URFs that was derived by EPA in 1990. An on-going work for the development of new URFs is in progress by EPA and the latest report from that work was published just a couple of days ago. However, this work is not finished yet and the application of the factors is not as simple as previously due to the way the data has been structured. Therefore, no attempt has been made to use this set of data at the moment. Furthermore, the review process of the final report is not yet finished.

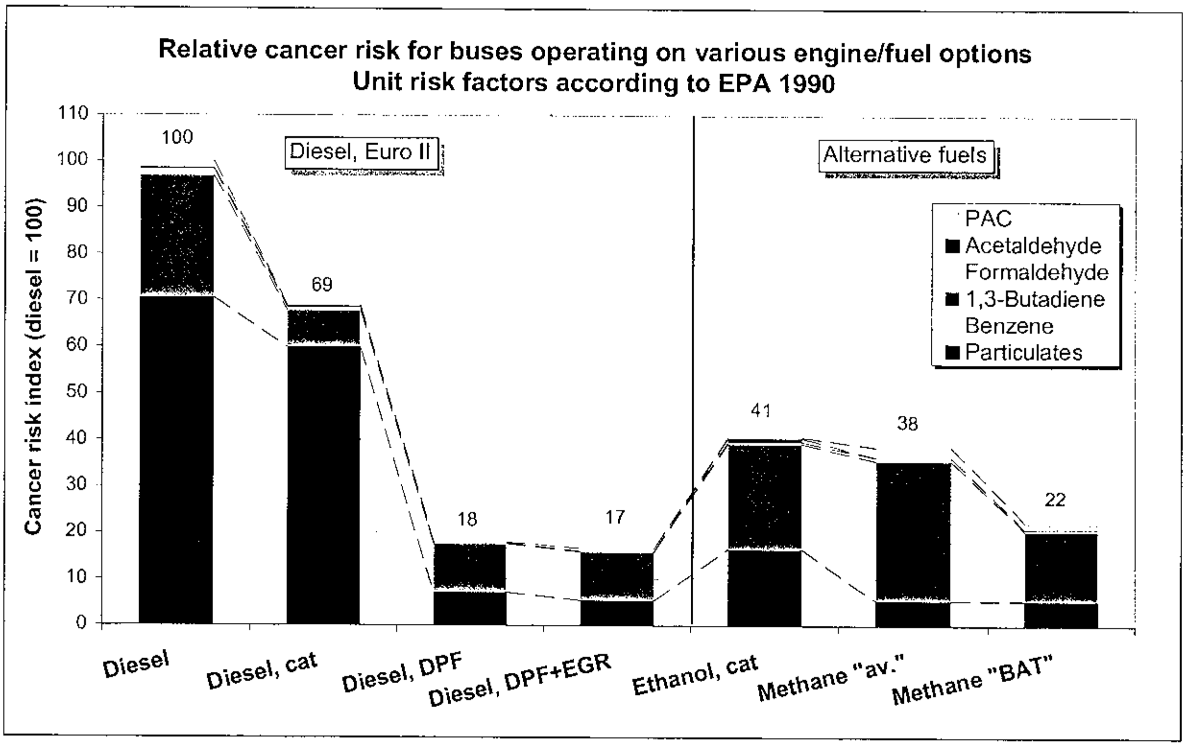

Figure 3: Cancer risk ranking, URFs according to EPA 1990

The results using the older factors by EPA show very similar results for the total index for most of the fuel and engine technology options above although the contribution of the individual compounds is different in both cases. The greatest relative difference is for diesel with a catalyst (index 69 with the EPA factors vs. 62 with the factors by Törnqvist and Ehrenberg).

The results for the case denoted "OEHHA case #0" in Figure 4 is considerably different to the previous cases. 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 results in Figure 4 are overestimated for all engine/fuel options. Furthermore, it is not known whether the PM from other fuels does have a similar 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 (much lower than previously) and this could have a significant impact on the results.

