Report for

Centre for Science and Environment

PoT-India

Possible abatement of air pollution from urban traffic in India

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Summary

Air pollution is a serious problem in all megacities in the world. In the developing countries, these problems can be even more critical than in the developed countries. The reason is the rapid growth of transport intensity in the developing countries. The urbanisation and population growth in the developing countries has also been very rapid. Another reason for the negative trend in air pollution in these cities is that emission regulations have not been introduced to the same extent and as progressive as in the developed countries. The increased cost, complicated maintenance and the lack of proper fuel qualities are several reasons for the delay in the introduction of emission regulations.

The project described in this report was commissioned to Ecotraffic by the Indian organisation, Centre for Science and Environment (CSE). This organisation is an independent organisation (independent from Indian government, industry etc...) working with policy research, communications and public awareness raising, campaigns and lobbying activities and documentation with the aim of decreasing pollution in India. The project was funded by the Swedish governmental agency for international development, Sida.

The aim of this report has been to generate some documentation that can be used in discussions with governmental and municipal authorities, as well as with the industry. Since the air pollution situation in India is so acute, immediate actions are necessary to reverse the current trend. Therefore, this study was focussed on measures that could be taken on short term but nevertheless considering that the actions proposed also must be relevant on a long-term basis.

Data for this study has been collected through literature surveys and interviews. A visit in India for one week by on of the staff persons from Ecotraffic was made in order to collect data from India and to meet with people from different organisations. The assistance from CSE was very helpful in this respect.

In order to assess the impact of different technology options, five different vehicle categories have been investigated. The choice of vehicle categories was made in consultation with CSE. The vehicle categories were:

- 2-wheelers
- 3-wheelers
- Cars
- Buses
- Trucks

Economic calculations have been made for the environmental benefit of the reduced emissions. The same factors that have been used by Swedish governmental agencies for the environmental cost of each emission component have been applied in these calculations. The incremental cost of operating the vehicles has been calculated for several options that can reduce the emissions. By subtracting the incremental cost of operation from the environmental benefit, the most cost-effective solu-

tions can be found. This has been calculated for several options in some of the vehicle categories.

The main findings in this report are:

- India has an oil industry with great capacity and knowledge. Due to the substantial diesel oil share of the market, the fuel qualities are generally lower than in Europe.
- Reformulation of Indian fuels could be made for local markets by the Indian refineries today and the import of such fuels is another option.
- The incremental cost of importing the Swedish Environmental Class 1 fuel quality (EC 1, sulphur level <0.0010 %) has been investigated as well as the impact on the fuel distribution system and the vehicles.
- The EC 1 fuel has some impact on the emissions but its main advantage is that it enables the use of aftertreatment devices, such as catalysts and particulate filters.
- There are several alternatives to the conventional 2-stroke engine for the 2 and 3-wheelers that substantially can reduce the emissions. However, some of them are not fully developed yet.
- There are many different options to reduce the emissions from petrol-fuelled cars. The best way of introducing these options is through economic incentives.
- The best available diesel technology in combination with EC 1 fuel and a particulate filter and a dedicated CNG engine are the two options that will have the greatest impact on the pollution from buses. Socio-economic calculation shows that these options also are beneficial compared to the base case.
- The impact on the emission components of health concern from the best options for buses and trucks could be up to three orders of magnitude in comparison to the base case.
- The introduction of cleaner fuels is an option that will have an immediate effect on the emissions from all vehicles. In some cases, the cleaner fuels are also prerequisites for the introduction of the new technology in the vehicles.
- Economic incentives are probably the best method of introducing vehicles with lower emissions than the current emission standards.

1 INTRODUCTION

Air pollution is a serious problem in all megacities in the world. In the developing countries, these problems can be even more critical than in the developed countries. The reason is the rapid growth of transport intensity in the developing countries. The urbanisation and population growth in the developing countries has also been very rapid. Another reason for the negative trend in air pollution in these cities is that emission regulations have not been introduced in the same extent and as progressive as in the developed countries. The increased cost, complicated maintenance and the lack of proper fuel qualities are several reasons for the delay in the introduction of emission regulations.

In some countries, such as India, the share of diesel-fuelled vehicles is very high leading to problems with high particulate emissions and the small fraction of these particles[1] (PM_{10} and $PM_{2.5}$). Likewise, the NO_X emissions are high, because of the high specific NO_X emissions from diesel engines and the high consumption of diesel fuel. In India, another particular problem is the high share of 2 and 3-wheelers with 2-stroke engines. These engines have particularly high emissions of unburned hydrocarbons (HC).

The outline of the report is made so that the main technical and economical issues are handled in the Appendices. The main report covers primarily the results from the Appendices. The methodology, the assumptions and explanations are covered in the Appendices. Therefore, most of the detailed information can be found in the Appendices but most of the relevant results and the conclusions are also covered in the main report.

2 BACKGROUND

The Swedish governmental agency Sida has recognised the problems described above and has introduced a strategic plan for sustainable urban development. According to this plan, guidelines for support in this area will be developed during 1998. During the last years, Sida has been funding many projects in this area. Funding has increased since the strategy for support in this area was established in 1994-1995. Public transport is an area of high priority in this respect. It has also been recognised that Sweden has unique competence in many fields of transportation that should be of interest for the developing countries.

The project described in this report was commissioned to Ecotraffic by the Indian organisation, Centre for Science and Environment (CSE). This organisation is an independent organisation (independent from Indian government, industry etc...) working with policy research, communications and public awareness raising, campaigns and lobbying activities and documentation with the aim of decreasing pollution in India. Since the air pollution situation in India is so acute, immediate actions are necessary to reverse the current trend. Therefore, this study is focussed on measures that can

[1] PM_{10} and $PM_{2,5}$ are particles with an aerodynamic diameter less than 10 an 2.5 μm respectively. These particles are of special concern regarding the health effects.

be taken on short term but considering that the actions proposed also must be relevant on a long-term basis.

3 SCOPE OF THE PROJECT

This study has been rather limited in terms of cost and time. Therefore, the aim has been to generate some documentation that can be used in discussions with governmental and municipal authorities, as well as with the industry. Since the air pollution situation in India is so acute, immediate actions are necessary to reverse the current trend. Therefore, this study was focussed on measures that could be taken on short term but nevertheless considering that the actions proposed also must be relevant on a long-term basis. The scope of the study is summarised in the following:

The result of the study should be concretised in the proposal of a number of measures that can be taken in the short-term future. A couple of possible actions should be compared with respect to their impact on the air pollution and the cost-effectiveness.

The strategy of achieving the goals above has been the following:

1. The current vehicle technology in India has been assessed and compared with several levels of improved technology with the scope of investigating the potential of reducing the emissions. Since the technology transformation will increase the cost of the vehicles, this cost has been estimated. Five types of vehicle categories have been studied, two-wheelers, three-wheelers, cars, buses and trucks.
2. The problem of particulate matter (PM_{10}) from the diesel-fuelled vehicles has been specifically addressed but in addition, the impact on other (regulated) emissions such as NO_X and HC has also been investigated.
3. The consequences of switching the diesel buses from diesel fuel to CNG or LPG have been investigated.
4. Conditions for using cleanest possible diesel oil (corresponding to the Swedish Environmental Class 1 diesel oil) in engines available in India and the resulting impact on exhaust emission levels have been assessed. Comparisons of the cost of standard diesel fuel used in India and imported clean diesel fuel have been made.

It should be noted that this study is only one step in a process that will change the negative circle to a positive. Therefore, it is of utmost importance that this process be continued in the future. We recommend that studies that are much more comprehensive should be made in some of the cases before effective large-scale pilot actions could be made in practice.

4 METHODOLOGY

4.1 Data collection

To collect and to assess the data for this study, two principal methods have been used. These methods are listed below:

- Literature survey
- Interviews

First, a literature survey has been made. Literature search has been carried out using the database of the organisation Society of Automotive Engineers (SAE). In addition, the available literature at Ecotraffic has been evaluated. The results from projects carried out in Sweden on alternative and reformulated fuels have been of special interest. Second, literature published in India has been collected with the help of CSE. Some very valuable reports have been obtained from CSE and the organisations visited in India, but in some cases, no information has been received yet.

A visit was made to India by one person from the Ecotraffic staff (Peter Ahlvik). With the help of CSE, several meetings with different industries and organisations were organised during a period of 8 days. The organisations visited were:

- Indian Oil Co. (IOC)
- Gas Authority of India Limited (GAIL)
- Maruti Ydong Limited (Maruti)
- Bajaj Auto Ltd. (Bajaj)
- Tata Engineering & Locomotive Co. Ltd (Telco)
- Indian Institute of Petroleum (IIP)
- Automotive Research Association of India (ARAI)
- Central Pollution Control Board (CPCB)

4.2 Technology assessment

In order to assess the impact of different technology options for the vehicles the literature collected and the information from India has been used. Five different vehicle categories have been investigated. The choice of vehicle categories was made in consultation with CSE. The vehicle categories were:

- 2-wheelers
- 3-wheelers
- Cars
- Buses
- Trucks

For the vehicle categories, several technologies have been evaluated and the impact on the emissions and the incremental cost has been assessed. In many cases, there are other possible technical measures that could be of significant interest, but since the input data has not always been reliable, no calculations have been made on these options.

4.3 Economic calculations

In the calculation of the environmental cost, the same cost assessments (except for CO) as the recent factors used by Swedish governmental authorities have been applied in these calculations. The cost factors used in this study have been listed in Table 1. Since the CO emissions are not considered a problem any more in Sweden, the cost for this emission component has been set to zero in the latest set of factors. We have used a relatively low factor for CO in urban traffic.

Table 1: *Emission cost in Sweden (modified for CO by Ecotraffic)*

	Emission cost (Rs/kg)					
Traffic mode	**CO**	**HC**	**NO_X**	**SO_2**	**PM**	**CO_2**
Urban	27	356	497	616	5853	2.05
Rural	0	92	232	86	972	2.05
Average	13	227	324	351	2916	2.05

The economic parameters used in the calculations of the incremental cost have been listed in Table 2. The interest rate should be seen as the difference between the interest rate in a bank and the inflation. The interest rate used in investment calculations in a company, taking the inflation into account and the necessary return of investment, is usually much higher (some 15 to 30 % are a common figures).

Table 2: *Economic parameters*

Currency (Jan. –99)			Interest	Fuel cost, petrol equiv. (Rs)				
US $	**SEK**	**Rs**	**rate (%)**	**Diesel**	**EC 1**	**Petrol**	**CNG**	**LPG**
1	7.742	41.81	7	9.71	11.36	24	9.0	12

In the calculation of the incremental cost of operation, some additional factors are taken into account. Some of these factors are:

- Useful life of the vehicle (6 or 12 years)
- Useful life of the after-treatment (catalyst and particulate filter) devices (6 years for the heavy-duty vehicles and 3 – 5 years for 2 and 3-wheelers)
- Fuel consumption
- Yearly mileage

- Incremental cost of maintenance
- Incremental vehicle cost
- Cost of the after-treatment devices

In the calculations to assess the cost-effectiveness of the different options, the environmental benefit has been calculated first. Then the incremental cost of operating the vehicles has been subtracted, which gives the socio-economic benefit (or loss) for each option. Consequently, the most effective options for each vehicle category can be selected.

5 RESULTS

To simplify the presentation of the results, the 2 and 3-wheeler vehicle categories have been covered in the same section. Similarly, most of the issues for the buses and the trucks have been covered in the section about the buses. In general, most of the focus has been put on the heavy-duty vehicles (trucks and buses), since the NO_X and the particulate emissions are presumably the worst problems in India. These vehicles categories are the main contributors of the pollution for these emission components. The 2-stroke engines for 2 and 3-wheelers are also of concern, since most of the petrol is used in these vehicles. In addition, these vehicles contribute substantially to the HC emissions due to the high specific emissions of this emission component from a 2-stroke engine.

5.1 Two-wheelers and three-wheelers

The results for the cost of emissions are shown in Figure 1. A lower value should be interpreted as a lower pollution load (reduction of emissions).

By scrutinising Figure 1, it can be concluded that a number of options have the possibility of substantially reducing the pollution load. Several options, such as the 2-stoke with catalyst, the 4-stroke 2000 cat, the 4-stroke with TWC and the CNG conversions have very low environmental cost. The best is the 4-stroke with TWC, but on the other hand, the incremental cost is very high for this option. It might also be argued that the NMHC emissions of the propane vehicle pose less health hazard than the HC emissions from the petrol options. Dedicated CNG and propane alternatives with catalyst would certainly have given better results. On the other hand, the cost would have been higher.

The comparison of the socio-economic benefit (or loss) is shown in Figure 2. The socio-economic benefit is obtained by subtracting the environmental cost by the incremental cost of operation.

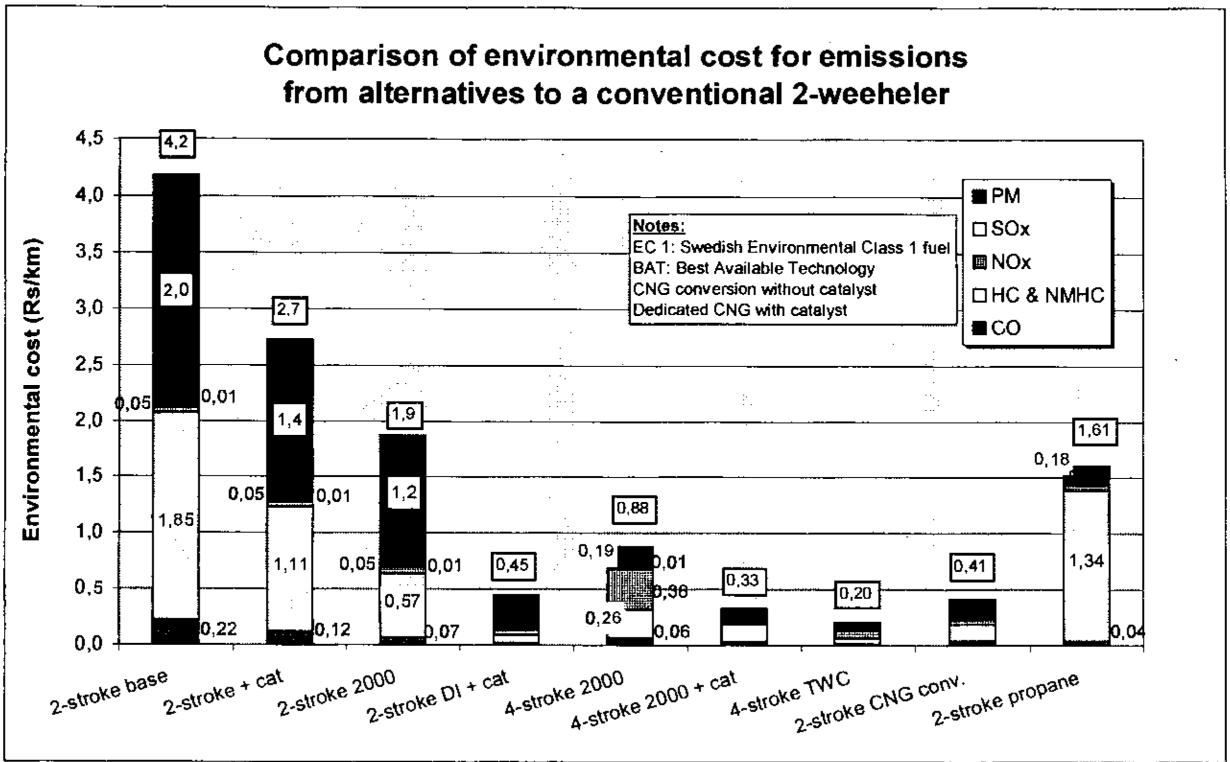

Figure 1: *Environmental cost for the emissions from various 2-wheeler options*

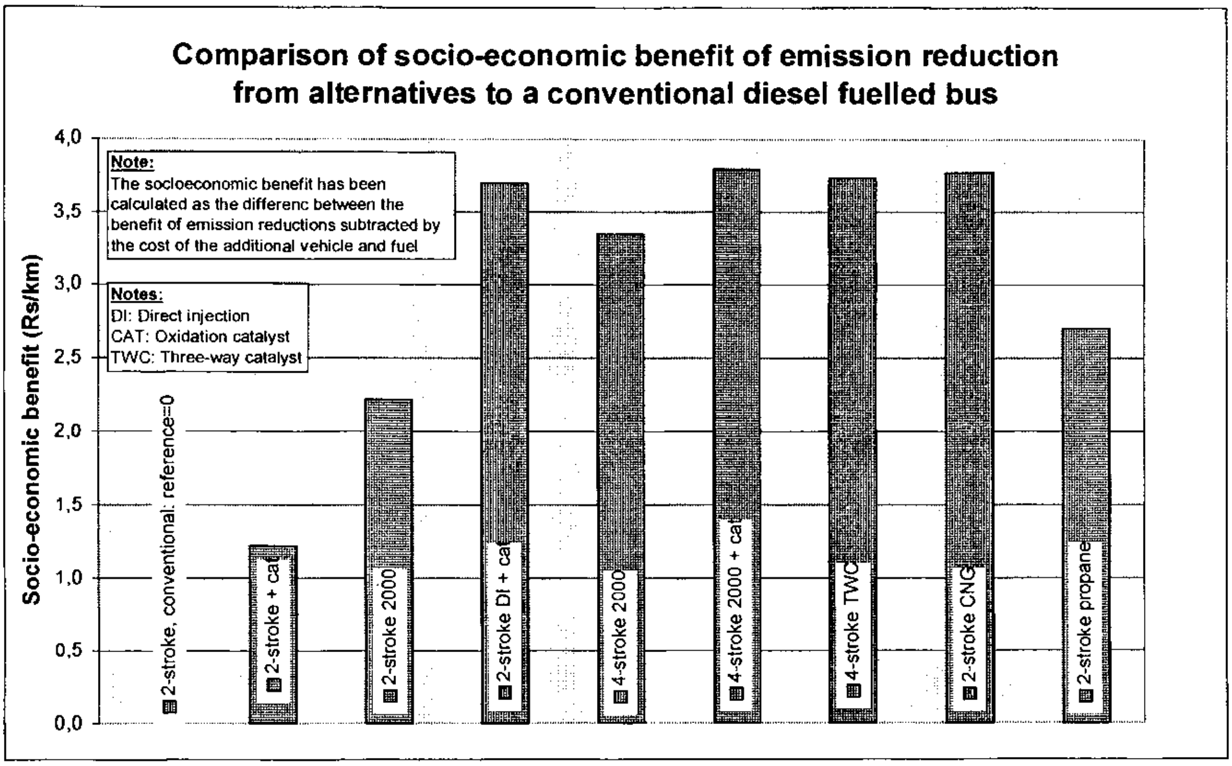

Figure 2: *Socio-economic benefit of various options for 2 wheelers*

The least effective option in Figure 2 is the retrofitting of catalysts on 2-stroke engines. The reason for this result is the additional cost of upgrading the engine and the shorter period of operation (6 years) in comparison to 12 years for many of the other options. The outcome could have been better if the calculation had been made for a newer vehicle (1996 model year). The CNG and propane options are somewhat hampered by the high investment cost. Using a catalyst on the propane 2-wheeler would have decreased the NMHC emissions. It is also conceivable that both the propane and CNG alternatives would have obtained better emissions if they had been dedicated vehicles from the vehicle manufacturer. The other options are more or less on the same level. When a choice is made between the options having similar cost-effectiveness, the option having the most impact on the emissions should be chosen. It is also interesting to note that all options show an socio-economic improvement. The reason for these positive results is the high emissions for the base case.

Many of the options for the 2 and 3-wheelers have possibilities of substantially reducing the emissions. Several options, as the 2-stoke with catalyst, the 4-stroke 2000 cat, the 4-stroke with TWC and the CNG conversions have very low environmental cost. Socio-economic calculations show that the benefit of many of these options is great. However, some development work has to be carried out before the best 2-stroke options can be commercialised.

5.2 Cars

Passenger cars is the category of vehicles, which generally is the most investigated of all categories of vehicles. Likewise, the emission standards are usually most strict for this category of vehicles. This is a logical conclusion for most countries, since the majority of the cars are petrol-fuelled and most of the fuel consumed is petrol. For example, ¾ of the world-wide automotive fuel consumption is petrol. In Sweden, the ratio between petrol and diesel fuel for automotive use is about 3:1. When all consumption of diesel fuel (off-road etc.) is taken into account, the ratio is 2:1. In India the situation is completely different, since the ratio between the two fuels is about 1:6. Furthermore, most of the petrol fuel is consumed by 2 and 3-wheelers. The conclusion is that passenger cars generally are of less concern for India than the heavy-duty vehicles and the 2 and 3-wheelers.

As mentioned above, the emission development is most advanced for passenger cars. Therefore, it is advisable to take advantage of this development also in India. The USA (especially California), Europe and Japan are the leading markets in this respect. Indian manufactures are following this development and have focussed on the European emission standards. The question is how much time delay there should be before the new emission standards are introduced in India.

5.2.1 Petrol-fuelled cars

The three-way catalyst (TWC) emission control system was originally introduced in a large scale on the US market in the late 1970´s. The Swedish car manufacturer Volvo was the pioneer in commercialising the first car equipped with this system. The TWC system was introduced about 10 years later in Europe. For the smallest cars, it actually lasted a couple of years more on most European markets. After some initial problems with durability of the emission control system and reduction of engine performance (mostly in the USA), the TWC system is now an established and accepted solution.

The TWC system is far from being fully developed yet. This can be seen in the emission standards, which are continuously tightened (see Appendix II). In India, the equivalent of the Euro I standard (about 1993 level for EU) will be introduced in the year 2000 and it is likely that the Euro II standards will be introduced in 2005. As described in Appendix II, the difference between the Euro III and Euro II is much greater than the difference between Euro II and Euro I. Consequently, India will be lagging behind if the current proposed schedule for implementation is to be taken. The first question is whether the Euro II emission standards could be introduced in advance of the proposed schedule in India. The second question is if the industry would be prepared for this move. In the investigations made by these authors we have come to the conclusion that the Indian automotive industry in general will not be prepared for the Euro II step already in the year 2000. On the other hand, some of the manufacturers can fulfil these limits already today. The simple proof of this is the export of vehicles to the European countries. One problem with the new standards is that the infrastructure for production (suppliers etc.) has not been prepared for the large-scale production of these vehicles yet. It takes time to build new factories and the import of components from abroad is somewhat restricted. On the other hand, the development on other markets have made the price gap between fulfilling the Euro II standard in comparison to the Euro I standard very small for a matured products in both cases (see Figure IV–1 in Appendix IV). It would be a pity not to utilise this development if possible.

Our proposal is that the Euro II standards should be introduced in advance through economic incentives. The focus should be on populated areas as the large cities. At the same time, an improved fuel quality should also be introduced. The incremental cost of an Euro II specification should, according to our assessments be in the order of 10 000 to 15 000 Rs. For some manufactures, this cost could be much higher but in some cases, the cost could be lower as well. The benefit of economic incentives is that the most cost-effective solutions will be commercialised first.

On the longer term, the Euro III standards could first be introduced in the same manner as described above for the Euro II standards. Besides from the significant reduction of the emission levels in the standards, the introduction of on-board diagnosis (OBD) is the most apparent advantage of the Euro III standards. The benefit of OBD is (presumably) a much lower failure rate for the emission control system and in case of failure, the car owner is prompted to repair the car.

5.2.3 Diesel-fuelled cars

Diesel cars seem to be very popular for the moment in India. The reason is the significant difference in price between diesel fuel and petrol in combination with the lower fuel consumption of the diesel car. As described in Appendix I and II, the most significant problems with the diesel cars are the NO_X and particulate emissions. The drawback in comparison with the petrol car using TWC is the lack of aftertreatment for NO_X reduction and the much greater formation of particulates due to the specific features of the diesel combustion system.

The engine-out emissions of CO, HC and NO_X are generally lower from a diesel engine than from a petrol engine, but the limited success of the NO_X aftertreatment has resulted in the disadvantage in comparison to the petrol engine. According to our assessments, NO_X-reducing catalysts (called $deNO_X$ catalysts) will not be ready for mass production within 3 years. This means that the diesel cars will have considerably higher NO_X emissions for many years to come. Another example, which confirms this assessment above, is the NO_X limits in the Euro III standards. The limits for the diesel cars is more than three times higher that for the petrol cars.

The second problem of the diesel car is the particulate emissions. Both the mass emissions of particulates and the number of particles are about one order of magnitude higher than for the petrol cars. Since the after-treatment devices to reduce particulate emissions are not fully developed yet, this disadvantage will remain for many years in the future. Our assessment is that a reliable particulate trap system for passenger car diesel engines[2] will not be ready for mass production within five years. It is also likely that these systems will be introduced on the Indian market later than in Europe. Furthermore, many of the particulate trap systems demand sulphur free fuel, which is not available on the Indian market yet.

Since NO_X and particulate emissions are the most severe pollution problems in the urban areas of India at the moment, any increase of the share of diesel-fuelled vehicles will worsen this problem. One countermeasure taken in Delhi has been to ban the use of private diesel cars. The ban on diesel cars in Delhi has upset the industry that apparently has been focusing on this market in their development during the last years. An alternative method would be to allow diesel cars that could meet future stricter emission standards. Our proposal is that the European 2005 standards would give approximately the same emission level of NO_X and particulates as the Euro I standards for petrol cars. However, it is not likely that the Indian manufactures could meet these standards in many years.

5.2.4 Alternative fuels for cars

The most interesting alternative fuel for passenger cars in India would be propane and CNG. LPG is not a viable option in India due to the high content of butane of the Indian LPG (see Appendix VII). The emission potential of CNG is described in Appendix VII and it can be concluded that propane has almost as low emissions as CNG. However, we advise against the conversion of older vehicle to CNG and/or propane operation – at least this should not be conducted in a larger scale. The reason is that the emissions are very sensitive to the air-fuel control and malfunctions in this system could give high emissions of some emission components. It is better that CNG and propane is used in new vehicles. The best solution is to use vehicles produced by the car manufacturers instead of converted vehicles.

[2] For heavy-duty engines there are already particulate traps in limited production.

There are many different options to reduce the emissions from petrol-fuelled cars. Our proposal is that the Euro II standards should be introduced through economic incentives. The focus should be on populated areas, as the large cities. Diesel-fuelled cars have much higher NO_X and particulate emissions than petrol-fuelled cars. These emission components are the most problematic emission components in the urban areas of India. Therefore, diesel cars should not be introduced on a larger scale in populated areas unless these emissions could be decreased to a very low level. It is best to use CNG and propane in new vehicles produced by the car manufacturer instead of converting old vehicles.

5.3 Buses

In these calculations, a conventional Indian bus is used as a reference (base case). The emission factors for that bus has been adopted from the Indian Institute TERI with some modifications.

The comparison of the environmental cost for the emissions for the various bus options is shown in Figure 3.

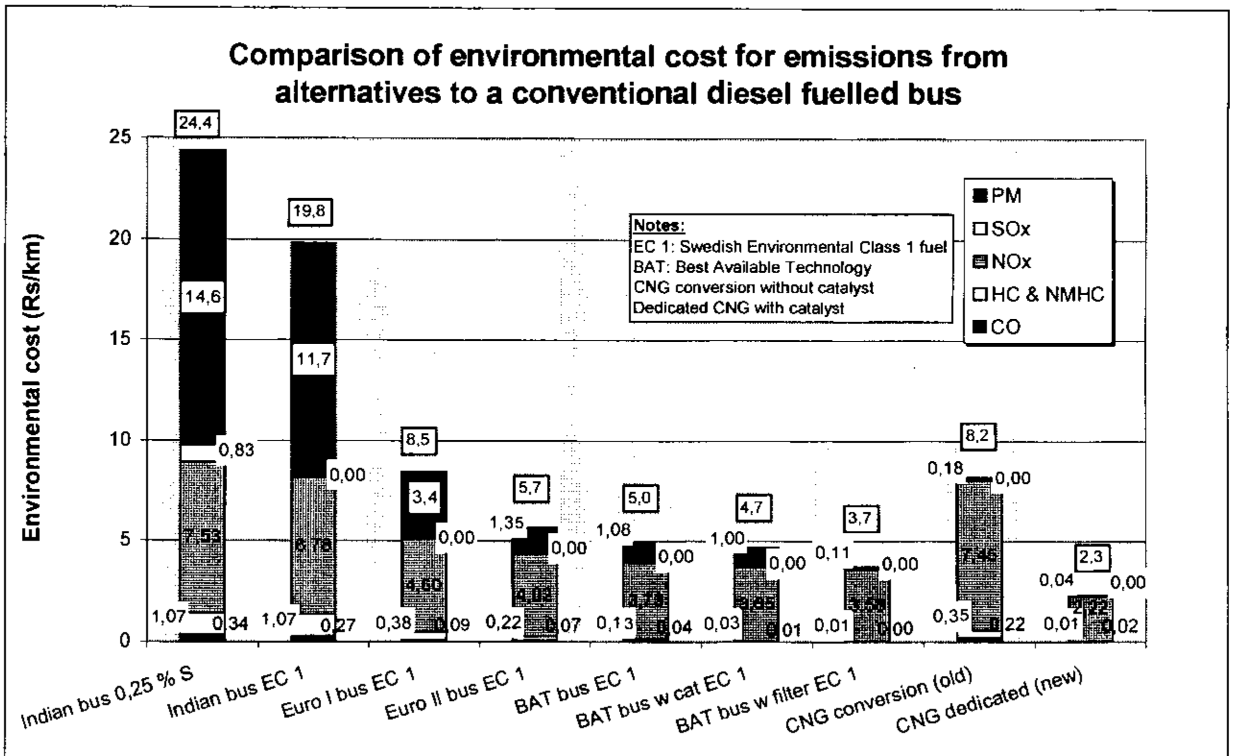

Figure 3: *Environmental cost for the emissions from various bus options*

The costs of the particulate and NO_X emissions are the highest costs for the base case. This is well in line with the generally accepted impression that these two emission components are the most problematic components for India. For the most advanced diesel options, the cost for the NO_X emissions is totally dominating the sum of emission costs. The dedicated CNG engine has the lowest emission cost, as expected. The difference between the dedicated CNG and the diesel option with particulate filter is mainly in the NO_X emissions.

The comparison of the socio-economic benefit (or loss) is shown in Figure 4. The socio-economic benefit is obtained by subtracting the environmental cost by the cost of operation.

Surprisingly, all options in Figure 4 show a benefit in comparison to the base case. The explanation is the very high emission level in the base case. Using the EC 1 fuel in an old Indian bus is the option that has the smallest benefit of all options. The simple CNG conversion is significantly better that the previous one. The other options are more or less on the same level. In the choice between options that have the same socio-economic benefit, the options that have the most impact on the emissions should be chosen. It is obvious that these two options are the diesel engine with particulate filter and the dedicated CNG engine.

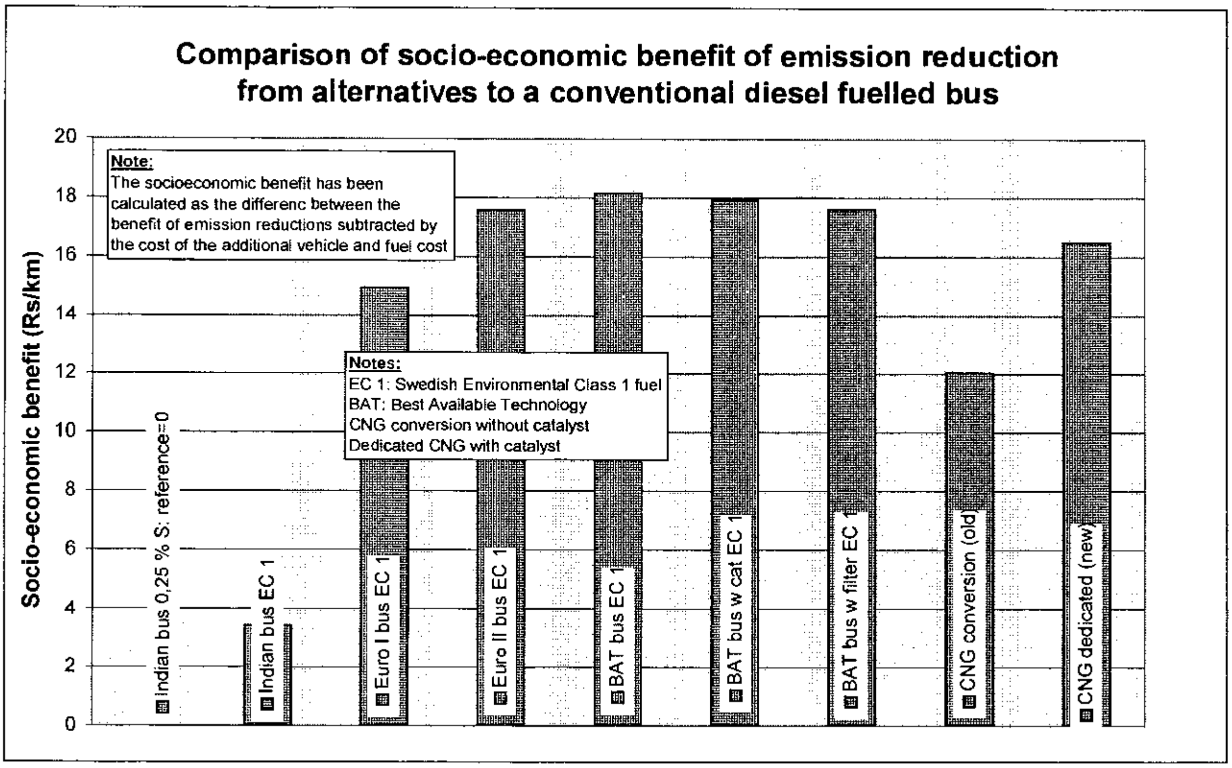

Figure 4: *Socio-economic benefit of various bus options*

Concluding the results shown above, there are several options available that can significantly decrease the emissions and that are advantageous from an socio-economic point of view. The introduction of EC 1 fuel alone, without changing the engine technology in the vehicle fleet, is the option that has the smallest socio-economic benefit. Some options, as the best available diesel engine with after-treatment (catalyst or filter) and the dedicated CNG engine, are the recommended options to be investigated further. If the best diesel engine technology or Euro II is not available, it should also be possible to use exhaust after-treatment on an Euro I engine. Regarding the CNG options, some measures should be taken to assure that the emission level is consistent with time. Unless this is supervised, some emission components could increase significantly. However, even if the control system is not working properly, the benefit for the particulate emissions will be substantial.

There is some environmental benefit of using cleaner diesel fuel as, for example the Swedish EC 1, but the most significant benefit of the fuel is that it can be combined with exhaust aftertreatment, such as catalysts and particulate filters. The best available diesel technology in combination with EC 1 fuel and a particulate filter and a dedicated CNG engine are the two options that will have the greatest impact on the pollution from buses. Socio-economic calculations show that these options also are beneficial compared to the base case. The impact on the emission components of health concern from the best options could be up to three orders of magnitude in comparison to the base case.

5.4 Trucks

There are many similarities between trucks and buses regarding the driveline[3] concepts. Smaller trucks in Europe usually have the same engines as the buses, even if there are variations in many cases. In India, the trucks are generally smaller than in Europe, and this implies that the differences between the two vehicle categories are even smaller. Therefore, most of the conclusions drawn for the buses are also valid for the trucks.

6 DISCUSSION

As shown earlier, there are many different technical options available that significantly could reduce the emissions. The results from the economic calculations show that some of them are the most cost-effective. Several of these options can be introduced immediately. However, much development work still has to be carried out to commercialise some of these options on a larger scale. The introduction of new technology should be made gradually. It is hardly the most cost-effective way to introduce new emission standards that the industry has to comply with for all their products at a certain date. Gradual introduction of new emission standards have, for example, been employed in the Californian LEV (Low Emission Vehicle) programme. The emission zones (for heavy-duty vehicles and off-road machinery) of the Swedish three greatest cities is another example. In Sweden, the retrofitting of catalysts and particulate filters is an alternative to the use of newer vehicles. Similar solutions as these mentioned should be investigated for India. Economic incentives are probably the best method of introducing vehicles with lower emissions than the current emission standards. The introduction of cleaner fuels is an option that will have an imme-

[3] The driveline comprise engine, gearbox, differential, etc...

diate effect on the emissions from all vehicles. In some cases, the cleaner fuels are also prerequisites for the introduction of the new technology in the vehicles

Economic incentives are probably the best method of introducing vehicles with lower emissions than the current emission standards. The introduction of cleaner fuels is an option that will have an immediate effect on the emissions from all vehicles. In some cases, the cleaner fuels are also prerequisites for the introduction of the new technology in the vehicles

7 CONCLUSIONS

The main findings in this report are:

- India has an oil industry with great capacity and knowledge. Due to the substantial diesel oil share of the market, the fuel qualities are generally lower than in Europe.
- Reformulation of Indian fuels could be made for local markets by the Indian refineries today and the import of such fuels is another option.
- The incremental cost of importing the Swedish EC 1 fuel quality has been investigated as well as the impact on the fuel distribution system and the vehicles.
- The EC 1 fuel has some impact on the emissions but its main advantage is that it enables the use of aftertreatment devices, such as catalysts and particulate filters.
- There are several alternatives to the conventional 2-stroke engine for the 2 and 3-wheelers that substantially can reduce the emissions. However, some of them are not fully developed yet.
- There are many different options to reduce the emissions from petrol-fuelled cars. The best way of introducing these options is through economic incentives.
- The best available diesel technology in combination with EC 1 fuel and a particulate filter and a dedicated CNG engine are the two options that will have the greatest impact on the pollution from buses. Socio-economic calculation shows that these options also are beneficial compared to the base case.
- The impact on the emission components of health concern from the best options for buses and trucks could be up to three orders of magnitude in comparison to the base case.
- The introduction of cleaner fuels is an option that will have an immediate effect on the emissions from all vehicles. In some cases, the cleaner fuels are also prerequisites for the introduction of the new technology in the vehicles.
- Economic incentives are probably the best method of introducing vehicles with lower emissions than the current emission standards.

I EMISSION TESTING OF VEHICLES AND ENGINES

1 Introduction

The aim of including this appendix was to give an overview of some of the different types of driving cycles used in Europe and the corresponding emission limits in different timeframes. This subject was not included in the project proposal but still it was added since the discussions in Delhi revealed the necessity to elucidate some of the particular issues in this area. To put some limitation on the work, only light-duty and heavy-duty vehicles are highlighted, even if a similar investigation could have been made for 2 and 3-wheelers as well. A more thorough compiled information of this subject can be found in the literature. For example, the Austrian consultant company AVL has made a comprehensive overview of the emission limits and test methods world-wide [1]. A quick update on the emission limits on the major markets in the World can also be obtained at the Internet site of DieselNet [2].

Driving cycles can be divided into a couple of different basic types. First, a distinction can be made between driving cycles intended for chassis dynamometers and driving cycles for engine dynamometers. Second, driving cycles can be classified according to the dynamic characteristics, i.e. if they are of the steady-state or if the transient type. The most advanced type of driving cycle – regarding the technology necessary for testing purposes – is a transient cycle for chassis dynamometer, and the simplest is a steady-state cycle for an engine dynamometer. Basically four combinations of the alternatives above can be made. However, some of these combinations are rarely used, as for example the steady-state type of driving cycle simulated on a chassis dynamometer. The ranking of cost for the test equipment (in descending order, i.e. from the most expensive to the least expensive) for the other three variants is as follows:

1. Transient chassis dynamometer
2. Transient engine dynamometer
3. Steady-state engine dynamometer

Sometimes the cost of the test equipment is not always the most critical cost in a particular investigation. If, for example, the engine to be tested on an engine dynamometer is mounted in a vehicle, the cost of dismounting and mounting the engine in the vehicle chassis is considerable. This is often the case when an engine from an in-use vehicle is to be tested. Under these particular circumstances, it can be more cost-effective to simulate the engine test on a chassis dynamometer (provided this can be performed with satisfactory measurement accuracy). This method has been used extensively in emission surveys of heavy-duty engines in Sweden, where the testing is usually carried out in the test facilities of MTC (a subsidiary of the Swedish Motor Vehicle Inspection Co.). On the other hand, in the basic development of an engine (at the engine manufactures site), an engine dynamometer is usually the most cost-effective method for testing. This is probably one reason for the engine manufacturer's preference for this method.

It has to be stressed that the chassis dynamometer test cycles reflect the driving conditions in real traffic much better than the other methods (provided that the driving bilities is the most expensive test equipment of all equipment referred to here. The use of an engine dynamometer is more practical and it is less expensive. There is also a great difference in cost between an engine dynamometer with transient capabilities and an engine dynamometer with steady-state capabilities only. Therefore, engine manufacturers have been very reluctant to accept transient engine driving cycles. In spite of this, a transient driving cycle has been used in the USA and in California for over 10 years, but in Europe, a (new) transient driving cycle will be phased in first after the year 2000. In the foreseeable future it is not likely that a chassis dynamometer will be used to certify heavy-duty vehicles, although this method would give the most relevant results. The emissions from engine dynamometers are expressed in g/kWh (or in g/bhp-hr in some countries); e.g., the mass emissions are divided by the engine work (which is performed in the driving cycle). The advantage of this method is that small and large engines can be directly compared[3]. The disadvantage is that it does not give the emission results in g/km. It is very difficult to convert the emission results in g/kWh to g/km, due to the lack of conversion factors and input data for the calculations. Therefore, the comparison between the emissions from heavy-duty and light-duty vehicles is a very complicated task.

3 Light-duty vehicle testing on a chassis dynamometer

As an example of two relevant chassis dynamometer driving cycles, the present (EDC) and the future (NEDC) EU driving cycles are shown in Figure I–1. These driving cycles are very similar except the starting procedure in the beginning of the driving cycle. The present EU driving cycle will be used in the Indian 2000 norms. As a comparison to the former driving cycles, the American FTP-75 driving cycle used in the US and the Californian emission regulations is shown in Figure I–2. It is obvious that there is a considerable difference between the driving cycles. Therefore, it is not possible to directly compare results generated in the two driving cycles.

Because of the differences between the driving cycles above mentioned, CO and HC emissions are usually higher in the European driving cycle. These emissions are also higher in the NEDC driving cycle than in the EDC driving cycle. The reason for the difference in the first case is that the weighting factors used in FTP-75 decrease the influence of the cold start. Another reason for the higher CO and HC emissions in the European test cycle is the lower engine load that increases the time and distance before the catalyst light-off. The reason for the difference in the second case is that omitting the first 40 seconds of idle without measurement will increase the emissions in the first phase of the NEDC cycle in comparison to the EDC cycle. Due to the 40-second idle period, which is omitted from the measurements in the EDC driving cycle, the *measured* cold start emissions are lower in this driving cycle compared to the NEDC driving cycle. It is obvious that the start procedure in the NEDC driving cycle better reflect the real driving conditions. It should also be stressed that direct comparisons between the results from the three driving cycles mentioned above should not be carried out without using proper care.

[3] It is more difficult to compare small and large vehicles (in g/km) since the emissions are influenced by the vehicle weight.

cycle is relevant for the application). Therefore, these driving cycles should be preferred in general, if the objective is to simulate real driving conditions in the most accurate way. There are, however, many applications where the cost for the test equipment is so high, or there are other practical aspects, that this method is prevented from being used. Some of the pros and cons of each method are discussed in more detail below.

2 The choice between engine and chassis dynamometer

Traditionally light-duty vehicles, as well as 2 and 3-wheelers, have been certified according to chassis dynamometer driving cycles. Similarly, heavy-duty engines, off-road engines (including marine engines etc) and locomotive engines have been certified according to engine dynamometer driving cycles. There are several reasons for the choice of test method in the cases above. For example, if the engine is to be used as a separate engine (e.g. in a generator set) the choice is obvious. The choice for the two categories light-duty and heavy-duty vehicles is not so obvious and therefore the main reasons for the choice need to be highlighted in somewhat more detail.

Light-duty vehicles are often sold in different body and chassis variants. However, even if the difference between these options, according to the customer preferences, is considerable, this has usually only a minor effect on the exhaust emissions[1]. Therefore, an engine family is generally certified for a couple of chassis and body variants. For practical reasons, only one vehicle needs to be certified even if the certificate is valid for a number of (engine) applications. Usually the vehicle manufacturer chooses the most critical application (e.g. a body with the highest weight, air resistance etc.) which gives some margin for the other applications in addition to the normal margin for production tolerances. In "conformity of production" and "in-use compliance" tests, the governmental agency (or its "technical service", i.e. a company/institute supporting the agency) can choose any chassis/body variant for testing, since all these must fulfil the emission limits. Referring to the discussion above, it is logical that light-duty vehicles are certified on a chassis dynamometer. Consequently, the emissions are expressed in g/km[2].

Engines for heavy-duty vehicles are used in vehicles where the applications are very much different from case to case. Furthermore, these variations are much greater than in the case of the light-duty vehicles. Therefore, it would be very difficult to choose a representative type of vehicle for certification. Thus, it is more practical to use an engine dynamometer for certification. Another factor of great importance has been that the cost for the test equipment is much higher for a heavy-duty chassis dynamometer than for a light-duty chassis dynamometer and an engine dynamometer. In many regulations, the maximum weight for a light-duty vehicle is less than 3.5 ton, but the maximum weight for a heavy-duty vehicle can be more than 40 ton (up to 60 ton in some EU countries, as in Sweden). It is conceivable that it is difficult to simulate the vehicle weight on a chassis dynamometer by using flywheels (due to the great mass) or by using an electrical motor/generator with transient control (accuracy under transient conditions). Therefore, a chassis dynamometer with transient capa-

[1] For example the difference concerning the exhaust emissions between a sedan and a station wagon variant of a specific vehicle is small.

[2] In some cases, g/test have been used as well, but since the driving distance in the test cycle is fixed, it is possible to recalculate the emissions in g/km also in this case.