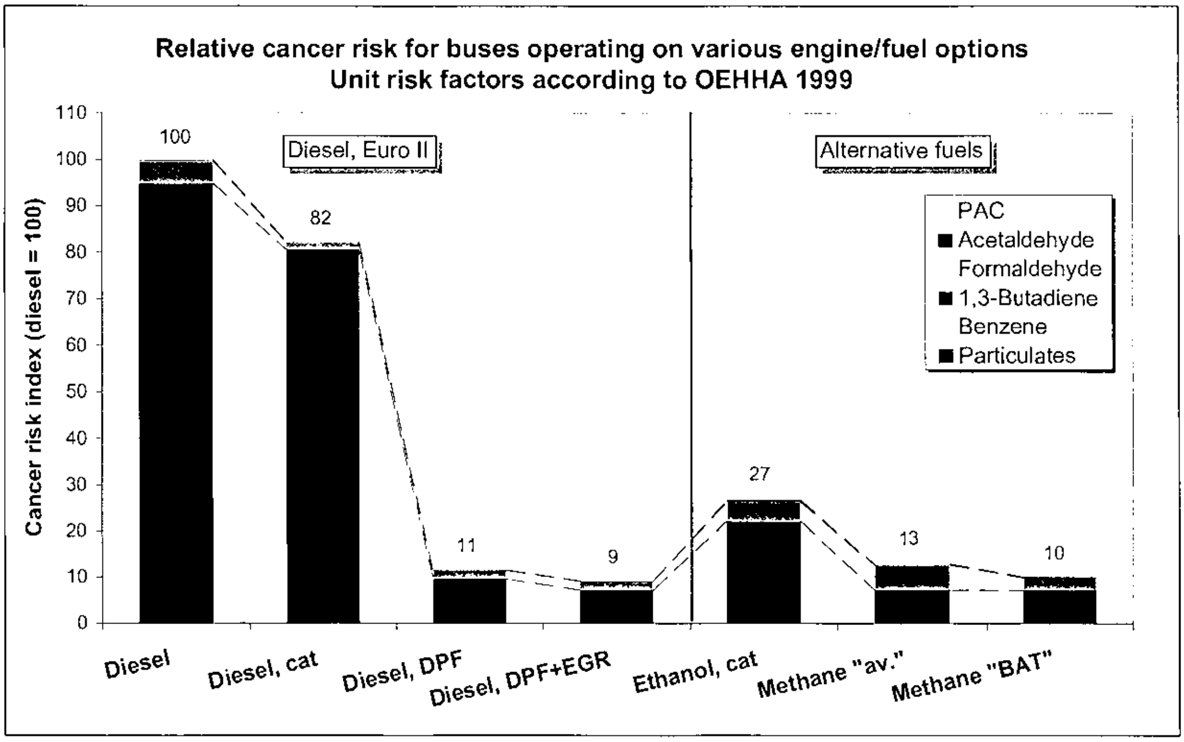

Figure 4: *Cancer risk ranking, URFs according to OEHHA 1999, OEHHA case #0 (all compounds)*

In Figure 5, the URF for diesel PM has been used for all options running on diesel fuel and the volatile organic compounds have been neglected due to the fact that all the URF is attributable to the PM. The URF for the particulate emissions from the alternative fuels have been set to nil.

The relative cancer risk for all the diesel fuel options in Figure 5 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 figure, the question 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 5.