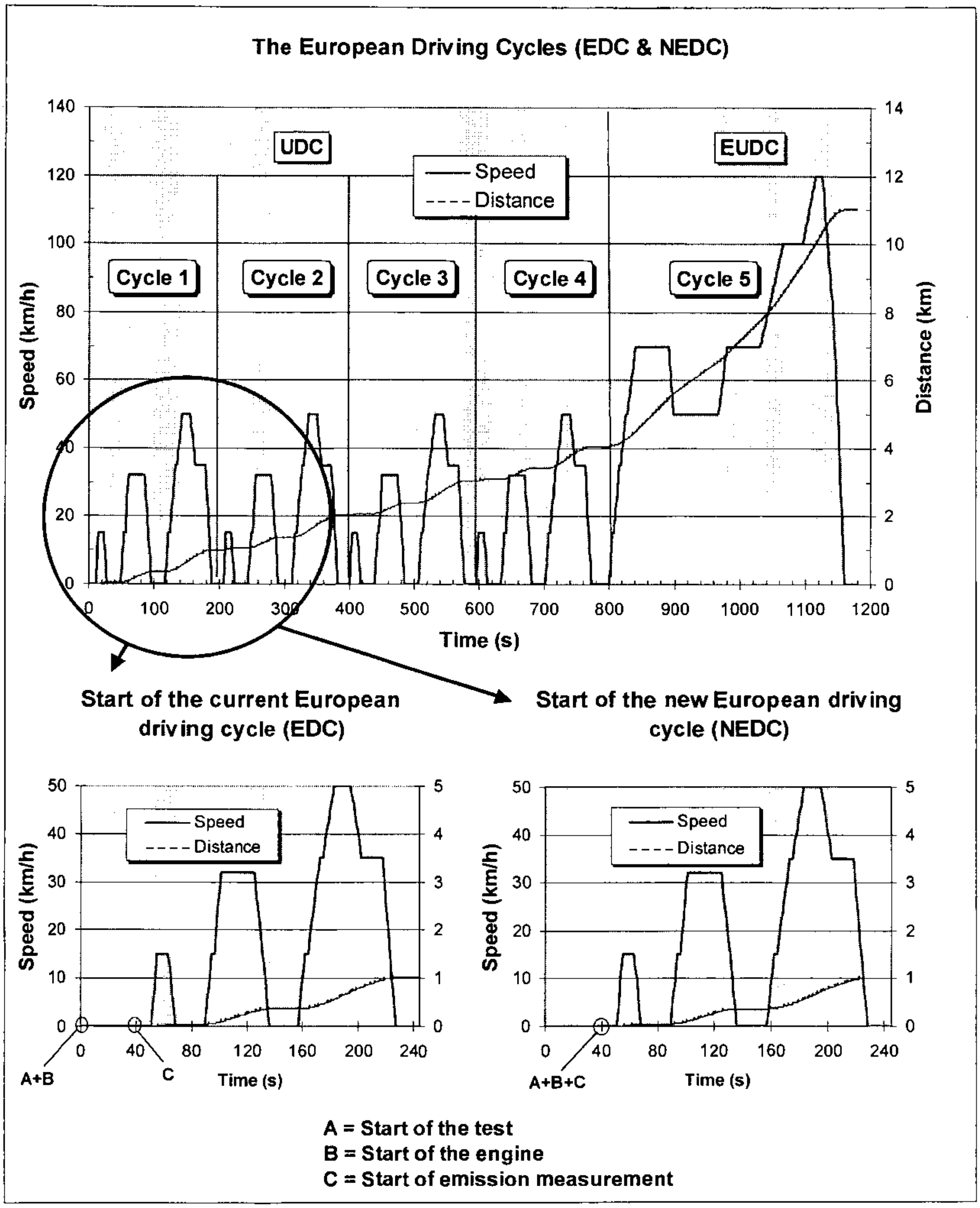

Figure I-1: *EDC and the NEDC driving cycles*

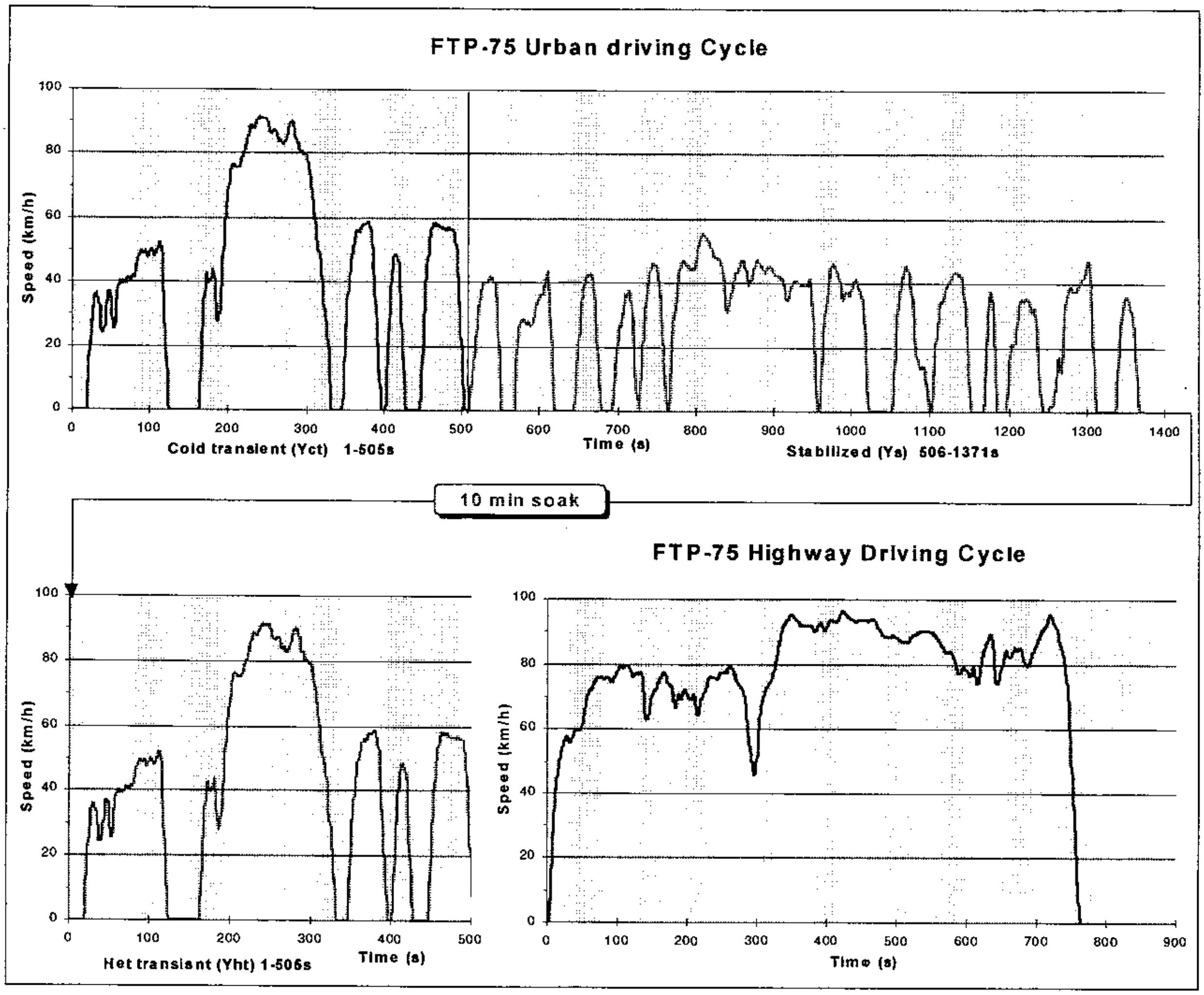

Figure I-2: *The FTP-75 driving cycle*

The considerations for India are that the test temperature in all these tests is specified to an interval of +20 – +30 °C. Even if the temperature in India often can be higher than the maximum temperature of this interval, the yearly average temperature in most areas of the country is rather close to the interval. Therefore, cold start[4] emissions are also of some relevance to India. The average trip length is presumably short in India, which further increases the impact of the cold start emissions. The trip length of the EDC and NEDC cycles is about 11 km, whereas the equivalent trip length per cold start in the FTP-75 cycle is about 28 km[5]. If the focus is placed on the cold start effects only, it is likely that the driving cycle most representative of the driving conditions in India would be the NEDC driving cycle. It has to be noted that the previous Indian regulations have used a warm engine instead of an engine soaked to the temperature interval specified in US and EU regulations.

[4] Cold start means that the engine (and vehicle) is soaked to the specified testing temperature (+20 – +30 °C), hence the denotation "cold". However, an "hot" engine is working at its operating temperature, which usually means that the cooling temperature is higher than +85 °C. Emissions from a cold engine are higher than from a warm engine.

[5] This is a calculated trip length. Due to the weighting factors used in the FTP-75 driving cycle, the trip length per cold start is longer than the total length of the driving cycle since the weighting factor for the first phase is 0.43.

One aspect of the EDC and NEDC cycles is, however, that these cycles have a maximum speed of 120 km/h – or the maximum speed of the vehicle if it cannot reach 120 km/h. This speed cannot be reached on most of the Indian roads due to the poor condition of the roads and the absence of highways. Therefore, the FTP-75 driving cycle would probably be better suited to the Indian driving conditions considering the driving pattern only.

4 Heavy-duty engine testing on an engine dynamometer

Heavy-duty engines are usually tested on an engine dynamometer. In Europe, the driving cycles have so far been of the steady-state category. One example of such a driving cycle is the 13-mode cycle used in the ECE R49 test procedure and in the Euro I and Euro II regulations. This test cycle is shown in Figure I–3.

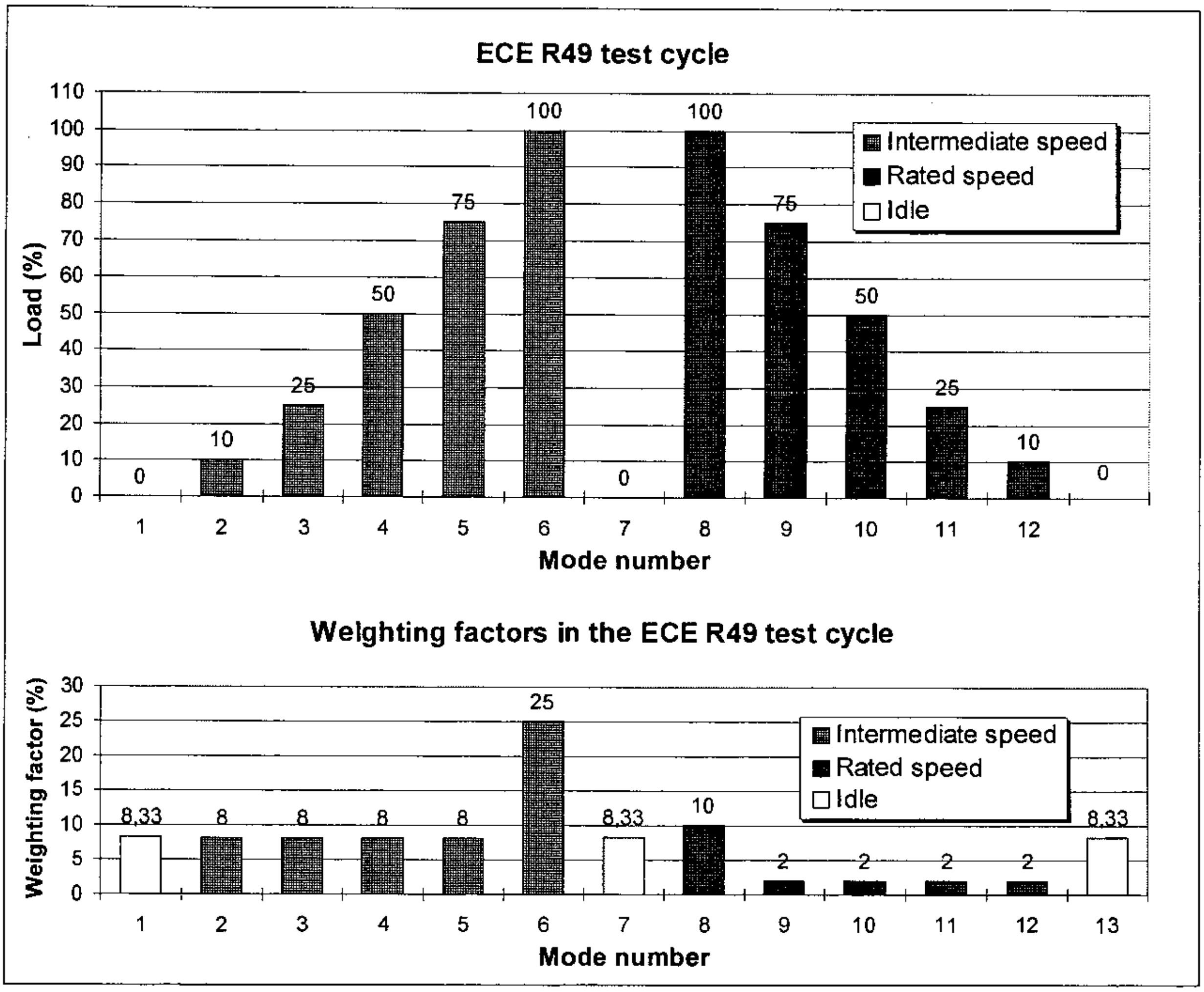

Figure I-3: ECE R49 driving cycle (engine dynamometer)

Another way of showing a steady-state driving cycle is to use a bubble diagram. In this type of diagram, the size of the bubbles are proportional to the relative weighting factors for each mode in the load and speed range of the engine. Figure I–4 shows the ECE R49 cycle as a bubble diagram for a hypothetical European city bus engine.

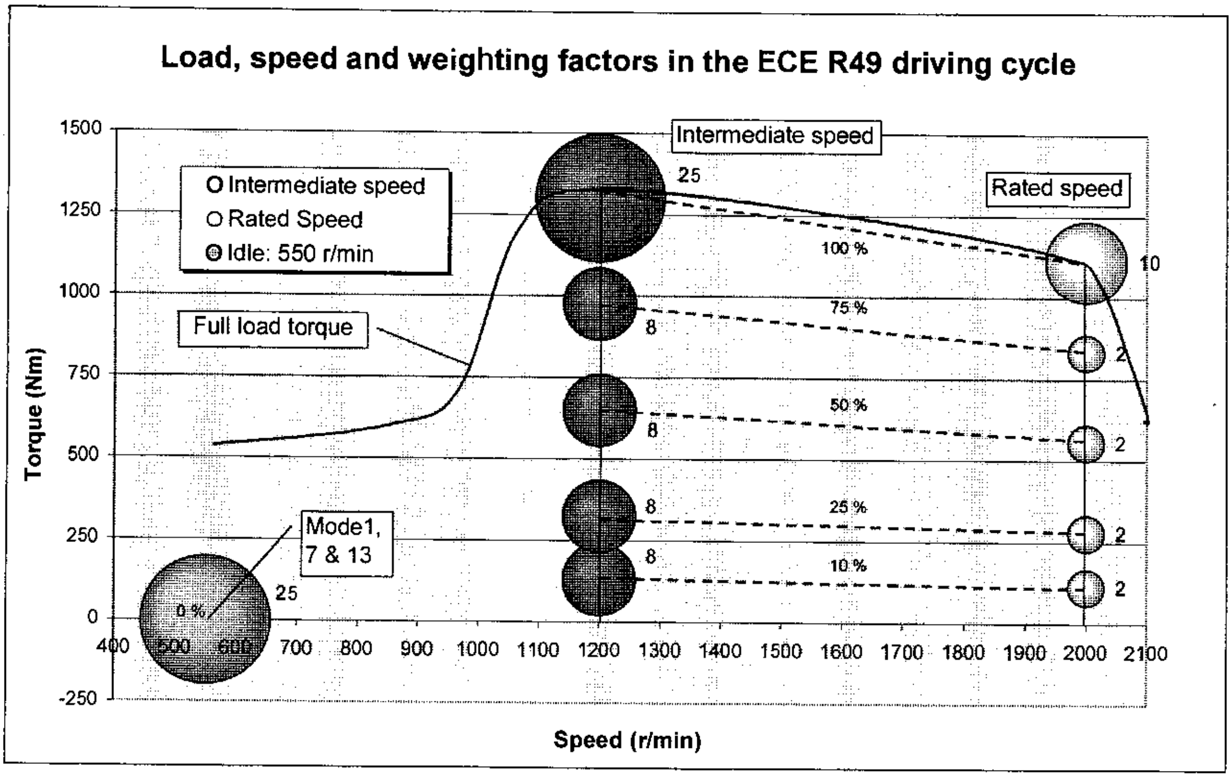

Figure I-4: ECE R49 driving cycle (engine dynamometer)

The ECE R49 cycle is run at three engine speeds – low idle, medium speed and rated speed – at 11 different modes. Since the low idle mode is repeated twice (total of three idle modes), the total number of modes is 13. By looking at the weighting factors, it is obvious that the full load test points (mode 6 and 8) are dominating the total emissions. Since the power is high at these modes as well, this further increases the relative weighting of these two modes. In some extreme cases, this can lead to that these two modes can contribute by up to 75 % of the total emissions in the test cycle for a specific emission component. Referring to the discussion above, it can be stated that the ECE R49 test cycle is representative of highway driving conditions for a highly loaded truck. The absence of transient effects is a great deviation from real driving conditions. Since the air pollution in India is most severe in urban areas, the ECE R49 test cycle is not very representative for this driving condition. However, it is likely that the emission regulations for the heavy-duty engines in India will use this driving cycle in the foreseeable future.

In the (proposed) EU regulation for the year 2000, the driving cycle will be changed, but still 13 different steady-state modes are to be used. The new driving cycle is called the ESC (European Steady-state driving Cycle). The ESC driving cycle is shown in Figure I–5. Instead of the two speeds in the ECE R49 (medium and rated speed), the ESC has three different speeds. Likewise, the loads in the modes are different, as well as the weighting factors.

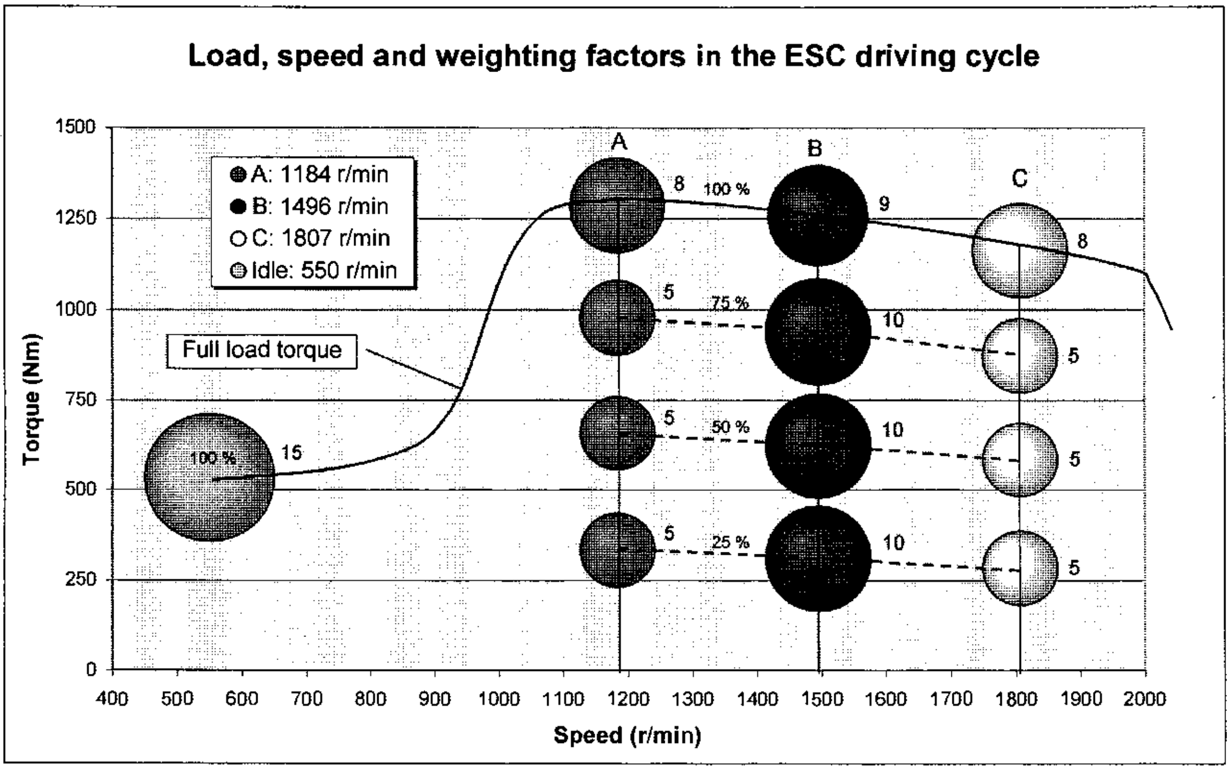

Figure I-5: *ESC driving cycle (engine dynamometer)*

In the USA and in California, a 13-mode cycle has also been used previously – in fact, the ECE R49 has been derived from this cycle, although some modifications have been applied. However, since 1988 a transient driving cycle (US Transient cycle) is used instead of the older 13-mode cycle. In this cycle, the engine load and speed is specified for each second of the 20 minutes (1200 seconds) in the test cycle. The US Transient cycle is shown in Figure I–6. By scrutinising Figure I–6, it is obvious that much of the time in the test cycle is spent at idle. Furthermore, a large portion of the test cycle is spent in city driving conditions. Therefore, it can be stated that this test cycle may not be very representative of the driving conditions at roads outside the city (where many of the trucks are operated). On the other hand, traffic pollution is more severe in urban areas so therefore it is logic that the test cycle is focussed on this type of driving.

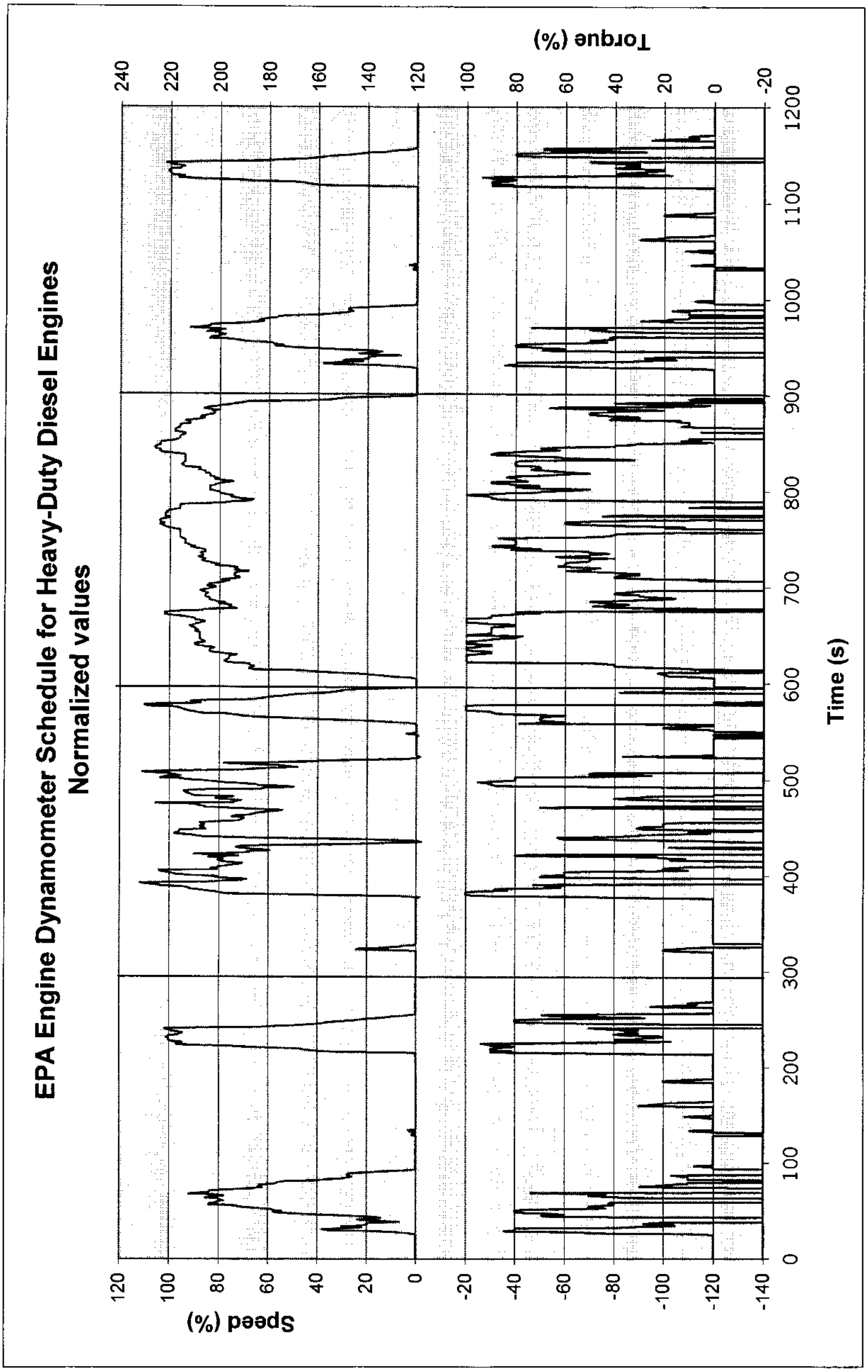

Figure I-6: *US Transient driving cycle (engine dynamometer)*

In the Euro III regulation for the year 2000, a complementary transient test cycle is to be used for some specific novel diesel engine technology (e.g. $deNO_X$ and particulate trap technology) and for alternative fuels. This test cycle is called the European Transient Cycle (ETC). This test cycle is shown in Figure I–7. In this Figure, it can be noted that the ETC test cycle is somewhat longer than the US Transient test cycle. Therefore, it appears as if the variations (load and speed changes) are steeper in the former cycle than in the latter cycle, due to scale effects. In general, the fraction of the time spent idling is much less in the ETC cycle than in the US Transient cycle. A more thorough investigation of the new European driving cycles (ESC and ETC) has been made by Hedbom at MTC [2].

By looking at Figures I–6 and I–7 it can be noted that it is difficult to get an clear understanding of how the vehicle[1] is run in the test cycle, since the load and speed of the engine are changed simultaneously. As the ETC test cycle is derived from logged vehicle data, it is also possible to obtain a chassis dynamometer driving cycle from these data. This variant is shown in Figure I–8. In this Figure, the three different parts of the driving cycle (urban, rural and motorway) can also be seen. It has to be stressed, however, that the chassis dynamometer version of the ETC test cycle will *not* be used in any emission regulation. This is presumably due to the previously discussed cost issues. Another fact worth mentioning is that a vehicle with a different gearbox than the model vehicle used to derive the engine load and speed from the logged data for the regulated (engine) version of the ETC test cycle will be subjected to a different load and speed than in the regulated cycle. Therefore, the (uncorrected) chassis dynamometer version of the ETC test cycle cannot be used to correctly simulate the engine dynamometer version of the ETC test cycle. Thus, it can be concluded that the use of a chassis dynamometer version can hardly be applied for in-use compliance testing of engines. The only alternative is to test the engine on an engine test stand.

[1] Although this question might be considered hypothetical it is of great interest if a comparison between light-duty and heavy-duty test cycles is to be carried out.

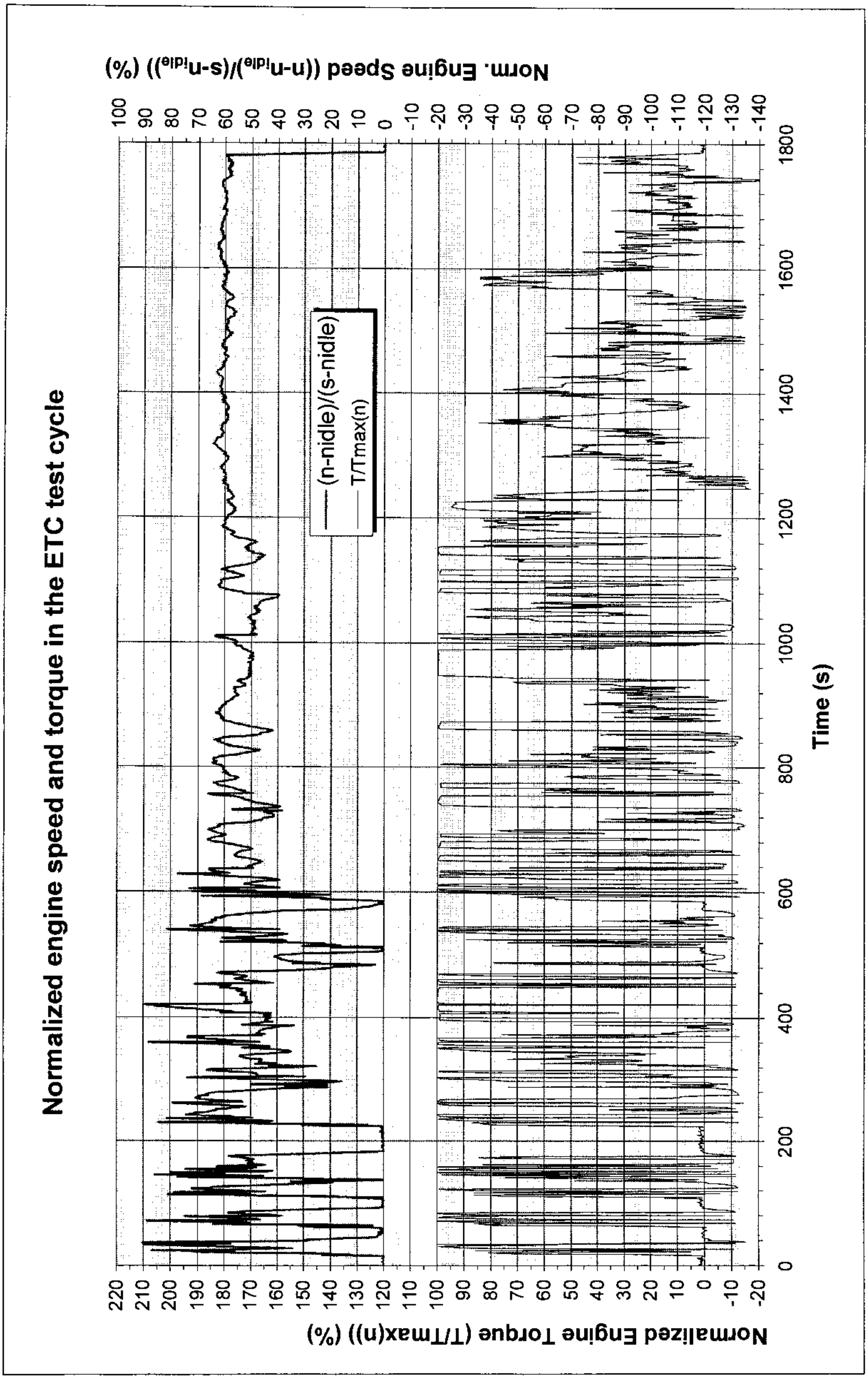

Figure I-7: *The European Transient Cycle (ETC) for engine dynamometer testing*

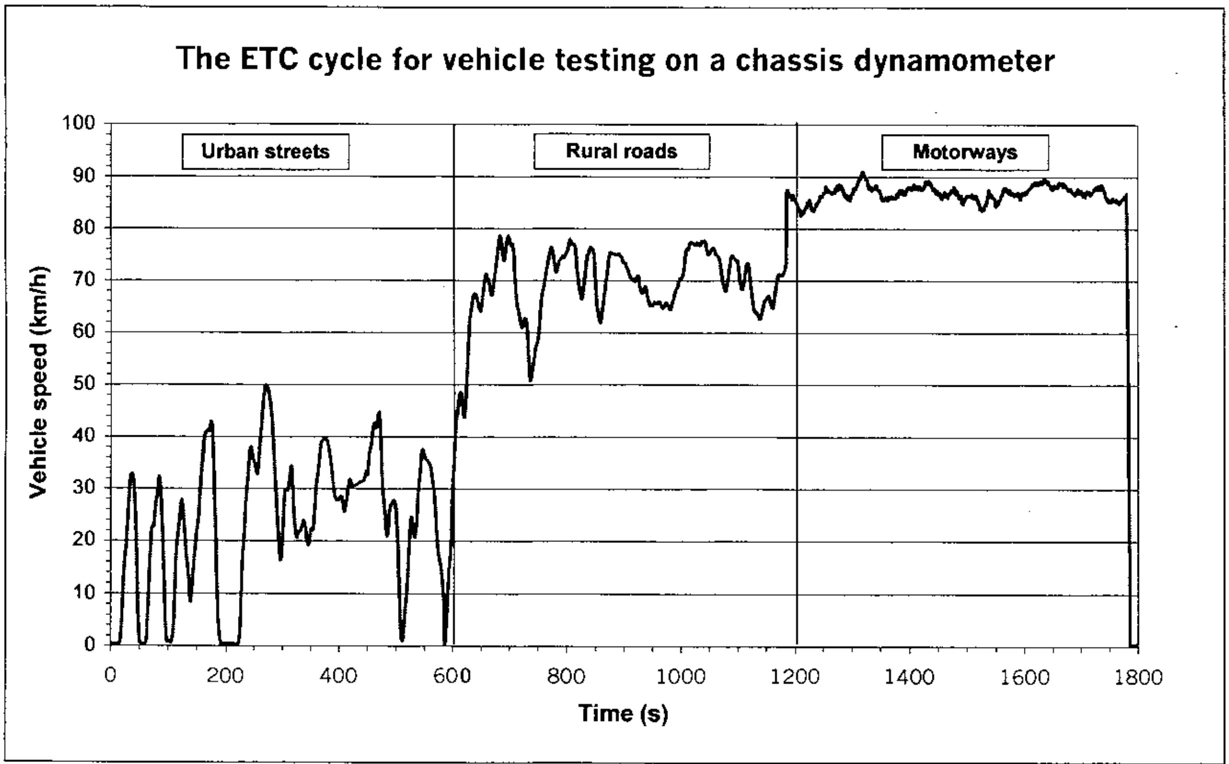

Figure I-8: The European Transient Cycle (ETC) for chassis dynamometer testing

5 EU Emission limits for light-duty vehicles

The emission standards for the light-duty vehicles are shown in Table 4. The limits for the year 2000 have been on debate for a very long time and the limits have finally been set during the summer of 1998.

The European regulation 91/441/EEC is the base for the Indian regulation for the year 2000. It is worth noting that the emission levels in this regulation were somewhat higher than the corresponding US 1988 regulation. For example, the HC and the NO_X limits in the US regulation were 0.25 and 0.62 g/km respectively vs. 0.97 g/km for the sum of HC and NO_X in the European regulation. However, since the driving cycles are different, the CO and HC emissions for a specific vehicle are generally higher in the European driving cycle (due to cold start and weighting factors, as mentioned above). Therefore, the difference in actual on-road emission level between these two regulations for CO and HC is probably less than the difference in the limits might indicate. This is true providing that the possibility of increasing the HC emissions and simultaneously reducing the NO_X emissions is not used to an extreme (the $HC+NO_X$ limit gives this option). Diesel engines are much less affected by cold start and driving conditions and, in this case, the European 91/441/EEC regulation was certainly more lenient than the corresponding US regulation.

Table I-1: *EU Emission standards*

Directive	Time[a]	CO	HC	NO_X	$HC+NO_X$	PM[b].
		Emission component and limit (g/km)				
91/441/EEC all	6/92 1/93	2.72	---	---	0.97	0.14
94/12/EC petrol	10/96 10/97	2.2	---	---	0.5	---
94/12/EC IDI[c] diesel	10/96 10/97	1.0	---	---	0.7	0.08
94/12/EC DI[d] diesel	10/96 10/97	1.0	---	---	0.9	0.10
Step III (2000), petrol[e]	10/2000 10/2001	2.3	0.20	0.15	---	---
Step III (2000), diesel[f]		0.64	---	0.50	0.56	0.05
Step IV (2005), petrol[e]	10/2005 10/2006	1.0	0.10	0.08	---	---
Step IV (2005), diesel[f]		0.50	---	0.25	0.30	0.025

Notes:

[a] Two dates designate that the timeframe for the regulation is stepwise, i.e. the first date is for new type approvals and the second date is for all new registrations.

[b] Particulate limit is for diesel vehicles only.

[c] IDI: indirect injection

[d] DI: direct injection

[e] The regulation for the year 2000 will use the NEDC test cycle and therefore the limit for CO (2.3 g/km) is actually stricter than the limit in the 94/12/EC regulation (2.2 g/km). Since the HC emissions are higher in the NEDC cycle as well, the actual reduction in the $HC+NO_X$ emissions (0.45 compared to 0.50) is much greater than the numbers would indicate.

[f] Diesel engines are less affected by cold starts than petrol engines and therefore a comparison between the limits for the year 2000/2005 and the previous limits is more relevant for diesel engines than for petrol engines

The current EU regulation (94/12/EC) separates cars using petrol and diesel engines. For the petrol engines, the $HC+NO_X$ limit was cut by approximately 50 % compared to the previous regulation (91/441/EEC), whereas the CO emission limit was not reduced as much. For the diesel engines, the CO emissions were reduced by approximately 60 %. In the current European regulation, there is also a separation between indirect injection (IDI) and direct injection (DI) diesel engines. The limits are higher for the DI engines in order to take into account the fact that these engines represented a novel technology when the regulation was introduced. Therefore, the emission control was not as advanced as that for the IDI engines. The limit for $HC+NO_X$ for the diesel engines was reduced by approximately 30 % for the IDI engines and by less than 10 % for the DI engines. The reason for having different limits for petrol and diesel engines can be discussed. It is known that the CO and HC emissions are generally lower for diesel engines than for petrol engines, whereas the NO_X and particulate emissions are higher. The emission limits presumably consider these fundamental facts. Therefore, the regulation has more stringent levels for the CO emissions from diesel cars and correspondingly more stringent $HC+NO_X$ emissions from the petrol cars. Another specific reason for allowing higher NO_X emissions from diesel engines than from their petrol counterparts has also been the lower fuel consumption and CO_2 emissions from the former engines. Note that the particulate emissions are not regulated for the petrol-fuelled cars. The reason for this is probably that the particulate emissions from these cars are more than an order of magnitude less than from the diesel cars. In summary, It seems like the current EU emission limits for the diesel-engined cars are somewhat more lenient than for the petrol-fuelled cars. The European industry also has a unique niche in diesel technology compared to the auto industry outside the EU and it is likely that the EU also intends to favour its own industry in some respect. It could be argued that all types of engines and fuels should comply with the same emissions limits in the long-term future.

In the EU step III[1] emission regulation (often called Euro III), the difference in the limits for petrol and diesel-fuelled cars is even greater than in the current regulation. For example, the difference in NO_X emissions is more than a factor of three. The most plausible reason for this difference is the difficulties in reducing the NO_X emissions from the diesel-fuelled cars. In contrary to the stoichiometric petrol (e.g. otto-cycle) engines, no NO_X reduction after-treatment (catalyst) with significant NO_X reducing capability has yet been commercialised. Even if NO_X reducing after-treatment technology eventually will be available in the future, it is not likely that the reduction efficiency will be as high as for the petrol-fuelled cars.

A proposal for the EU step IV limits (Euro IV) has been put forward as well, but for the moment, these levels have not been finalised. Even if the proposed limits are very uncertain, they have been included in Table I–1.

6 EU Emission limits for heavy-duty engines

The European emission limits for the heavy-duty engines are shown in Table I–2. Please note that some of the regulations use different driving cycles are therefore the emission limits in the Table cannot be directly compared with each other.

Table I–2 shows that the emissions limits for the heavy-duty vehicles in Europe will be reduced, even if the reduction is not as great (in relative terms) as for the petrol-fuelled passenger cars. Since the new driving cycles, ESC and ETC, differs from the current ECE R49 driving cycle it is somewhat difficult to compare the emission limits. Generally, the difference between the ECE R49 cycle and the new ESC cycle is relatively small. The difference between the ECE R49 cycle and the ETC cycle is much greater. The same can be said about the comparison between the ESC and the ETC cycles. This can also be seen in the Euro III, IV and V standards, where the corresponding emission levels for both cycles are given.

[1] The step III regulation is sometimes called Euro III, even if this denotation is more often used for the heavy-duty engines.

Table I-2: EU Emission standards

Directive	Emission comp. and limit (g/kWh) Time	CO	HC	NO_X	PM
ECE R49[a]		14	3	18	n.l.[b]
ECE R49.01 (88/77/EEC)[c]	86 – 88	11.2	2.4	14.4	n.l.
Euro I	7/92 10/93	4.5	1.1	8.0	0.612/0.36[d]
Euro II	10/95 10/96	4.0	1.1	7.0	0.25/0.15[e]
Euro III[f] ESC&ELR[g]	10/2000 10/2001	2.1	0.66	5.0	0.10/0.13[h]
Euro III[f] ETC[i]		5.45	0.78	5.0	0.16
Euro IV[j] ESC&ELR[g]	10/2005 10/2006	1.5	0.46	3.5	0.02
Euro IV[j] ETC[h]		4.0	0.55/1.1[k]	3.5	0.03
Euro V[l] ESC&ELR[g]	10/2008 10/2009	1.5	0.46	2.0	0.02
Euro V[l] ETC[h]		4.0	0.55/1.1[k]	2.0	0.03

Notes:

[a] This was the base level for the ECE and EU emission limits for HD engines. The ECE R 49 driving cycle was used from the original ECE R49 regulation until the Euro II regulation.
[b] n.l.: not limited.
[c] This limit imposed a reduction of the ECE R49 limits by 20 % and therefore it is often referred to as ECE R49 – 20 %. These limits were originally introduced in Germany as a voluntary measure and thus the adoption of the limits by the engine manufactures was somewhat gradual.
[d] The higher particulate limit is for engines with a power below 85 kW.
[e] The higher particulate limit is for engines with a cylinder capacity of less than 700 cm^3 per cylinder and a rated speed higher than 3000 rpm.
[f] Proposal for the year 2000.
[g] ESC: The new steady-state EU 13-mode cycle; ELR: The new EU smoke test.
[h] The higher particulate limit is for engines with a cylinder capacity of less than 750 cm^3 per cylinder and a rated speed higher than 3000 rpm.
[i] ETC: The new EU transient cycle.
[j] Preliminary (only indicative) proposal for the year 2005.
[k] Lower limit is for NMHC and higher limit is for methane (CH_4)
[l] Preliminary (only indicative) proposal for the year 2008.

In general, it can be stated that the heavy-duty emission limits in Europe have been getting much tighter in the recent regulations. For example, the NO_X emissions in the proposed Euro III regulation are only about 30 % of the base level for a conventional diesel engine (typically 15 – 16 g/kWh for a DI heavy-duty engine). The reduction of the particulate emissions is even more dramatic, since a level of about 1 g/kWh (and sometimes higher) was quite common in the late 1970´s. The reduction in the Euro III regulation is about one order of magnitude in comparison to the base level. A level of 1 g/kWh is the approximate level that can be expected from current (i.e. relatively new) diesel engines produced in India. The use of fuel having higher sulphur level than 0.25 % increases the indicated particulate level from the Indian vehicles further.

Looking even further into the future reveals that the most significant impact in the Euro IV and V will be on the particulate limits (0.02 g/kWh). Compared to the current new Indian vehicles, the reduction is a factor of 50 and in comparison to older vehicles in India, the reduction is (presumably) more than two orders of magnitude. With the knowledge of today, these limits cannot be met without a particulate filter. However, this level has already been demonstrated with commercial particulate filters on diesel engines (see Appendix IV and V). Alternative fuels, such as CNG or alcohols, have the potential to meet this level without after-treatment devices (see Appendix VII).

7 References

1 AVL: "Current and future exhaust emission legislation" AVL List GmgH Austria, 1992.

2 "Emission Standards", DieselNet, www.dieselnet.com, 1998.

3 Hedbom A.: "The Fige transient cycle and the OICA/ACEA steady-state cycle with dynamic load response test." MTC Report MTC 9511A, 1995.

II PARTICULATE MATTER FROM DIESEL VEHICLES – A PARTICULAR AIR POLLUTION PROBLEM IN INDIA

1 Introduction

The main portion of this appendix is an overview of some of the data generated in a project funded by the Swedish EPA (SEPA), which was commissioned by SEPA to Motortestcenter (MTC) of the Swedish Motor Vehicle Inspection Co. This subject was not included in the project proposal but it was added anyway since the discussions in Delhi revealed the necessity to elucidate some of the particular problems in this area.

The project aim was to investigate the particle size distribution from both light-duty and heavy-duty vehicles. One of the authors of the present report (Peter Ahlvik) was the project manager in charge of this project. Two reports have so far been published from this project. The first report was published be SAE in February 1998 [1] and the second report has been published by MTC in January 1999 [2]. A third report will be published by MTC in the beginning of 1999.

2 Background

Particulate emissions have been very much in focus recently due to the anticipated health effects. Daily mortality and morbidity as well as the probable cancer risk have been of most interest. It has been shown by Pope et al. [3, 4], that daily mortality correlates with particle concentration in the ambient air. It seems that the correlation is better for smaller particles ($PM_{2.5}$) than larger particles[1] (PM_{10}), indicating that smaller particles may be more harmful in this respect. In earlier work, it was thought that the cancer induced on rats by vehicle exhaust had been related to the hydrocarbons (mainly PAH) adsorbed on the particles. However, it has recently been shown in for example studies by Heinrich et al. [5], Gallagher et al. [6], and Heinrich et al. [7], that even inert particles such as carbon black and titanium dioxide can induce cancer in animals. This subject has been discussed intensively during recent years in Sweden as well as in the rest of Europe and in the USA. A report authored by the environmental commission of the Swedish insurance company Scandia, has summarised recent research in this field and has elucidated the present situation in Sweden concerning the particle emissions originating from different sources [8].

After the introduction of the mandatory Swedish A12-Regulation for light-duty vehicles in 1989, most petrol-fuelled passenger cars have used the so-called three-way catalyst (TWC) emission control system. This emission control system is very effective as it can reduce most emission components by more than an order of magnitude when the engine (and catalyst) is hot. However, during warm-up conditions and in the case of malfunction, the emissions can be considerably higher, i.e. on the same level as for an engine without the TWC system. In order to gain more knowledge of the emissions under these conditions, it is of interest to investigate the emissions in cold

[1] PM_{10} and $PM_{2,5}$ refer to particles with an aerodynamic diameter smaller than 10 μm and 2.5 μm respectively.

ambient conditions[2] and those of in-use vehicles with high mileage. The particulate emissions from petrol fuelled cars, and in particular petrol-fuelled cars equipped with TWC emission control, are considerably lower than those from diesel-fuelled cars. Thus, particulate emissions are not even regulated (at present) for petrol fuelled vehicles. However, it is expected that the particulate emission will increase in cold conditions and due to ageing for these cars. Moreover, characterisation of the particulate emissions from petrol cars (mass and size distribution) is of great importance, as a reference for comparisons with diesel-fuelled cars.

Since the diesel-fuelled vehicles emit significantly higher particulate emissions than their petrol-fuelled counterparts, an increased share of diesel-fuelled vehicles will inevitably increase the particulate emissions from light-duty vehicles. This fact has been of great concern for the Swedish Environmental Protection Agency (SEPA). In a recent report by SEPA commissioned by the Swedish Government, the consequences of an increased share of diesel-fuelled passenger cars have been investigated [9]. The sales of diesel-fuelled passenger cars have traditionally been very low in Sweden until the last years. Typically, only about 1 % of the sales of new cars was diesel-fuelled vehicles between 1986 and 1993 [9]. This was significantly lower than the almost 20 % share of the market in the EU[3] during the same period. Since 1993, the share of diesel-fuelled vehicles has increased considerably in Sweden. In 1998, the share (including privately imported used cars) has been estimated to be about 15 % [9]. In the report by SEPA, it was stated that an increased share of diesel-fuelled passenger cars would increase the emissions of NO_X, particulates and carcinogenic substances. Consequently, the Swedish Government will presumably introduce some economic incentives[4], such as an increase in the taxation on diesel-fuelled cars (or on the diesel fuel), or try to limit the share of new diesel-fuelled cars by other measures.

In the current regulations for diesel-fuelled vehicles, only the particulate mass is regulated. As mentioned above, it has been suggested by some researchers that smaller particles can be more harmful than larger particles and therefore the regulation of mass alone is not sufficient to fully characterise the particulate emissions. At present, very few data are available on the particle size distribution in the exhaust from diesel-fuelled passenger cars and even fewer data are available for petrol-fuelled cars. It has therefore been of interest for SEPA to carry out a survey on the particle size distribution from a couple of in-use vehicles, in order to be able to assess these levels from motor vehicles.

2 Project objective and methodology

The primary scope of the SEPA funded project at MTC on light-duty vehicles was to generate data on particle size distribution from some petrol and diesel-fuelled light-duty vehicles. All the other regulated emissions, as well as particulate emissions that are not regulated for petrol-fuelled cars, were also measured.

[2] The cold conditions mentioned here refer to temperatures below the interval of +20 – +30 °C used in most test cycles.

[3] In some EU countries, the share of the diesel-fuelled vehicles has sometimes been more than 50 % (for example in Austria and France).

[4] Today, the diesel fuel tax is less than the petrol tax but the yearly vehicle tax is considerably higher for diesel cars.

The strategy for the work was to carry out the measurements on several vehicles representing types of emission control strategies. The tests were also carried out under different driving conditions (temperature) and in real transient driving cycle. The new European driving cycle was chosen and it was divided into three parts in order to be able to study the effects of different driving conditions on the emissions. The following parameters were of primary interest to investigate:

- Emission control technology
- Deterioration (vehicle mileage and age)
- Fuels; diesel oil and petrol
- Temperature, +22 °C and –7 °C
- Total and modal emissions of all measured emission components

The test vehicles selected were 11 petrol and 5 diesel-fuelled vehicles. All the petrol vehicles were equipped with three-way catalyst (TWC) emission control. The model years for the petrol cars was from 1988 to 1996, and the odometer reading covered a wide range, from 14 000 to 180 000 km. The diesel cars were somewhat newer, i.e. from model year 1993 to 1997. Consequently the odometer readings were generally lower for the diesel cars than for the petrol cars and they ranged from 9 000 to 83 000 km. Both vehicle categories were selected to represent different emission control technologies. All the petrol-fuelled cars used the TWC emission control system, but they were certified according to different emission regulations. Two of the diesel-fuelled vehicles used indirect injection (IDI) combustion system and three of the vehicles used the direct injection (DI) combustion system. All the diesel-fuelled vehicles were equipped with an oxidation catalyst.