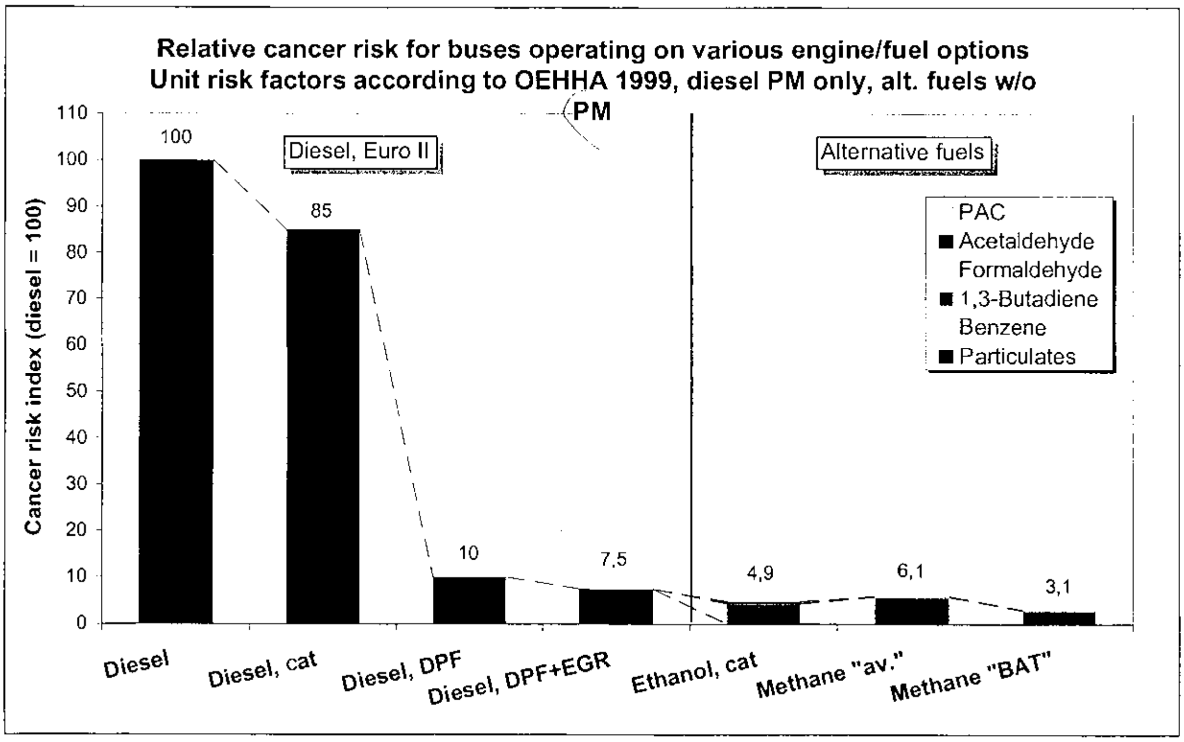

Figure 5: Cancer risk ranking, URFs according to OEHHA 1999, OEHHA case #1 (PM only for diesel, w/o PM for the alternative fuels)

Figure 6 shows the relative cancer risk for the various options without the contribution from the particulate matter (in all cases). The total cancer risk index in Figure 6 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 is the lower emissions of 1,3-butadiene for the best diesel options but the other volatile components are also lower for the diesel-fuelled options. This appears to follow a general trend 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. A similar situation has been noted in a comparison of the health effects from light-duty vehicles by these authors [18]. Consequently this result could be an effect that is a feature of the engine type (CI vs. SI) and not that much attributable to the fuel composition. Although it should be noted that certain compounds in the fuel, such as e.g. diolefines could have an impact on the 1,3-butadiene emissions. If the URF of 1,3-butadiene would be changed this would have a significant impact on the results.