3 Particle size distributions from petrol and diesel-fuelled cars

In Figure II-1, which is an excerpt from the project report [2], a comparison of the particle size distribution from the petrol- and the diesel-fuelled cars at +22 °C is shown. The results in this Figure show the results for the total driving cycle as well as the different modes (see appendix I) of the driving cycle. Other emission results and comparisons are covered in the project report [2].

Figure II-1 shows that the number of particles was much less for the petrol-fuelled cars compared to the diesel cars in all parts of the driving cycle (Figure II–1). In bag 1, the difference was more than one order of magnitude and in bag 2, the difference was 2 – 3 orders of magnitude. In the EUDC phase, the difference was significantly less than in the two other parts of the cycle and for the smallest particles in this phase, the difference was very small. The shape of the distributions in the EUDC phase indicates that the number of particles smaller than 30 nm, in this part of the cycle, might be as high or higher for the petrol-fuelled cars as for the diesel-fuelled cars.

In general, the number of particles was much higher for the diesel-fuelled cars than for the petrol-fuelled cars. It has to be stressed that this comparison was within the interval of the measurement equipment. If the measurements could have been made for even smaller particles the results could have changed.

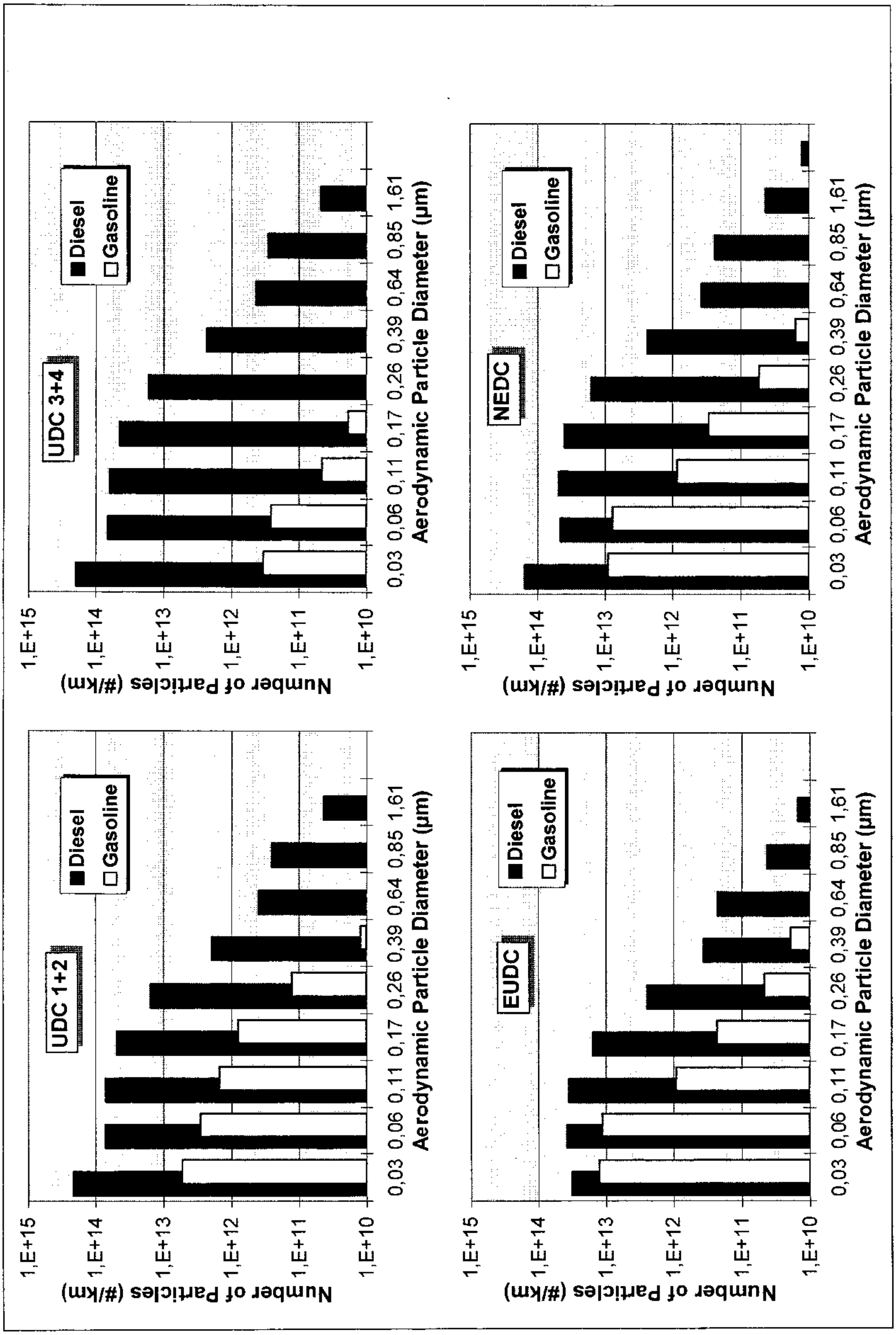

Figure II-1: *Average particle size distribution at +22 °C, petrol- and diesel-fuelled cars*

4 Discussion

4.1 *Particle size distribution measurements*

It is obvious that the measurement technology and the instrumentation must be further developed to meet the needs for the characterisation of the particulate emissions. This instrument used in this test series must be further developed to be able to measure even smaller particles. On the other hand, the real-time capabilities of this instrument facilitate the possibility of testing the objects in a transient driving cycle. An instrument without these capabilities is not practical under these conditions.

4.2 *Particle size distribution from petrol-fuelled vehicles*

One of the most interesting findings for the petrol-fuelled cars was the influence of cold start and the relatively high particle number in the EUDC phase. By comparing bag 1 and bag 2, it can be seen that the cold start can increase the particle number by more than one order of magnitude in some cases. It must therefore be stated that the cold start is an essential part of the test cycle for petrol-fuelled cars and that the use of only hot starts can give erroneous results. Concerning the higher number of particles in the EUDC phase, no clear explanation has been found. However, a higher number of particles at high speed have been found in other investigations. One example of a recent report is of a joint project by several oil companies [10]. In that project, measurements were carried out on a number of cars at constant speeds of 50 km/h and at 120 km/h. The number of particles from the petrol-fuelled cars increased disproportionately as the speed was increased. The increase in the number of particles was some 3 orders of magnitude when the speed was increase from 50 to 120 km/h.

Since most of the particles in the exhaust from the petrol-fuelled cars are formed during cold-start and at high speed, there is some scope for future development in these areas. This could decrease the particulate emissions (mass and number) even further. On the other hand, it has previously been shown by this author that the new direct injection technology currently being commercialised for petrol-fuelled engines leads to *higher* particulate emissions than from conventional petrol-fuelled cars [11]. It is recommended that this matter should be further investigated.

4.3 *Particle size distribution from diesel-fuelled vehicles*

The number of particles from the diesel-fuelled cars were largely unaffected by the driving pattern and temperature. Furthermore, the number of particles from the diesel-fuelled engines was higher than from the petrol-fuelled engines, which is conceivable due to the higher particulate mass emissions from the former cars. During all the driving conditions investigated here, the number of particles was higher for the diesel-fuelled cars for all sizes of particles. Since the instrument used in the measurements of particle size cannot measure smaller particles than 30 nm, there *could* be some conditions where the number of particles, which are smaller than this size, is higher for the petrol-fuelled cars.

Diesel engines using high injection pressure have been suspected of emitting a higher number of small particles. This has been stated by Baumgard et al. in a recent report [12]. No apparent difference was found between the DI and IDI cars tested here, although the difference in injection pressure between the different cars must be considerable. However, none of the DI cars investigated in this study did use an engine that utilised extremely high injection pressure (2000 bar). It is therefore of interest to investigate the particulate emissions from these types of engines as soon as they become commercially available. Furthermore, it should be noted that the two combustion systems (DI and IDI) are different in many other aspects than just the injection pressure. It is likely that many other parameters could have a significant impact on the particle size distribution and the particle mass emissions.

It has been previously shown that the particle size number was significantly less from petrol-fuelled cars than from diesel-fuelled cars. This trend was expected, however, due to the fact that there was also a great difference in particle mass emissions. The question is to what extent this trend will increase the pressure on the development of and emission regulations for diesel-fuelled cars. In California, for example, future particulate limits of 0.01 g/mile (0.0062 g/km) are presently being discussed. Economic incentive is another method that will be used by some governmental authorities. There should also be a discussion about whether there is some available technology or some future development that could lower the particulate emissions. Three areas are of interest in this respect.

1. Improvement of the combustion system (e.g. high injection pressure, etc.)
2. After-treatment devices
3. Radical new combustion system (i.e. homogenous combustion)

Drawing on the results of the comparison of light-duty engines with heavy-duty engines, it can be stated that the particulate emission index (EI[1]) is considerably less for the latter category. This indicates that the combustion system is more advanced for heavy-duty engines (e.g. higher injection pressure). Using the best results for particulate emissions from heavy-duty engines in the heavy-duty US Transient cycle would result in a particulate emissions level of about 0.01 – 0.02 g/km from a passenger car. On the other hand, passenger car engines have to meet tighter NO_X emission limits than heavy-duty vehicles and therefore they use EGR, which somewhat increases the particulate emissions. Using present knowledge, a particulate emission limit of 0.01 g/mile seems extremely difficult to achieve by in-cylinder methods. As mentioned above, there is additionally some concern about the indication that the higher injection pressure could increase the number of the smallest particles [12].

Using after-treatment devices such as particulate traps is a viable method of significantly decreasing the particulate emissions. Before such devices can be used commercially on a large scale (in passenger cars[2]), however, considerable development must be carried out. Moreover, there is some concern about that there might be an increase in the number of smallest particles for some of the trap types. Although many of these effects appear to be due to sampling and measurement effects, this potential problem should be evaluated before traps are introduced on a larger scale.

[1] Emissions Index, EI, is the mass emissions (in g/kWh or g/km) divided by the mass of fuel used (in g/kWh or g/km).
[2] There are actually some commercially available particulate traps for heavy-duty vehicles.

In the long-term, a radically new combustion system that uses homogenous charge would probably be the best solution for the diesel engine. Homogenous charge is used in the petrol-fuelled engines and this is the reason for the low soot (and particulate) formation in these engines. It is theoretically possible to use homogenous charge in compression ignition engines as well. Another benefit of this system is the potential of reducing the NO_X emissions by 2 to 3 orders of magnitude. However, much development work has to be carried out before this combustion system could become a practically viable solution.

5 Specific considerations for India

Since the share of diesel vehicles in India is very high, it is no surprise that the particulate emissions probably is the most significant problem of all air pollution problems. The introduction of better diesel fuel will decrease the particulate (mass) emissions due to the lower sulphur levels. Results in the literature indicate though, that there is no apparent reduction of the smallest particles by using premium diesel fuel [10]. The only viable immediate solution to decrease the emissions of the smallest particles would be to use particulate traps or to switch to another fuel. Since this particulate trap technology is most mature for heavy-duty vehicles, other non-technical solutions must be found to decrease the particulate emissions from light-duty emissions. Economic incentives or the ban of diesel-fuelled light-duty vehicles in the most polluted areas seems to be the only other alternatives left. In the long term, other solutions should be evaluated as well.

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III MOTOR FUELS IN INDIA

1 Background – Present supply

India's crude oil supply by recovery from own oil fields is around 780,000 b/d mainly from offshore fields NW of Bombay. This corresponds to about 45 % of the demand, and the import needs thus are great. The estimated proved reserves, which have been estimated as static during the 90's, now are 4,300 million barrels corresponding to about 15 years recovery at present rate, but only 7 years of oil consumption (1,750,000 b/d or 90 Mt/yr). Depletion midpoint (= half of ultimate recovery) is estimated to be at year 2000. Crude imports are dominantly from Middle East. It is not known how imports are split on crudes and finished products.

The Indian crudes from the major oil fields seem to be sweet, light crudes, 37-50 °API, and highly varying from the minor fields, 16-45 °API. The character of the crudes is not known (paraffinic/naphtenic?). Import crudes should be mainly paraffinic with medium to high sulphur content.

The Indian refining industry, organised in seven companies, has a total refining capacity of over 1.1 million b/cd (about 60 Mt/yr) divided on14 refineries, but only one is sizeable and nears the 200,000 b/d capacity. Indianoil Corp. is the biggest and it operates 6 of the refineries and is almost entirely owned by the Government of India, which also holds a majority interest in all other refineries but one.

Most refineries have vacuum distillation as basis for cracking (thermal and catalytic) and cooking, and asphalt and lube oil production. Units for upgrading of petrol are small (catalytic reformers) or non-existing (isomerisation, polymerisation, alkylation, etherification), only one TAME unit is under construction. Expansion seems to be in the field of new grassroots refineries (one in Gujarat and one very large, 360,000 b/d, in Southwest, though with unknown configurations) and capacity will be increased to 130 Mt/yr. Some expansion of the gas oil desulphurisation capacity is under way.

The petrochemical industry based on steam cracking of naphtha to olefins is sizeable.

Natural gas reserves are estimated to some 500 Gm3 and the production rate at 21 Gm^3/yr and increasing. In parallel, over 600,000 t/yr of liquid hydrocarbons (LPG etc) are produced. Large expansions are planned. Gas pipelines run from the western coast to the Delhi area and other cities in central north India. LPG pipelines have been proposed.

2 Motor fuels

Motor fuel usage is mainly diesel oil, about six times the petrol usage. The qualities are specified in Indian Standards (IS). No follow-up survey of marketed fuels is, however, known.

With a ***petrol*** market with largest usage as 2-stroke engine fuels, the demand for high-octane petrol should be low. This is supported by the fact that the reforming capacity of the refineries is low (only three of refineries use reformers for petrol upgrading) and the content of olefinic, cracked petrol is very high. The standard (IS 2796:1995) requests only min. RON 87 or AKI min. 82 for the unleaded grade and AKI will be increased to 84 (88 for a higher grade) in year 2000, when new exhaust gas limitations will require catalytic converters on all new cars and 2- and 3-wheelers. The benzene content will be maximised to 5.0 %vol, and the sulphur content is kept at max. 0.2 %wt. It should be noted that these octane levels are not optimal in the entire system engine-refinery, as increased car fuel consumption outweighs the savings in refinery fuel consumption at the production of lower octane petrol. For comparison, optimum levels for unleaded petrol are calculated to be RON 95 and MON 85 (AKI 90).

Evaporative and exhaust emissions must be analysed and judged from health and environmental point of view. High emissions of toxic and ozone-forming components such as butadiene, olefins, and aromatics are not desired but might be expected to be high. Suitable measures might be reformulation of the petrol to reduce its contents of light olefins, benzene and sulphur. This can be done by modification of the reformer feed to reduce benzene precursors, decreased reformer severity, isomerisation, etherification and/or alkylation to reduce light olefins and enhanced hydrotreating and/or omitting of heavy cracked petrol. With the advent of catalytic after-treatment in India the sulphur content of the petrol will be of paramount importance, as the activity of the catalysts for reduction of unburned fuel and nitrogen oxides, NO_X, is dependent on the sulphur content

The quality of the Indian ***diesel oils*** (IS 1460:1995) might be feared to be low (low cetane, high content of sulphur), in spite of possible favourable crude quality, due to its large share of the motor fuels and the probable high content of cracked, aromatic oils. The 1996 Indian specification requires only cetane number (CN) min. 45 and allows 1.0 %wt of sulphur, which from year 2000 will be changed to CN min. 48 and max. 0.25 %wt of sulphur. On-going construction of new HDS units at Indian refineries will make this possible and be a base for further reductions, following the trend in other parts of the world.

Low cetane properties of the diesel oil will lead to high emissions of nitrogen oxides and particulates containing high amounts of toxic PAC (Polynuclear Aromatic Compounds). Measures to mitigate this could be to lower the end boiling point (or T95) to avoid the heaviest components rich in PAH (Polynuclear Aromatic Compounds) and increase the severity of desulphurisation to reduce the sulphur content to make catalytic after-treatment possible. Large reduction of the boiling range of the diesel oil, however, decreases its availability, and preferable measures would be to hydrogenate the vacuum gas oil cracker feed (mild hydrocracking), which will lead to improved diesel oil quality (higher cetane, low sulphur content, and greatly reduced content of PAH). There is today no hydrocracking capacity at Indian refineries, although one unit is reported to be under construction. Investments in hydrocracking are capital intensive.

The extreme diesel oil qualities in use in the Nordic countries, sometimes called "city diesel oil", have very narrow boiling range and specified low content of PAH (defined as polycyclic aromatics with three rings or more, which are the biologically active ones and were identified as a major cancer risk source in urban air). It should be emphasised that the focus for these diesel oils was a very low content of PAH, which is directly related to the content of PAH in the exhaust. A very low sulphur content will then also be obtained (but was not the main focus), which will make use of catalytic after-treatment possible and is widely applied on heavy duty buses. The result is largely reduced toxicity of the exhaust gases. Due to this the tax on this diesel oil (environmentally classified oil) has been differentiated compared to the old quality as support for its penetration of the market, which in Sweden now is over 90 %.

Introduction of diesel oils with similar specification, Table 1, is proposed for India in first hand for use in urban areas. The immediate effect would be lowered emissions of particulates (black smoke), nitrogen oxides and greatly reduced toxicity of the exhausts. Use of catalytic after-treatment on at least new vehicles will then be possible (ultimately use of particle filters and deNO_X-catalysts) and further reduce the toxicity to make the fuel viable also in urban areas. If hydrocracking will be possible at an Indian refinery, the possibility to produce such diesel oils domestically should be investigated. Otherwise, imports might be a possibility.

If ***LPG*** will be widely used as motor fuel, it is important to specify fixed propane to butanes relation to safeguard proper control of the air–fuel ratio. Moreover, a low content of olefins should be specified to avoid problems with deposits in the fuel system and to bring down the toxicity of the exhaust gases. Use of catalytic after-treatment is recommendable.

The advantage with LPG is above all that it is free from aromatics and has low content of olefins being precursors to toxic benzene and butadiene respectively in the exhaust. Compared to diesel oil fuelled vehicles, the advantage is almost eliminated fuel related particle emissions, but the penalty is increased fuel consumption due to switch-over to otto-cycle operation. Low NO_X-emissions will depend on well functioning fuel supply control, be it stoichiometric or lean burn systems.

CNG has much of the same or even better advantages from emissions point of view as mentioned for LPG. Technique for its use as motor fuel is in principle the same. CNG (and LPG) must be seen as local niche motor fuels as the costs of distribution, refuelling and vehicles are much higher than in systems using easily handled liquid motor fuels. Thus, CNG can only be considered where gas pipelines already exist.

3 Discussion

Delhi in India is said to be the second most polluted city in the world concerning the air. In absence of any known recordings of which harmful compounds are most prevailing we list commonly known effects in urban and rural areas and compounds/precursors causing them.

• Acidification, corrosion, erosion	– sulphur and nitrogen oxides
• Acute health threats (airway diseases)	– oxidants such as ozone, nitrogen dioxide, and aldehydes, sulphur dioxide and particles
(heart diseases)	– carbon monoxide
• Cancer risks	– PAC, benzene, butadiene, ethene aldehydes, particulates
• Crop and forest damages	– ozone, acidifying agents
• Climate effects	– greenhouse gases such as carbon dioxide, methane, dinitrogen oxide, etc.

For several of these compounds (carbon monoxide, sulphur and nitrogen dioxide, ozone, particles of small size, PM_{10} or PM2.5) limits for contents in air have been set by the World Health Organisation (WHO) or national authorities, e.g. on benzene. Other limits have been set for crop damages (ozone) or are limited by deposition rates/critical loads (sulphur and nitrogen oxides and acids).

Emissions of sulphur oxides can only be reduced by limiting the sulphur content of the fuels. This is important not only to control the content of sulphur dioxide in the air, to decrease particle mass emissions and their the acidity, and to reduce acidification of soils, reduce corrosion of metals and erosion of building materials, but also to enhance the activity of catalytic systems to decrease emissions of unburned fuel and nitrogen oxides. The proposed max. sulphur content of petrol (0.10 %wt) and diesel oil (0.25 %wt) in India are still much higher than desirable. The auto industry worldwide fuel charter suggests 0.003 %wt (30 ppmwt) as ultimate limit! The technique for reductions in refineries is available but seems to be more difficult to apply in India due to the uniquely high proportions of cracked, high sulphur streams in the refineries. Still this can be achieved in connections with other goals (below).

Reductions of nitrogen oxides is a matter for control of combustion conditions and catalytic after-treatment as their formation takes place in the combustion chambers by thermal reactions in the flame, particularly in hot zones. Diesel oil fuelled diesel engines are the main source in the transport sector. Improved diesel oil qualities with higher cetane numbers and improved fuel injection/ engine systems have shown remarkable progress during later years and will continue to be developed. For 4-stroke petrol engines 3-way catalytic reduction of both nitrogen oxides and unburned fuel is well-proven technique and should be generally used in new vehicles, requiring unleaded (and low sulphur) petrol. The technique is applicable also when using alternative fuels as LPG, CNG, and alcohols (methanol, ethanol). In 2-stroke engines, normally running rich, nitrogen oxide formation is low and is not considered a problem. For diesel engines catalytic reduction technique, $deNO_X$, is not yet commercially available and would require fuels with very low sulphur content. Some of the alternative fuels are less prone to form nitrogen oxides due to lower flame temperature (alcohols) and capability to burn safely in very lean flames with large excess of combustion air. Very good control of the fuel/air ratio is, however, necessary.

Ozone does not exist in the exhaust gas but is formed in the atmosphere by precursors of unburned fuel and nitrogen oxides and sun light radiation. All organic compounds do not have the same potential to form ozone and it therefore important to know and influence the composition of both fuel and exhaust gas. In petrol, light olefins and alkylated aromatics have high ozone potential whereas methane (CNG), propane and methanol have low potential. In the exhaust gases olefins (ethene, propene, butenes) and aldehydes have the highest potential. Mitigation of the ozone formation thus means low emissions of precursors by evaporation and exhaust. With petrol engines, catalytic after-treatment is necessary to reduce the otherwise high emissions of unburned fuel, and the petrol should be reformulated to control volatility and content of light olefins. Diesel engines usually have low, although reactive emissions of incompletely burned fuel but high emissions of nitrogen oxides.

Known cancer risk compounds (genotoxic "air toxics") are PAC, particulates, benzene, butadiene, ethene, propene, and aldehydes. All compounds do not have the same potency to induce cancer and are therefore assigned weighting factors to be able to judge the total risk with different fuels. There is not full agreement about the factors, but among the gaseous compounds, butadiene and benzene are usually ranked highest while propene and acetaldehyde are given the lowest values and there is no unity about formaldehyde and ethene. PAC have mainly origin in the PAH, of which those with three or more ring are of interest as biologically active. PAH are found above all in diesel oils but can also be found in the heavy end of petrol and be emitted during the cold start and warm-up period. Decreasing the content of PAH in the fuel is the most efficient way to reduce the PAC in the exhaust, as a direct relationship between those parameters has been shown. This is the main focus for reformulation of the diesel oils in the Nordic countries, and it is accomplished by mild hydrocracking of the cracker feedstock or use of hydrocracker and HDA-unit streams. Polycyclic aromatics are more easily hydrogenated than mono-aromatics.

Processing for PAH-removal also leads to very low sulphur content (10 – 30 ppmwt) of the product. This in turn makes use of catalytic after-treatment possible and oxidation catalysts can be used to further reduce the gaseous harmful compounds as well as semivolatile PAC. High particulate emissions are characteristic for diesel oil fuelled diesel engines and particles loaded with PAC are classified as carcinogenic. Reformulated diesel oils, low in PAH and lowered 95 % and end point, will result in lowered particle emissions and toxicity, but ultimate removal of particle emissions requires both improved engines and particle filters. Such are in operation commonly on buses in Sweden and used in combination with city diesel oils.

Reformulation of petrol to lower cancer risks involve reduction of its content of light olefins, being precursors to butadiene, and of benzene and to some extent total aromatics. Benzene is limited to 1 %vol in the reformulated petrol in the U.S. and West-Europe. To compensate for octane loss by reduction of aromatics high octane, non-aromatic oxygenates (alcohols, ethers) can be used as components (as outlined in IS 2796:1995). This will also mean a way to introduce non-oil-based components in the petrol pool.

Alternative fuels such as CNG and methanol, being chemically very simple and non-carcinogenic fuels, yield no or very low emissions of fuel-related particles and exhausts with very low toxicity towards cancer risks.

Greenhouse gases may cause effects on the future climate and the main compound to worry about is carbon dioxide originating from fossil fuels. It is important to examine the whole chain from fuel feedstock recovery to end use in the vehicles to judge the greenhouse gas effect correctly as considerable contributions may arise from the earlier steps in chain. The greatest reduction of greenhouse gases in the transport sector, however, will be achieved if biomass feedstocks are used for the production of the motor fuels. The carbon dioxide emitted from them will be consumed within a short time frame through the photosynthesis to build new biomass and thus not contribute to an increase of the carbon dioxide content of the atmosphere.

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4 "WORLDWIDE REFINING – INDIA.", Oil & Gas Journal Dec. 22,1997

5 "WORLDWIDE CONSTRUCTION – REFINERIES – INDIA.", Oil & Gas Journal Oct. 5, 1998.

6 "WORLDWIDE LOOK AT RESERVES AND PRODUCTION.", Oil & Gas Journal, Jan. 1998.

7 Campbell, C.J.: "Depletion Patterns...", Oil & Gas Journal Special Dec. 29, 1997.

IV EMISSION REDUCTION POTENTIAL FOR DIFFERENT VEHICLE CATEGORIES

1 Introduction

In this Appendix, some of the different technical measures of reducing the emissions are covered. Only technical measures are described, although some economic incentives are probably necessary to introduce many of them. The environmental benefit of the measures is calculated using the same cost assessments for emission components as Swedish governmental agencies. Since most of the measures significantly rise the cost of operating the vehicle (investment, maintenance, fuel etc.), this cost has to be taken into account as well. Subsequently, the different measures are ranked according to their cost-effectiveness.

2 Methodology

In this study, five different vehicle categories are investigated. The choice of vehicle categories has been made in consultation with CSE. The vehicle categories are:

- 2-wheelers
- 3-wheelers
- Cars
- Buses
- Trucks

To simplify the presentation of the results, the 2 and 3-wheeler categories have been covered in the same chapter. Similarly, most of the issues for the buses and the trucks have been covered in the chapter for the buses. In general, most of the focus has been put on the heavy-duty vehicles (trucks and buses), since the NO_X and the particulate emissions are presumably the worst problems in India. These vehicles categories are the main contributors of the pollution for these emission components. The 2-stroke engines for 2 and 3-wheelers are also of concern, since most of the petrol is used in these vehicles and they contribute substantially to the HC emissions.

For the vehicle categories, several technologies have been chosen and the impact on the emissions and the incremental cost has been evaluated. In many cases, there are other possible measures that could be of significant interest, but since the input data has not always been reliable, no calculations have been made for these options.

3 Cost of new technology

In cost estimates of the transition to new technology, the initial costs (during the first year or the first and the consecutive year) are mostly evaluated. This does not give the complete picture of the cost of technology transition since the initial costs are often high but after that phase there is usually a steady decrease in cost as the technology is matured. A schematic example of this trend can be seen in Figure IV–1 (unfortunately the figure text is in German, but some text has been translated by Ecotraffic).

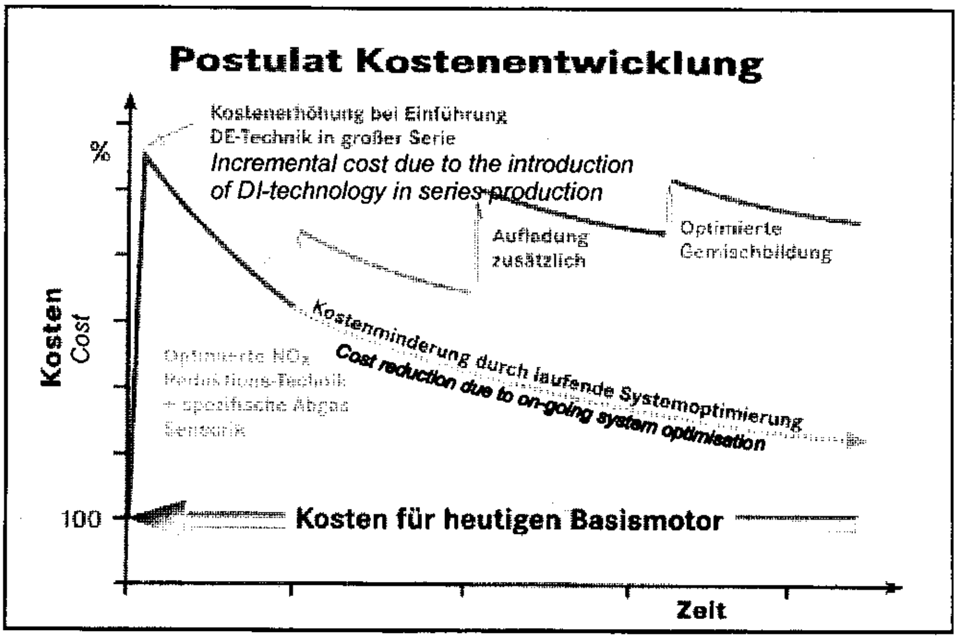

***Figure IV-1**: Development of cost with time (schematic) for different engine technology for passenger car petrol engines (source: MTZ & Mercedes) [1]*

Figure IV–1 shows the cost assessment in relative terms of introducing a variety of different technologies for passenger car petrol engines. The left curve shows the cost increase of introducing direct injection of petrol. It is obvious that the initial cost increase is high, but with subsequent optimisation of the production technology, the cost is reduced (dotted line) – though it never decreases to the same level as for a conventional engine. What is of importance is of course the average cost during a certain period. The length of such a period could be the time between two subsequent emission regulations. This period is usually some 2 to 5 years, which is also a common period between updates of engine technology. Rare exceptions from that rule, such as the Hindustan case in India, can exist on markets without any emission regulations and/or lack of competition in certain niches.

In the case that new technology is introduced, this sometimes also can increase the customer value of the product. One example is that fuel injection was quite common in mid and upper classes of vehicles in Europe long before emission regulations were introduced. The reason for this was the increased power and the refinements in some areas, such as driveability and comfort. When the cost of transition to three-way catalyst was estimated by the industry in the mid 1980´s, this fact was seldom taken into account. Furthermore, the cost was often calculated as the total cost of all the necessary components in the emission control system, not taking into account that many of these parts were essential anyway. Thus, the true incremental cost was not assessed.

Referring to the discussion above, it is of importance that the most relevant assumptions are made in the assessment of the incremental cost. In this report, we have been trying to evaluate the average incremental cost during a certain timeframe. It is very difficult to obtain relevant cost estimates from the industry. We have been asking these questions and sometimes we have obtained answers, sometimes not. There are also some estimates available in the literature, but unfortunately, most of them cover the situation in the USA, which is not so relevant for India. We have also obtained some information from outside India that is of confidential nature. Due to these circumstances, we have chosen not to cite any of the sources in India. Instead, we have made our own estimates based on the available knowledge. Therefore, no source reference is given in most of the cases.

3 Cost estimates

3.1 Environmental cost

In the calculation of the environmental cost, the same cost assessments (except for CO) as the recent factors used by Swedish governmental authorities have been applied in these calculations. The cost factors used in this study have been listed in Table IV–1.

Table IV-1: *Emission cost in Sweden (modified for CO by Ecotraffic)*

	Emission cost (Rs/kg)					
Traffic mode	CO	HC	NO_X	SO_2	PM	CO_2
Urban	27	356	497	616	5853	2.05
Rural	0	92	232	86	972	2.05
Average	13	227	324	351	2916	2.05

The emission costs in Table IV–1 are the same as the factors used by the Swedish agencies except the factors for CO emissions. It has been assessed that the CO emissions no longer pose a real health problem in the Swedish cites and therefore the value in the most recent set of cost factors have been set to zero for the CO emissions. We have used a relatively low factor for CO in urban traffic. The traffic type is divided into three different modes: urban, rural and (weighted) average. The modal split of the traffic is approximately 50:50 between urban and rural and therefore the weighted average is very close to the arithmetic average.

It can be debated if the costs in Table IV–1 are relevant or not for the Indian situation, but since there are no more appropriate and well accepted values, the Swedish urban factors have been used. Sweden is not a very densely populated country in comparison to India and therefore it has been anticipated by these authors that the Swedish urban factors are more relevant than the average for Sweden. The factors for CO_2 have not been used, since this calculation should be carried out in a life cycle perspective (for all fuels and engine combinations), and this was beyond the scope of this investigation.

3.2 *Incremental cost of operation*

Some common economic parameters have been used in all calculations. These parameters have been listed in Table IV–2.

Table IV-2: *Economic parameters*

Currency (Jan. –99)			Interest	Fuel cost, petrol equiv. (Rs)				
US $	SEK	Rs	rate (%)	Diesel	EC 1	Petrol	CNG	LPG
1	7.742	41.81	7	9.71	11.36	24	9.0	12

The interest rate should be seen as the difference between the interest rate in a bank and the inflation. The interest rate used in investment calculations in a company, taking the inflation into account and the necessary return of investment, is usually much higher (some 15 to 30 % are a common figures). The petrol is taxed today and CNG and LPG/propane are presumably subsidised, which makes the comparison somewhat incorrect. It should also be stressed that the calculations made are rough estimated and are only intended to give some general comparison between the various options.

When the results of the economic calculations are described in the following, the most comprehensive coverage is made for the buses. The other vehicle categories are not described in such detail, but the same methodology has been used for these vehicles as well.

5 Emission factors for India

Emission factors are very important when the calculations for an emission inventory are made or when comparisons are made between different vehicle categories. Likewise, in the decision process where the most cost-effective solutions for emission reductions are to be chosen, the level of the emission factors is one of the most essential issues. Several sets of emission factors have been determined for India by different institutes and organisations. In this report, the emission factors compiled by TERI and CPCB have been used as the basis for the calculations. These investigations have been using previous results by, for example, IIP and ARAI as input data. The emission factors according to TERI are shown in Table IV–3. The emission factors used by CPCB is shown in Table IV–4. This set of emission factors is used in the calculation of air pollution in Delhi and they are based on emission factors calculated by IIP and ARAI.

Table IV-3: Average fuel efficiency and mass emissions factors of vehicles on Indian roads (source: TERI; round-off of some values made by Ecotraffic)

Vehicle/ Technology	Fuel type	Fuel eff. (km/GJ)	Mass emissions under a typical Indian driving cycle (g/km)					
			CO	HC	NO_X	SO_X	TSP	Pb
2-w: 2-stroke	Petrol	1233	8.3	5.18	0.1	0.5	0.0473	0.0034
2-w: 4-stroke	Petrol	1800	8.3	0.72	0.39	0.08	0.0323	0.0023
2-w: 4-stroke	Petrol	1804	2.4	0.72	0.72	0.08	0.0323	0
3-w: 2-stroke	Petrol	566.5	12.2	7.65	0.1	0.5	0.103	0.0073
3-w: 2-stroke	Prop.	833.3	*(0.16)*[a]	*(4.68)*	*(2.47)*	*0*	*0*	*0*
Car: old model	Petrol	261.7	28.9	6.2	2.7	0.33	0.2229	0.0159
Car: new model	Petrol	393.5	9.5	1.5	1.9	0.25	0.1483	0.0106
Car: cat. conv.	Petrol	410.8	2.6	0.3	0.6	0.08	0.1421	0
Car	Diesel	232.4	1.1	0.28	1.4	0.6	0.9326	0
Car	CNG	579.7	*(0.22)*	*0*	*(3.52)*	*0*	*0*	*0*
Taxi	Petrol	261.7	28.9	6.2	2.7	0.33	0.2229	0.0159
Taxi	Diesel	232.4	1.1	0.28	1.4	0.6	0.9326	0
Taxi	CNG	385.4	*(0.22)*	*0*	*(3.52)*	*0*	*0*	*0*
Bus	Diesel	86.57	12.7	2.1	21	2	2.5039	0
Bus	CNG	89.53	*(0.22)*	*0*	*(3.52)*	*0*	*0*	*0*

Notes:

[a] Emission factors in parenthesis are expressed in g/m^3 for CNG and therefore these figures are not compatible with the other figures in the Table.

Although the data in Tables IV–3 and IV–4 probably are the best available today, some comments about the results can be made.

The particulate emissions for the 2-stroke 2 and 3-wheelers are low in the table by TERI and they are neglected by CPCB. Limited data from ARAI and IIP indicate that the level might be considerably higher than assumed by TERI, e.g. in the region of 0.2 to 0.4 g/km in Indian driving conditions. It has to be recognised that this level is almost on the same level as an old diesel car (0.4 – 0.9 g/km) and certainly much higher than for a new diesel car (0.06 – 0.15 g/km). Although the total particulate emissions in India are dominated by the heavy-duty vehicles today, it is important to include the particulate emissions from 2 and 3-wheelers in the calculations as well.

The emission factors for the NO_X emissions from old buses and heavy goods vehicles are very high. Two contradictory factors affect the NO_X emissions in comparison to newer vehicles. First, the injection timing was set earlier than for new engines, and this increases the NO_X emissions. Second, the injection pressure was considerably lower, which decreases the NO_X emissions. Experience from tests on older vehicles in Sweden by the Swedish EPA (some 150 vehicles) has shown that the NO_X emissions seldom were higher than 15 g/kWh for these engines. By using the fuel consumption in the data from TERI (and SEPA), the NO_X emissions can be calculated from engine test data to (approximately) represent the same driving conditions as in India. This yields NO_X emissions of about 15 g/km. This figure has been used in our calculations.

Table IV-4: *Emission factors of different vehicles used by CPCB*

Type of vehicles	Year	Mass emissions (g/km)					
		CO	HC	NO_X	SO_X	TSP	Pb
2-wheelers	Up to 1991	8.3	5.18	0.1	0.023	–	0.008
	1991-1994	6.49	4.5	0.1	0.023	–	0.008
	1994-1996	6.49	4.5	0.1	0.023	–	0.002
	1996-2000	5.0	4.32	0.1	0.023	–	0.002
	2000-2005	2.4	2.4	0.1	0.023	–	0.0002
3-wheelers	Up to 1991	12.0	7.0	0.26	0.029	–	0.019
	1991-1994	12.0	7.0	0.26	0.029	–	0.019
	1994-1996	12.0	7.0	0.26	0.029	–	0.005
	1996-2000	8.1	6.48	0.26	0.029	–	0.005
	2000-2005	4.8	2.4	0.26	0.029	–	0.0004
Car. Jeep and taxi	Up to 1991	25	5.0	2.0	0.053	–	0.030
	1995-2000	19.8	2.73	2.0	0.053	–	0.0003
	2000-2005	3.16	0.56	0.56	0.053	–	0.0003
Buses and goods	Up to 1991	12.7	2.1	21.0	1.5	3.0	–
	1991-1996	12.7	2.1	21.0	1.5	3.0	–
	1996-2000	9.96	1.44	16.8	0.75	2.4	–
	2000-2005	5.35	0.66	9.34	0.37	2.4	–

Source: S. A. Datta and B. Sengupta, "Air quality Goals for Delhi – Options to meet them by 2005.

Due to the transient behaviour of the real driving conditions, which increases the HC emissions, the level of 2 and 2.1 g/km respectively in the data by TERI and CPCB is probably somewhat too low for older buses. We have used 2.5 g/km instead.

6 Two-wheelers and three-wheelers

6.1 Introduction

In this chapter, an overview of the possible emission reduction technologies is made. Since the technology for both 2 and 3-wheelers are similar (2-stroke engines), both are covered in the same chapter. Due to the special emission characteristics of the 2-stroke engine, which is the basis for the comparisons, this engine is described in more detail.

6.2 The two-stroke engine

First of all, to obtain an understanding of the emission characteristics of the 2-stroke engine, a brief explanation of the working principle is necessary. Comparisons to the working principle and the emissions characteristics of the 4-stroke engine are essential as well. A more detailed description of 2-stroke engine emissions has been made by Nuti [2].

In contrary to the 4-stroke engine, the (simple) 2-stroke engine generally has no valves. Furthermore, the whole working cycle is covered in only one engine revolution for the 2-stroke engine, in comparison to two revolutions for the 4-stroke engine. Within one engine revolution, the piston makes two strokes (up and down), hence the designations 2-stroke and 4-stroke engines.

Due to the absence of valves and the reduced number of strokes, the induction and exhaustion processes of a 2-stroke engine, have to be made simultaneously (scavenging). In the simple 2-stroke engine, these processes are controlled by the piston. Some of the different schemes for the scavenging process for simple 2-stroke engines are shown in the cases a to c in Figure IV–2 (Nuti [2]). It is obvious that the scavenging process results in the loss of some fresh charge to the exhaust. Since the fresh charge is a mixture of fuel and air, some of the fuel is directly lost through the exhaust port. This inevitably leads to an increase in CO and HC emissions, as well as an increase in the fuel consumption.

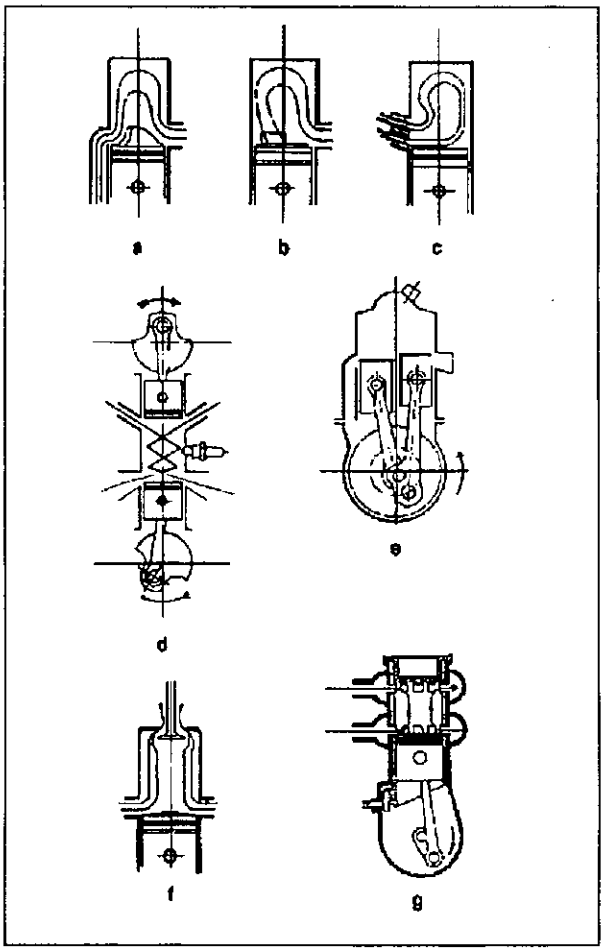

***Figure IV-2**: Different scavenging possibilities for 2-stroke engines (Nuti [2])*

The NO_X emissions are generally very low from a 2-stroke engine and therefore they are of limited concern for these types of engines. The lean mixture, the high percentage of rest-gases (mainly exhaust) and the low cylinder pressure are some of the reasons for the inherently low NO_X emissions from this engine type. The CO emissions from a 2-stroke engine are generally on approximately the same level as for a 4-stroke engine. The main problem for the 2-stroke engine is the HC emissions, due to the loss of fresh mixture as described above. Another problem not so often debated is the particulate emissions. As shown in the previous chapter these emissions are on approximately the same level as from diesel passenger cars and therefore this problem must be seriously considered.

6.2.1 Improved scavenging

One way of overcoming the problem with charge loss is to use longitudinal scavenging, i.e. the inlet is in one end of the cylinder and the outlet is in the other end. Thus, the mixing of fresh charge with exhaust is minimised and simultaneously the loss of fresh charge can be reduced. As Figure IV–2 shows, there are several possible schemes to achieve longitudinal scavenging. Unfortunately, most of the systems showed in Figure IV–2 are much too complicated and expensive to be used in an engine for 2 and 3-wheelers.

There are numerous examples in the literature of attempts to improve the scavenging process. The problem has always been that the traditional simple design of the 2-stroke engine cannot be maintained. One example of such a solution is shown in Figure IV–3. It is obvious that a design as complicated as in this Figure is an impractical and too costly solution for the 2 and 3-wheeler vehicles in India. Other methods have to be found to reduce the emissions.

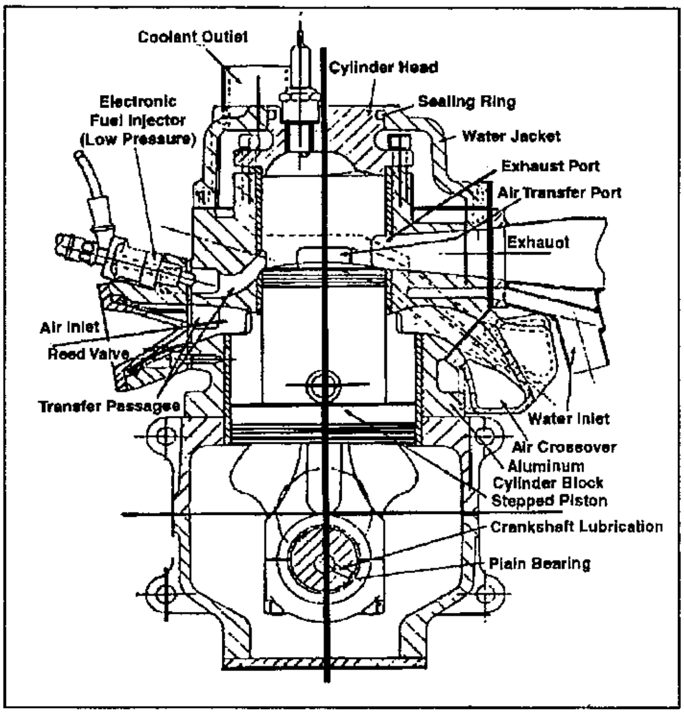

Figure IV-3: *Stepped piston*

Although the ideal scavenging cannot be achieved without considerable effort and cost, there are still methods to reduce the scavenging losses. Using modern diagnostic tools for measurements of the scavenging process, as well as numerical calculations, such as computational fluid dynamics (CFD), the scavenging process can be further optimised. The advantage of these solutions is that the necessary modifications for production of the engine are relatively inexpensive. One disadvantage of optimising the scavenging process for lower emissions is that there might be a slight reduction of the engine power.

Further improvements of the scavenging process could be achieved by using a rotary exhaust valve in the exhaust port. This technology has already been commercialised by some Japanese motorcycle manufacturers. Although this increase the cost of the engine, this increase is far less than the cost for the longitudinal scavenging systems shown above.

6.2.2 Improved carburettors

Improvement of the carburettors is another method to reduce the emissions from a 2-stroke engine. It should be noted that the carburettors for these engines are much simpler than the carburettors for an ordinary 4-stroke passenger car engine. Obviously, there is at least some scope of reducing the emissions by improvements in this area.

6.2.3 After-treatment of the emissions

After-treatment of the emissions is an alternative or a complementary measure to reducing the engine-out emissions. In the case of very strict emission limits, it is obvious that both measures have to be taken.