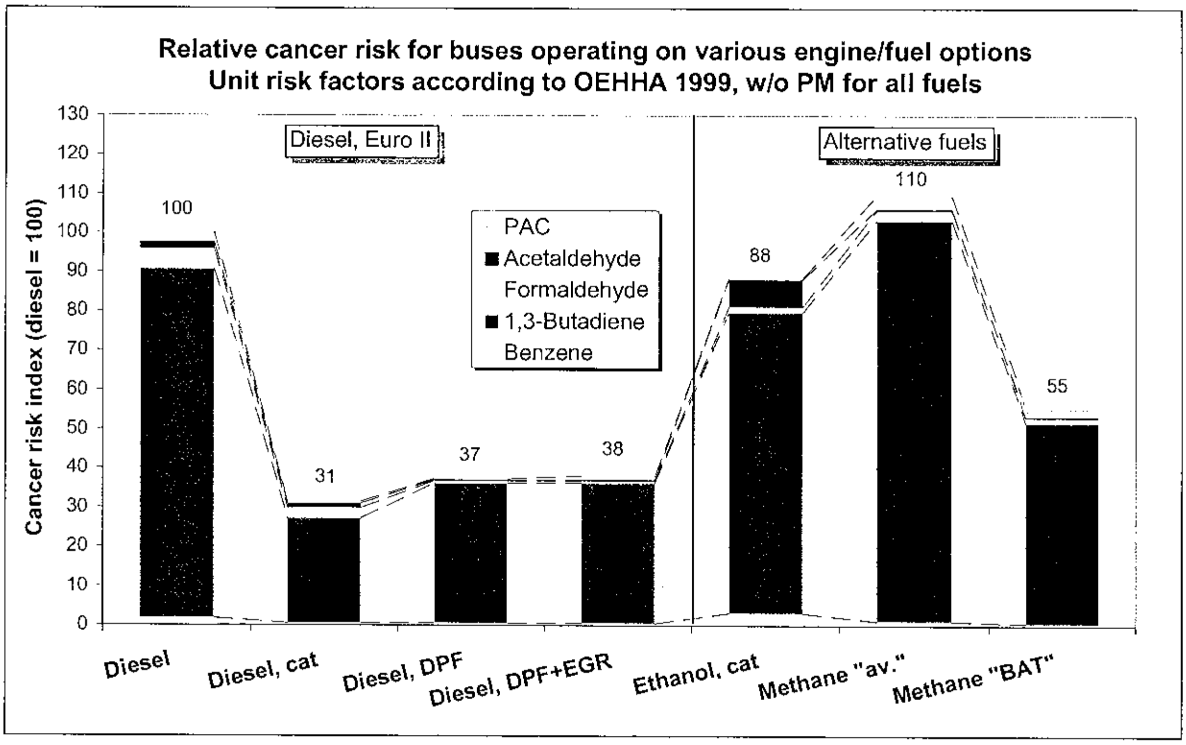

Figure 6: *Cancer risk ranking, URFs according to OEHHA 1999, OEHHA case #2 (w/o PM for all fuels)*

In summary, the evaluation of the cancer risk using the basic data from the SAE Paper by these authors have showed the following:

- The relative cancer risk is very similar for the URFs by EPA and by Törnqvist and Ehrenberg. For both sets of URFs, methane has no apparent advantage over diesel fuel.
- Using the OEHHA URFs in OEHHA case #0 gives approximately equal cancer risk for methane and diesel fuel with DPF.
- Using the PM URF only for diesel and a PM URF set to nil for the alternative fuel (OEHHA case #1) gives a relative advantage in the order of 2 – 3 for methane in comparison to diesel fuel with DPF.
- If the URF for PM is excluded from the evaluation for all fuels the best diesel fuel options are somewhat better than the best methane option.

4 DISCUSSION AND CONCLUSIONS

The data presented in this memorandum shows that the cancer risk index for a diesel vehicle running on the best available commercial diesel fuel and equipped with a DPF could have a cancer risk on a similar level as CNG. Depending on the set of URFs used, the level could be somewhat lower or somewhat higher. The finding mentioned is, of course, valid only for the emission results generated on the city buses used in Sweden (using the fuel quality mentioned). The obvious question is whether there is some difference between the engine technology used in Sweden and in the USA. The difference in fuel specifications (diesel fuel and CNG) must also be taken into account.

The diesel engine used as reference in the SAE Paper by the authors is an engine corresponding to an emission level similar to Euro II. Now, the Euro III directive is being introduced, which generally should reduce the emission level. In the comparison between engine types, the PM and the NMHC emissions could be taken as a crude indications of the relative cancer risk (from PM and from the volatile organic compounds respectively). A rough estimate shows that current US bus engines should have a PM level at least 50 % lower than the reference engine in our SAE Paper. The difference for NMHC emissions could be much greater. An example of the improvement potential is shown in Figure where a recalculation of the NMHC emissions used in the SAE Paper has been made for the new ETC test cycle. These results are compared with the engine dynamometer test results from an engine (Iveco) having a so-called VCO nozzle (far right) and some other modifications of the combustion system. The current Euro III limit, as well as the voluntary EEV limit (Environmentally Enhanced Vehicles) is also shown.