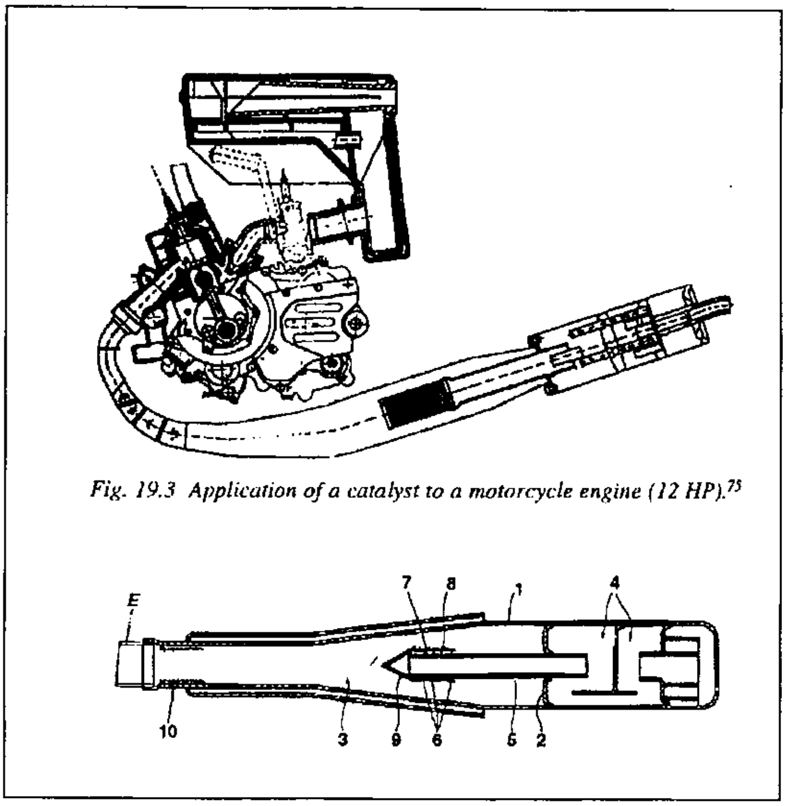

***Figure IV-4**: Application of a catalyst on a motor cycle engine (Nuti [2])*

Whereas the applications of catalyst for passenger cars, such as the three-way catalyst (TWC), is a well known technology, similar technology has not yet evolved for small 2-stroke engines. The simple reason for this is that 2 and 3-wheelers are just a small fraction of the vehicle population in the Western World, where the emission limits generally are the strictest. Therefore, the incentive to decrease the emissions from these vehicles has not been as strong as for the passenger cars. It has to be recognised that the emission regulations for India in the year 2000 are among the strictest in the World. There is some limited experience from the application of catalytic converters on some European motorcycles and mopeds, but so far, not many results are available. One example of a catalyst installation is shown in Figure IV–4.

The catalyst on a 2-stroke engine works as an oxidation catalyst for the CO and HC emissions and has very little or no effect on the NO_X emissions. Since the NO_X emissions generally are very low from 2-stroke engines, this is not a particular problem. The application of an oxidation catalyst on a 2-stroke engine is much more difficult than on a (4-stroke) passenger car engine. One reason is that the exhaust contains very high concentrations of unburned components (CO and HC), and therefore the heat generation within the catalyst can be severe. Another problem is that the temperature range for the exhaust is greater. Furthermore, the exhaust from a 2-stroke engine contains much unburned oil, which can deteriorate the effectiveness of the catalyst with time. Due to the difficult conditions for the application the catalyst, it has to be installed differently than on a car engine. Due to the severe thermal stress, a conventional ceramic monolith cannot be used. The thermal stress on the washcote is also greater. Metal monoliths and pellet catalysts are possible solutions for these problems.

There is considerable knowledge about the application of catalysts on 2-stroke engines in India. One example is the IOC and ACC who have developed a pellet catalyst for these engines [3]. Likewise, the vehicle manufacturers have gathered much experience in this field. It has to be recognised that there are business opportunities for India of exporting this technology to other countries.

At present, there is limited data on the long-term stability of catalysts for 2-stroke engines in real driving conditions and it has to be anticipated that these catalysts must be replaced and/or checked on a regularly basis. The schemes and the means for supervising this have yet to be worked out.

6.2.4 Direct injection

Since a large portion of the air-fuel mixture is lost in a 2-stroke engine during the scavenging process, an obvious measure to avoid this problem is to inject the fuel directly in the cylinder. The injection should be carried out after the ports in the cylinder have been closed. This type of fuel injection is called direct injection in opposition to indirect injection, which takes place in the inlet port or inlet pipe of the engine. As a comparison, it can be mentioned that 4-stroke passenger car engines generally use indirect injection. The direct injection technology for 2-stroke engines has been pioneered by the Australian development company Orbital Engine Co. [4]. Since the system comprise more features than only the injection system, it has been designated the name OCP, Orbital Combustion Process by the company. A schematic picture of the features of the OCP system is shown in Figure IV–5.

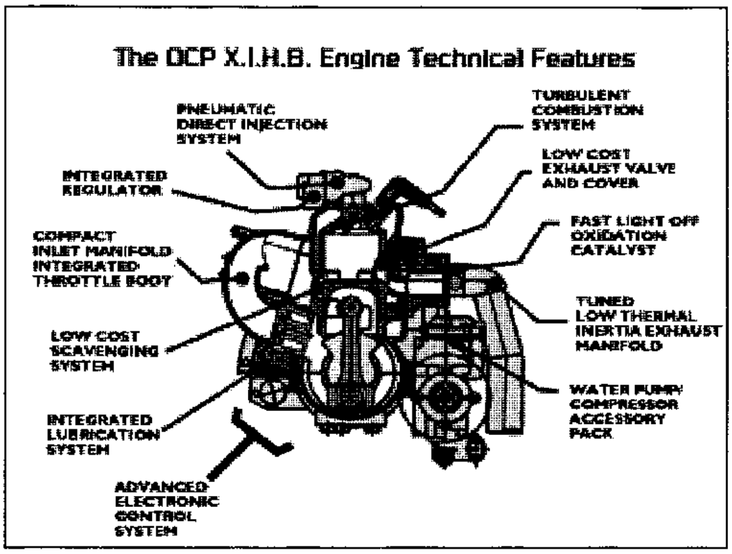

***Figure IV-5**: The Orbital Combustion Process [4]*

A special feature of the Orbital injection system is the use of air-assist (compressed air) for the injection of the fuel. Orbital's injection is primarily used on outboard marine engines today as the first commercial application, even if the technology originally was primarily intended for 2-stroke passenger car engines. Another offspring of the system is the development of direct injection for 4-stroke passenger car engines. Development has also been made by Orbital for the use of direct injection on small 2-stroke engines such as, for example, motorcycles and scooters. Recently, the Italian motorcycle and scooter manufacture Aprilia has announced that the Orbital injection will be released in production on some of their models in 1999.

The Orbital direct injection system is only one of the possible systems that can be used on 2-stroke engines. An apparent problem for all these systems is the considerable increase in cost in comparison to the conventional carburettor. This incremental cost has to be compared to the conversion of the engine to the 4-stroke operating system. An additional benefit of using direct injection on a 2-stroke engine is the significant reduction in fuel consumption that can be achieved. The fuel consumption can be reduced to the same level as for a 4-stroke engine and under some conditions, it could be even lower.

6.2.5 Oil consumption and particulate emissions

As mentioned above, the particulate emissions from a 2-stroke engine are not negligible. Much of the particulate emissions are apparently condensed hydrocarbons, mainly from the engine oil and the fraction of solid carbon is less than from diesel engines. No results from a particulate analysis from typical Indian 2 or 3-wheelers have been found in the literature, though. It is not clear from the literature whether the impact on human health (cancer and daily mortality and morbidity) of "wet" aerosols is less, or higher, than from solid aerosols. In any case, the mechanisms of the health hazards from particles are not yet fully understood. However, the problem of particulate emissions should be addressed because of the relative magnitude and the potential health hazards.

One way of significantly decreasing the particulate emissions from 2-stroke engines is to use better lubrication oil (i.e. synthetic or semi-synthetic) that can be used in lower concentrations. It is obvious that the oil must fulfil all performance criteria, as well as having a potential of reducing the smoke and particulate emissions. Since much of the effect from improved oil is due to its ability to be used in lower concentrations, the mixing should be controlled in some way. Premixing of fuel is a simple way of handling this problem and it has been proposed that the separate sales of oil should be forbidden to avoid the use of oil in too high concentrations. Even if this solution is very simple, there is one objection. Separate lubrication is another possibility to significantly decrease the particulate emissions. By using separate lubrication, no more oil than necessary is added. This means that the oil consumption can be significantly reduced at low load with a subsequent reduction of the particulate emissions. By forbidding the sale of separate oil, this option is precluded.

The use of separate lubrication is not a new technology. Most of the Japanese motorcycle manufacturers used this system already more than 20 years ago on practically all 2-stroke engines larger than 80 cc. In India, there has been some activity in this area by ARAI focussed on the retrofit of a system for separate lubrication [5]. The specific feature of the ARAI system is that it is a pumpless system. Therefore, it is possible to use the system for after-market conversions. The area of separate lubrication is considered very important, not only because of the potential reduction of the particulate emissions, but also because separate lubrication will be necessary for engines dedicated to alternative fuels such as propane, LPG and CNG. It is recommended that activities focussing on the retrofitting of separate lubrication systems be stimulated by local and governmental authorities.

6.3 *The four-stroke alternative*

A 4-stroke engine is an obvious alternative to the simple 2-stroke engine. The 4-stroke engine has very little mixing between fresh mixture and exhaust gases in comparison to the 2-stroke engine, and thus the HC emissions (and sometimes the CO emissions as well) are lower in the former case. Particulate emissions are much lower due to the separate lubrication, but the NO_X emissions are generally higher.

The Indian emission limits for the year 2000 can be fulfilled with a 4-stroke engine without any exhaust gas after-treatment. Further reduction of the CO and HC emissions could be obtained by using an oxidation catalyst. The reduction rate would be approximately 50 %, but the potential could be as high as 75 %. NO_X emissions are also reduced in a catalyst, provided that the catalyst formulation is made with the necessary noble metals (rhodium and/or palladium). Further NO_X reduction can be obtained by using exhaust gas recirculation (EGR). The realistic potential of NO_X reduction by EGR is about 50 %.

The ultimate solution for a 4-stroke engine is to use a TWC system. The reduction rate of all emission components, in comparison to a conventional 4-stroke engine, could be higher than 90 %. There are however, some practical problems to be taken care of if this potential is to be exploited. First, the air-fuel ratio must have feedback control. This is best achieved by using (indirect) injection of the fuel and by using an air-fuel sensor for feedback control. Second, fuel injection should be used instead of a carburettor. Some limited success has been made by using an electronically controlled carburettor on car engines in the past, but in Europe, most of these systems have disappeared from the market. There have been substantial problems with the durability of the emission control system in these cases. It is obvious that the sophistication level of a TWC system for 2 and 3-wheelers are on almost the same level as on car engines. Therefore, the cost increase would be prohibitive, at least with the technology available today. However, there are some examples of TWC systems on 2-wheelers and one is the motorcycles of BMW. In this case, the cost of the motorcycle is on the same level as for a medium sized passenger car so it is obvious that the incremental cost for the emission control equipment is almost negligible.

6.4 *Two-stroke or four-stroke?*

As described above there are several solutions available for reducing the emissions from 2 and 3-wheelers. Some of the alternatives, such as direct injection or catalysts, need further development before they can be commercialised on a larger scale. The most conservative solution (lowest commercial risk) today is the 4-stroke engine, but it has to be recognised that there are many alternatives available for the 2-stroke engine as well. Reports by Orbital have shown that approximately the same emission level can be achieved from an advanced 2-stroke engine as from a 4-stroke engine with TWC. These results can be applied on smaller engines as well. Consequently, the 2-stroke engine is not dead (...yet).

6.5 *Diesel engines in 2 and 3-wheelers?*

There are several diesel engined 2 and 3-wheelers on the Indian market today. The reason is obvious since the fuel cost advantage in comparison to a conventional 2-stroke engine can be up to a factor of five. The gaseous emissions from a 4-stroke diesel engine can be reduced to meet the 2000 regulations without too much development. On the other hand, the particulate emissions will be very high from these engines. In order to achieve low emissions for all emission components, high-tech solutions are the only possibility. This would include the adoption of high-pressure direct injection, turbocharging, intercooling and EGR. It is conceivable that a high-tech engine of this size would bee far too expensive to become a commercial success. Still the particulate emissions would be about one order of magnitude higher than from the petrol-fuelled 4-stroke engine.

From the discussion above it is clear that a diesel engine in such a small vehicle is hardly the best choice of drivetrain from an environmental point of view and therefore its use should not be encouraged.

6.6 Considerations for the emission regulations

Today there are several options for reducing the emissions from this category of vehicles. Only the engineers in the industry have the complete picture to be able to choose the most cost-effective solution. Therefore, the proposals for reducing the emissions from these categories of vehicles should be as technology neutral as possible. Stricter emission limits can be introduced in the future as the technology evolves. Emission limits is better than to ban a certain technology. One of the most urgent matters for future regulations of 2 and 3 wheelers is the amendment of the regulation with a limit for particulate matter (2-stroke and diesel).

6.7 Cost comparisons

It has been very difficult to estimate the cost of the different technology options for the 2 and 3-wheeler vehicles. First, the market for these vehicles is much smaller in the countries with stringent emission limits. Second, the emission control equipment is not fully developed yet as for passenger car engines.

An estimate of several alternatives for the conventional 2-stroke engine has been made by Nuti [2]. The results from this study is shown in Table IV–5. Even if this study was published recently, several of the options in the Table are not fully developed yet. Therefore, it is most likely that the cost estimates are not very accurate.

Although the results in Table IV–5 can be questioned, some interesting observations can be made.

Table IV-5: *Cost comparison*

Engine type	Rel. Cost. (%)
2-Stroke standard	100
HP solid injection[a]	140 – 160
HP electr. contr. solid injection	170 – 190
HP external scavenge	240 – 260
LP in-cylinder injection[b]	120 – 140
Air-ass, IAPAC injection[c]	150 – 170
FAST injection[d]	120 – 140
FAST electr. contr. inj.[e]	140 – 160
4-Stroke engine	150 – 170

Notes:

a HP solid injection is high pressure (liquid) direct fuel injection without air assist.

b Low-pressure direct injection.

c Air-assisted injection from IFP in France.

d FAST is an injection system developed by Piaggio.

e As d but with electronic control.

The simple 2-stroke engine is the most inexpensive engine of all options, as expected. Converting to a 4-stroke engine is a considerably more expensive option. The direct injection systems are also more expensive, but some of them could actually be cheaper that a 4-stroke engine. Therefore, different 2-stroke options could still be used although the emission limits are tightened.

6.7 Cost-effectiveness of different options for 2 and 3 wheelers

As mentioned before, most of the emission factors used in this study were adopted from TERI and CPCB. Still some modifications were made by Ecotraffic .The emission factors used in the calculations here are shown in Table IV–6.

Table IV-6: *Emission factors for buses used by Ecotraffic*

		Mass emissions (g/km)					
Type of engine	**Fuel**	**CO**	**HC**	**NMHC**	**NO_X**	**SO_X**	**PM**
2-stroke base	Petrol	8.3	5.18	4.97	0.10	0.023	0.35
2-stroke + cat	Petrol	4.57	3.11	2.98	0.10	0.023	0.25
2-stroke 2000	Petrol	2.50	1.60	1.54	0.10	0.023	0.20
2-stroke DI + cat	Petrol	0.8	0.20	0.19	0.10	0.020	0.05
4-stroke 2000	Petrol	2.40	0.72	0.69	0.72	0.020	0.03
4-stroke 2000 + cat	Petrol	1.32	0.43	0.41	0.04	0.020	0.02
4-stroke TWC	Petrol	0.48	0.14	0.17	0.14	0.020	0.01
2-stroke CNG conv.	CNG	1.5	3.0	0.3	0.10	0.00	0.03
2-stroke LPG conv.	LPG	1.5	3.0	2.7	0.10	0.00	0.03

The assumptions made for the investigation of the cost-effectiveness of the different options are listed in Table IV–7. Besides the economic factors described above, some estimates of the cost for the vehicle technology and the fuel have been made. A more detailed description of the methodology in the calculations is made for the buses in chapter 8. The same methodology has also been followed for 2 and 3-wheelers.

It should be noted that the figures in Table IV–7 are considered for production vehicles except the catalytic retrofitting of the 2-stroke engine, and that the CNG and propane options are conversions. The 2-stroke engine for the year 2000 is assumed to have a carburettor but a lot of advanced technology instead. Therefore, this engine is more expensive than the DI engine, where a matured direct injection system is foreseen instead. However, this injection system is hardly available as early as in 2000. The cost for the CNG and propane conversions is high. It is possible that the cost could be reduced for production vehicles.

Table IV-7: Assumptions for the different options investigated for 2 and 3 wheelers

	Useful life				Cost (Rs)[a]	
Technology / fuel	**Veh.**	**Aft.**	**Rel. FC[b]**	**km/yr.[c]**	**Vehicle**	**Catalyst**
2-stroke std.	12		1	4 725	0	0
2-stroke + cat	6	3	1.01	4 725	970	1 350
2-stroke 2000	12		1	4 725	2 430	0
2-stroke DI + cat	12	5	0.86	4 725	1 900	1 350
4-stroke 2000	12		0.85	4 725	2 270	0
4-stroke 2000 + cat	12	5	0.86	4 725	2 270	1 350
4-stroke TWC	12		0.87	4 725	6 010	1 900
2-stroke CNG conversion	6		0.95	4 725	10 800	0
2-stroke propane conversion	6		0.95	4 725	6 480	0

Notes:

[a] The cost has been divided into the incremental vehicle cost and the cost for the catalyst.

[b] Relative fuel consumption in petrol equivalent

[c] Yearly driving distance.

The environmental cost for the different 2-wheeler options (which are relevant for 3-wheelers as well) are shown in Figure IV–6. These costs have been calculated using the environmental cost for each emission component described earlier.

Figure IV–6 shows that the particulate and NO_X costs are the highest emission costs for the base case. This clearly shows the impact of the high particulate emissions and that these emissions must be taken into account in the assessment of emissions from 2 and 3-wheelers. The emission reduction of the advanced 2-stroke and 4-stroke options is significant. The best option would certainly be the TWC 4-stroke engine but the cost of this technology is probably too high to be accepted in the near future for this category of vehicles. The simple 4-stroke is a viable solution that will have a significant impact on the emissions from these vehicles. However, it is also of interest to note that the 2-stroke engine also has a considerable development potential, as indicated in previous sections. Conversions of engines to CNG and LPG are other methods to lower the emissions. It has to be stressed that dedicated engines from the vehicle manufacturers that are optimised for these fuels would give much better results than the converted engines. The reason is that the dedicated engines would have much more sophisticated emission control systems.

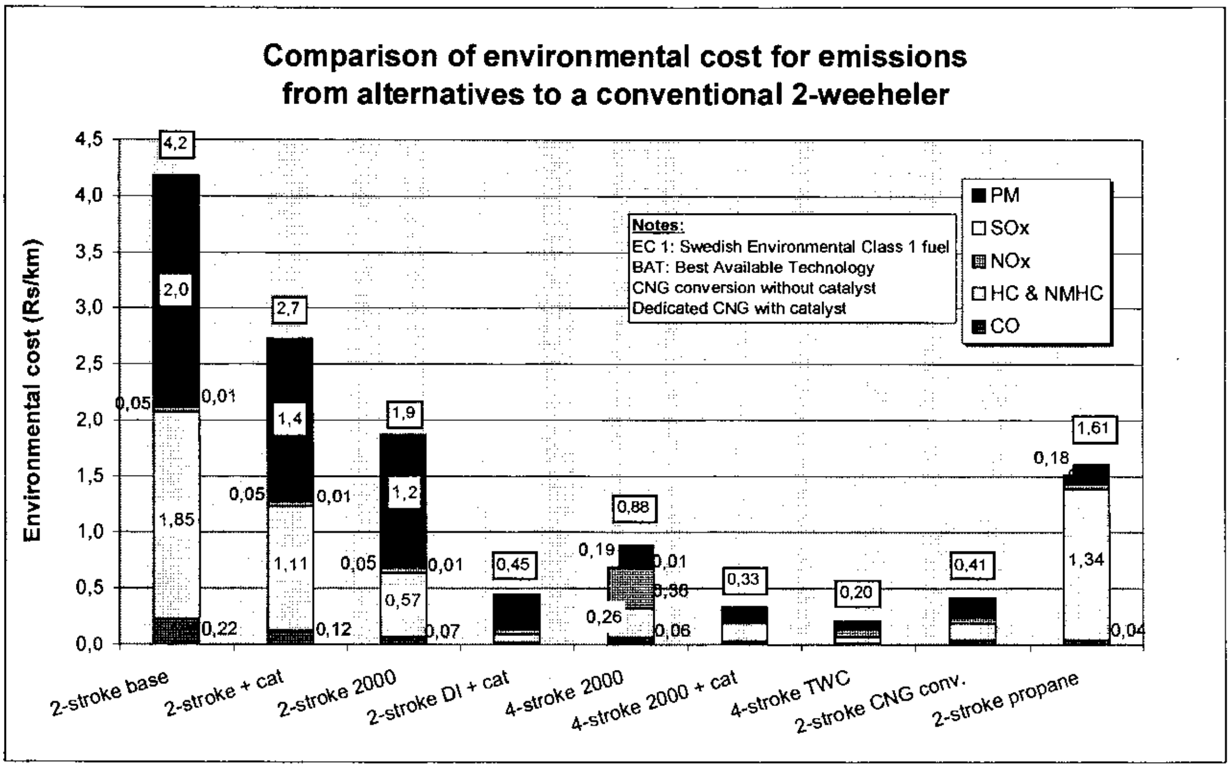

Figure IV-6: *Environmental cost for the emissions from various options for 2 wheelers*

By summarising the results in Figure IV–6, it can be concluded that a number of options have the possibility of substantially reducing the pollution load. Several options, such as the 2-stoke with catalyst, the 4-stroke 2000 cat, the 4-stroke with TWC and the CNG conversions have very low environmental cost. The best is the 4-stroke with TWC, but on the other hand, the incremental cost is very high for this option. It might also be argued that the NMHC emissions of the propane vehicle pose less health hazard than the HC emissions from the petrol options.

In order to assess the relative cost-effectiveness, the economic benefit of the emission reductions has been calculated and the incremental cost of vehicle operation has been subtracted from that cost. The methodology is described in more detail in chapter 8. The results for the socio-economic calculations are shown in Figure IV–7.

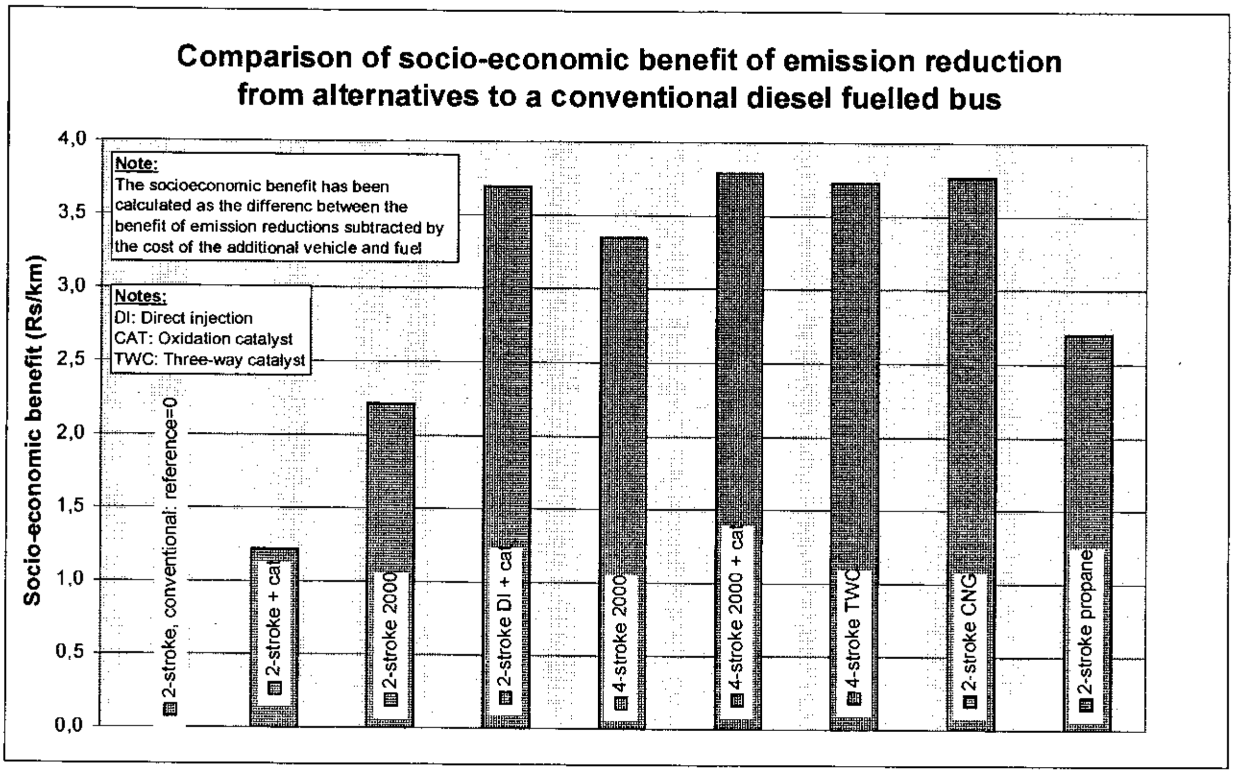

***Figure IV-7**: Socio-economic benefit of various options for 2 wheelers*

In Figure IV–7, the least effective option is the retrofitting of the catalyst on the 2-stroke engine. The reason for this is the additional cost of upgrading the engine and the shorter period of operation (6 years) in comparison to 12 years for most of the other options. The outcome could have been better if the calculation had been made for a newer vehicle (1996 model year). The CNG and propane options are somewhat hampered by the high investment cost. Using a catalyst on the propane 2-wheeler would have decreased the NMHC emissions. It is also conceivable that both the propane and CNG alternatives would have obtained better emissions if they had been dedicated vehicles from the vehicle manufacturer. The other options are more or less on the same level. It is also interesting to note that all options show an socio-economic improvement over the reference vehicle. The reason for these positive results is the high emissions for the base case.