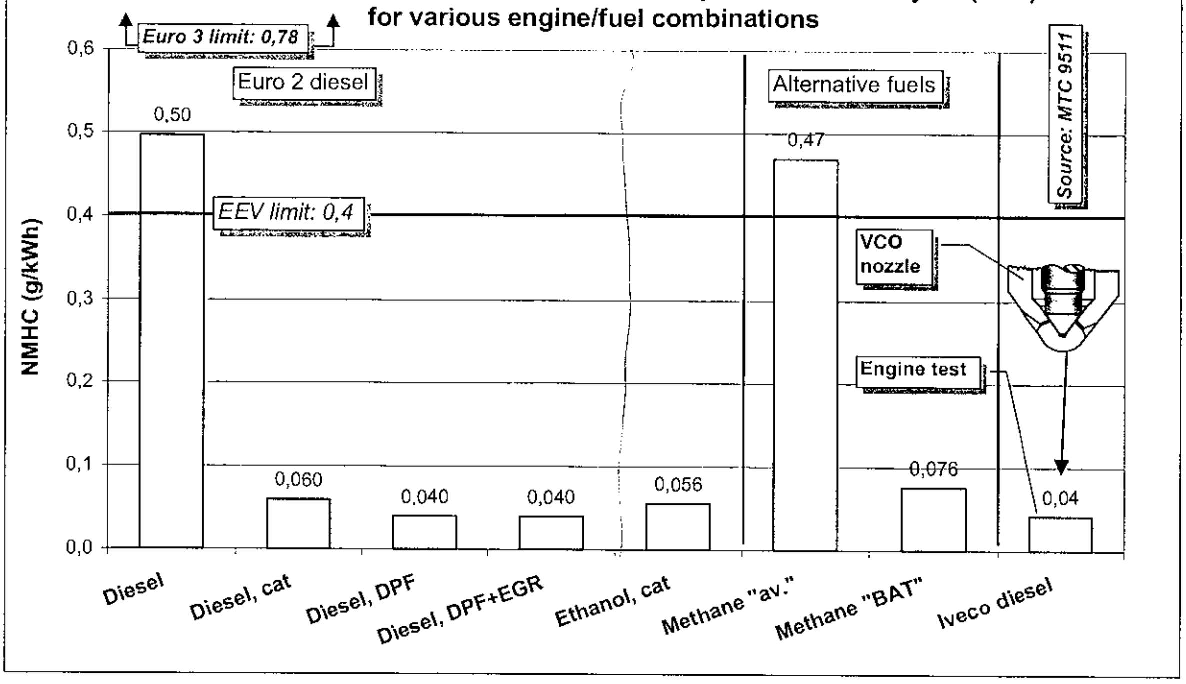

Figure 7: NMHC improvement potential for diesel engines

Note that the Iveco engine in Figure 10 use no aftertreatment devices. In spite of that, the engine-out NMHC emission level was one order of magnitude lower than the base level used in the SAE Paper (far left). This indicated that there is a great improvement potential in this area. Some US engines (e.g. DDC Series 60 and 50) have used this technology for more than a decade. Therefore, the US diesel engines could be better than the diesel engine technology used in our SAE Paper.

It should also be noted that there is a significant improvement potential for the CNG engines. One particular problem with the engines used so far in Sweden has been the air-fuel control. A closed loop feedback control of the air-fuel ratio was introduced on some US engines a couple of years ago. Now the same technology is being introduced in Sweden. A reduction of the average NMHC emission level (as well as NO_X) should be one effect of a better control system. The assessment of the impact of these modifications was beyond the scope of this investigation.

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