7 Cars

Passenger cars is the category of vehicles, which generally is the most investigated of all categories of vehicles. Likewise, the emission standards are usually most strict for this category of vehicles. This is a logical conclusion for most countries, since the majority of the cars are petrol-fuelled and most of the fuel consumed is petrol. For example, ¾ of the world-wide automotive fuel consumption is petrol. In Sweden, the ratio between petrol and diesel fuel for automotive use is about 3:1. When all consumption of diesel fuel (off-road etc.) is taken into account, the ratio is 2:1. In India the situation is completely different since the ratio between the fuels is about 1:6. Furthermore, most of the petrol fuel is consumed by 2 and 3-wheelers. The conclusion is that passenger cars generally are of less concern for India than the heavy-duty vehicles and the 2 and 3-wheelers.

As mentioned above, the emission development is most advanced for passenger cars. Therefore, it is advisable to take advantage of this development also in India. The USA (especially California), Europe and Japan are the leading markets in this respect. Indian manufactures are following this development and have focussed on the European emission standards. The question is how much time delay there should be before the new emission standards are introduced in India.

7.1 Petrol-fuelled cars

The three-way catalyst (TWC) emission control system was originally introduced in a large scale on the US market in the late 1970's. The Swedish car manufacturer Volvo was the pioneer in commercialising the first car equipped with this system. The TWC system was introduced about 10 years later in Europe. For the smallest cars, it actually lasted a couple of years more on most European markets. After some initial problems with durability of the emission control system and reduction of engine performance (mostly in the USA), the TWC system is now an established and accepted solution.

The TWC system is far from being fully developed yet. This can be seen in the emission standards, which are continuously tightened (see Appendix II). In India, the equivalent of the Euro I standard (about 1993 level for EU) will be introduced in the year 2000 and it is likely that the Euro II standards will be introduced in 2005. As described in Appendix II, the difference between the Euro III and Euro II is much greater than the difference between Euro II and Euro I. Consequently, India will be lagging behind if the current proposed schedule for implementation is to be taken. The first question is whether the Euro II emission standards could be introduced in advance of the proposed schedule in India. The second question is if the industry would be prepared for this move. In the investigations made by these authors we have come to the conclusion that the Indian automotive industry in general will not be prepared for the Euro II step already in the year 2000. On the other hand, some of the manufacturers can fulfil these limits already today. The simple proof for this is the export of vehicles to the European countries. One problem with the new standards is that the infrastructure for production (suppliers etc.) are not prepared for the production of these vehicles yet. It takes time to build new factories and the import of parts from abroad is somewhat restricted. On the other hand, the development on other markets have made the price gap between fulfilling the Euro II standard in comparison to the Euro I standard very small for a matured products in both cases (see Figure IV–1). It would be a pity not to utilise this development if possible.

Our proposal is that the Euro II standards should be introduced in advance through economic incentives. The focus should be on populated areas as the large cities. At the same time, an improved fuel quality should also be introduced. The incremental cost of an Euro II specification should, according to our assessments be in the order of 10 000 to 15 000 Rs. For some manufactures, this cost could be much higher but in some cases, the cost could be lower as well. The benefit of economic incentives is that the most cost-effective solutions will be commercialised first.

On the longer term, the Euro III standards could first be introduced in the same manner as described above for the Euro II standards. Besides from the significant reduction of the emission levels in the standards, the introduction of on-board diagnosis (OBD) is the most apparent advantage of the Euro III standards. The benefit of OBD is (presumably) a much lower failure rate for the emission control system and in case of the failure, the car owner is prompted to repair the car.

7.2 Diesel-fuelled cars

Diesel cars seem to be very popular for the moment in India. The reason is the significant difference in price between diesel fuel and petrol in combination with the lower fuel consumption for the diesel car. As described in Appendix I and II, the most significant problems with the diesel cars are the NO_X and particulate emissions. The drawback in comparison with the petrol car using TWC is the lack of aftertreatment for NO_X reduction and the much greater formation of particulates due to the specific features of the diesel combustion system.

The engine-out emissions of CO, HC and NO_X are generally lower from a diesel engine than from a petrol engine, but the limited success of the NO_X aftertreatment has resulted in the disadvantage in comparison to the petrol engine. According to our assessments, NO_X-reducing catalysts (called deNO_X catalysts) will not be ready for mass production within 3 years. This means that the diesel cars will have considerably higher NO_X emissions for many years to come. Another example, which confirms this assessment above, is the NO_X limits in the Euro III standards. The limits for the diesel cars is more than three times higher that for the petrol cars.

The second problem of the diesel car is the particulate emissions. Both the mass emissions of particulates and the number of particles are about one order of magnitude higher than for the petrol cars. Since the after-treatment devices to reduce particulate emissions are not fully developed yet, this disadvantage will remain for many years in the future. Our assessment is that a reliable particulate trap system for passenger car diesel engines[1] will not be ready for mass production within five years. It is likely that these systems will be introduced on the Indian market later than in Europe. Furthermore, many of the particulate trap systems demand sulphur free fuel, which is not available on the Indian market yet.

Since NO_X and particulate emissions are the most severe pollution problems in the urban areas of India at the moment, any increase of the share of diesel-fuelled vehicles will worsen this problem. One countermeasure taken in Delhi has been to ban the use of private diesel cars. The ban on diesel cars in Delhi has upset the industry that apparently has been focusing on this market in their development during the last years. An alternative method would be to allow diesel cars that could meet future stricter emission standards. Our proposal is that the European 2005 standards would give approximately the same emission level of NO_X and particulates as the Euro I standards for petrol cars. However, it is not likely that the Indian manufactures could meet these standards in many years.

[1] For heavy-duty engines there are already particulate traps in limited production.

7.3 *Alternative fuels for cars*

The most interesting alternative fuel for passenger cars in India would be propane and CNG. LPG is not a viable option in India due to the high content of butane of the Indian LPG (see Appendix VII). The emission potential of CNG is described in Appendix VII and it can be concluded that propane has almost as low emissions as LPG. However, we advise against the conversion of older vehicle to CNG and/or propane operation – at least this should not be conducted in a larger scale. The reason is that the emissions are very sensitive to the air-fuel control and malfunctions in this system could give high emissions of some emission components. It is better that CNG and propane is used in new vehicles. The best solution is to use vehicles produced by the car manufacturers instead of converted vehicles.

8 Buses

When the different options for the buses are compared, it is important to compare the options on a similar technology level. Therefore, the similar options are first compared separately and later all alternatives are compared. A conventional Indian bus is used as a reference.

The emission factors for that bus has been adopted from TERI with the modifications described above. The emission factors used in the calculations are shown in Table IV–8.

Table IV-8: *Emission factors for buses used by Ecotraffic*

	Mass emissions (g/km)					
Type of bus and fuel	**CO**	**HC**	**NMHC**	**NO_X**	**SO_X**	**PM**
Indian bus 0,25 % S	12.70	3.00	2.94	15.16	1.35	2.500
Indian bus EC 1	10.16	3.00	2.94	13.65	0.007	2.000
Euro I bus EC 1	3.47	1.08	1.06	9.25	0.007	0.578
Euro II bus EC 1	2.70	0.62	0.60	8.10	0.007	0.231
BAT bus EC 1	1.47	0.36	0.35	7.50	0.007	0.185
BAT bus w cat EC 1	0.22	0.07	0.07	7.35	0.007	0.170
BAT bus w filter EC 1	0.07	0.04	0.03	7.20	0.007	0.019
CNG conversion (old), no cat.	8.01	7.00	0.70	15.00	0.000	0.030
CNG dedicated (new), cat	0.64	0.64	0.02	4.46	0.000	0.007

8.1 *CNG conversion and Euro I diesel engine*

The options discussed here for CNG and diesel are the same as in Appendix V and VII. In Figure IV–8, a CNG converted engine and a Euro I diesel engine are compared.

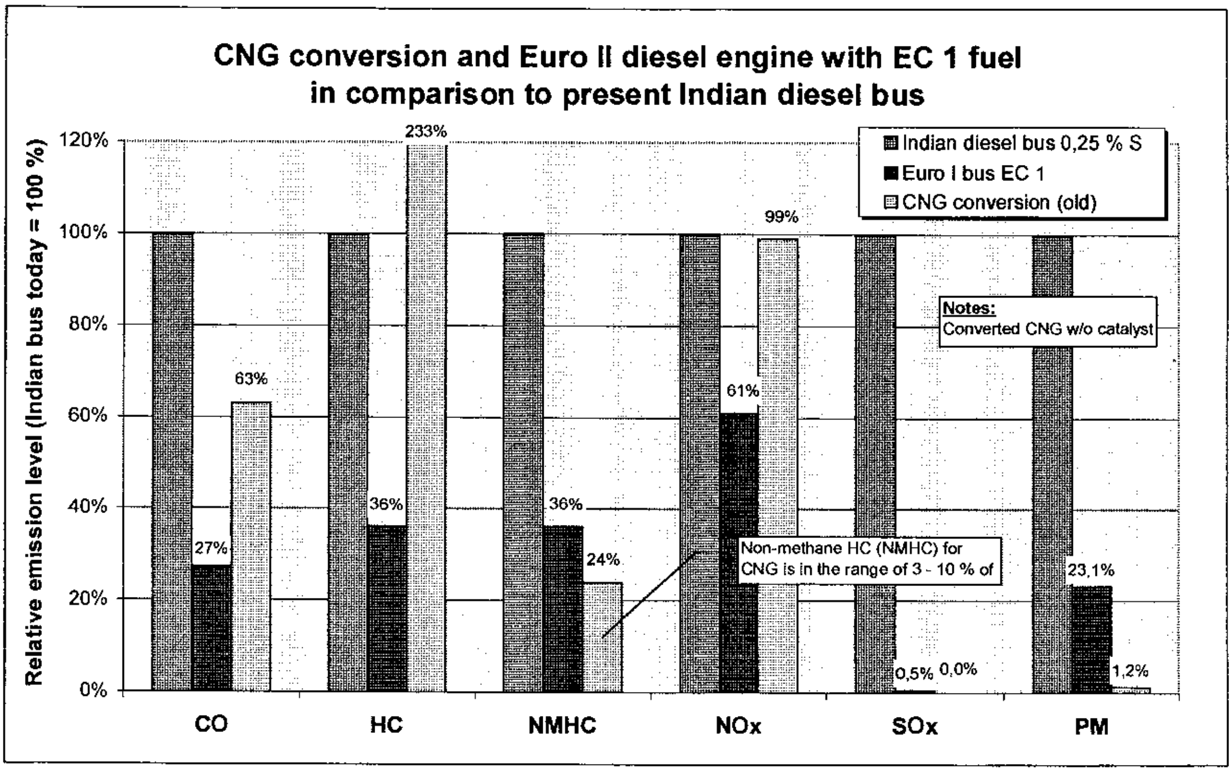

***Figure IV-8**: Impact of modern diesel technology and CNG conversion on emissions*

CO emissions are lowest for the Euro I diesel engine but some reduction can also be achieved by using CNG.

The total hydrocarbon (HC) emissions are lowest for the Euro I diesel, whereas the CNG engine has the highest HC emissions. Since most of the HC emission from CNG operation is unburned methane, the NMHC emissions are lowest from this option. Methane is considered harmless to humans and therefore the comparison between the NMHC emissions is more relevant from a health perspective. It is also likely that the biological activity is lower in the NMHC emissions from CNG than from diesel, so CNG should have an inherent advantage in this respect as well.

NO_X emissions are reduced by some 40 % for the Euro I engine but no reduction is expected for CNG. The reason for this is that the CNG engine is assumed to be a stoichiometric engine. Operation under these conditions gives very high NO_X emissions and ultimately the NO_X emissions could be twice as high as indicated. This corresponds to NO_X emissions in a 13-mode cycle of 25 – 30 g/kWh. We have assumed a lower level than that and eventually there is also a potential to decrease the NO_X emissions from the simple CNG converted engine below the level of the diesel engine. However, this scenario is not very likely if the conversion is to remain simple.

The greatest advantage for the CNG converted engine is regarding the SO_X and particulate emissions. SO_X is virtually eliminated and the particulate emissions are more than one order of magnitude lower than for the Euro I engine and almost two orders of magnitude lower than for the base level diesel engine.

8.2 *Dedicated CNG engine and best available diesel technology*

The dedicated diesel engine uses the lean-burn combustion system, turbocharging, aftercooling and an oxidation catalyst. The control system should be electronic with some feedback of the air-fuel ratio or some other type of combustion control. The most appropriate base engine to convert would be an Euro II diesel engine or possibly, an Euro I engine. The modifications in both cases would be so extensive that the engine should be considered as a dedicated engine.

The best available technology (BAT) diesel engine is essentially a low emission Euro II engine with some modifications to further decrease the particulate and HC emissions. Such engines have been used in Swedish buses since the beginning of this decade. Even lower emissions can be found on engines certified for the US regulations. The BAT engine is fitted with a commercially available particulate trap (CRT[2] or similar). The diesel fuel is EC 1.

The comparison between the options described above are shown in Figure IV–9.

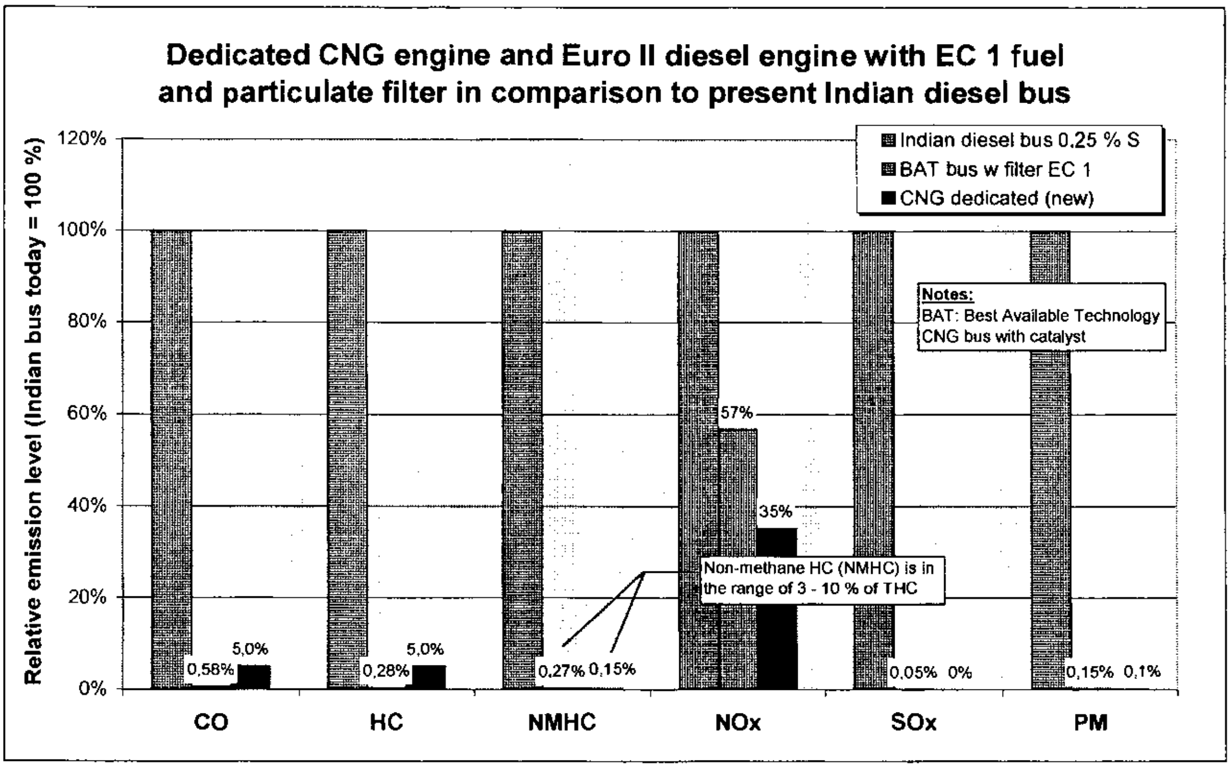

***Figure IV-9**: Impact of advanced diesel technology with particulate filter and dedicated CNG with catalyst on emissions*

Figure IV–9 shows that all emission components but the NO_X emissions are virtually eliminated for both alternatives. The reduction of the NMHC and particulate emissions is especially important, since these emissions are responsible for many of the health hazards (cancer etc.). It is somewhat difficult to determine which alternative would the best in this respect. The investigations at MTC on buses similar to the al-

[2] CRT: Continously Regenerating Trap; see Appendix V.

ternatives above (except that the diesel engine had a catalyst, not a filter) have shown very low levels of biological activity [6, 7]. For both BAT diesel and CNG, the levels in the biological tests are on the detection level. There might be some advantage for the CNG alternative but the difference is not statistically significant and the testing was carried out at separate occasions.

8.3 Cost-effectiveness of different options for buses

The assumptions made for the investigation of the cost-effectiveness of the different options are listed in Table IV–9.

Table IV-9: *Assumptions for the different options investigated for buses*

	Useful life				Cost (Rs)[a]		
Technology / fuel	**Veh.**	**Aft.**	**Rel. FC[b]**	**km/yr.[c]**	**Maint.**	**Vehicle**	**Aft. dev.**
Indian bus 0,25 % S	12		1	45 000	0	0	0
Indian bus EC 1	6		1.02	45 000	0	5 400	0
Euro I bus EC 1	12		0.969	45 000	0	54 000	0
Euro II bus EC 1	12		0.969	45 000	0	86 400	0
BAT bus EC 1	12		0.969	45 000	0	118 800	0
BAT bus w cat EC 1	12	6	0.9785	45 000	0	118 800	64 800
BAT bus w filter EC 1	12	6	0.988	45 000	5 400	118 800	216 000
CNG conversion (old)	6		1.3	45 000	8 099	486 000	0
CNG dedicated (new)	12	6	1.1875	45 000	10 799	999 500	75 600

Notes:
a The cost has been divided into the incremental vehicle cost and the cost for the catalyst.
b Relative fuel consumption in petrol equivalent
c Yearly driving distance.

A useful life of 12 years has been assumed for most of the alternatives except the old bus running on EC 1 fuel and the CNG conversion. The after-treatment devices (catalyst or filter) are expected to be replaced after 6 years.

The EC 1 fuel has a lower energy content per volume than ordinary diesel fuel and therefore the volumetric fuel consumption will be about 2 % higher. The advanced diesel engines have a lower fuel consumption that the base engine has, although the emission level is lower in the former case. The fuel consumption is increased somewhat by the addition of a catalyst and a filter due to the increased backpressure. The simple CNG conversion is anticipated to have 30 % higher fuel consumption (in energy terms) than the basic engine. The dedicated CNG engine is better in this respect and a difference of 20 % in comparison to the Euro II engine has been anticipated.

An increase in the maintenance cost is anticipated only for the bus with a particulate filter and for the CNG options. The incremental vehicle cost is highest for the CNG buses. The cost for the particulate filter is also very high and, at the moment, its useful life is not known so it is anticipated that it should be replaced after 6 years. Limited evidence from the market indicates, though, that oxidation catalysts and particulate filters might have a longer life than that. This possible cost reduction has not been anticipated since the assumptions are supposed to be conservative. On the other hand, catalysts for CNG engines have been prone to deterioration.

The environmental cost for the different bus options are shown in Figure IV–10. These costs have been calculated using the environmental cost for each emission component shown earlier.

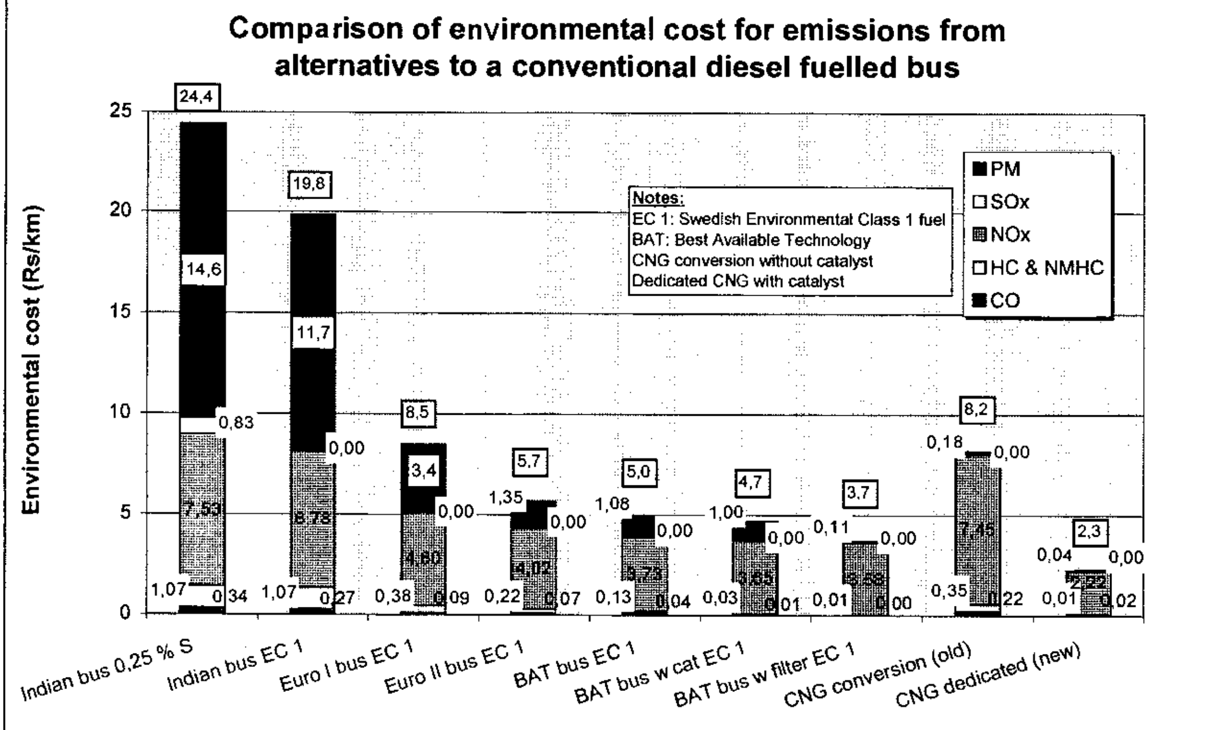

Figure IV-10: *Environmental cost for the emissions from various bus options*

The costs of the particulate and NO_X emissions are the highest emission costs for the base case. This is well in line with the generally accepted impression that these two emission components are the most problematic components for India. For the most advanced diesel options, the cost for the NO_X emissions is totally dominating the total emission cost. The dedicated CNG engine has the lowest emission cost, as expected. The difference between the dedicated CNG and the diesel option with particulate filter is mainly in the NO_X emissions.

The increased cost of operating the vehicles is shown in Figure IV–11. In this Figure, the cost has been calculated using the conditions described before. To elucidate some of the most important factors, the cost has been divided into four different areas (fuel, maintenance, vehicle and after-treatment).

The cost increase for most of the diesel options is dominated by the increase in the fuel cost (EC 1). The cost of the after-treatment system is also high for the option with the particulate filter. Both CNG options have higher cost than the other alternatives and the cost is highest for the most advanced option, as expected. Since CNG is subsidised today, the calculation is not fully correct and the cost should maybe be increased somewhat to consider the subsidies. No data on the level of subsidies has been found, though. The cost in the European countries for CNG at the filling station is considerably higher than the corresponding cost in India, which might lead to that the cost for the CNG options are underestimated in the calculations here.

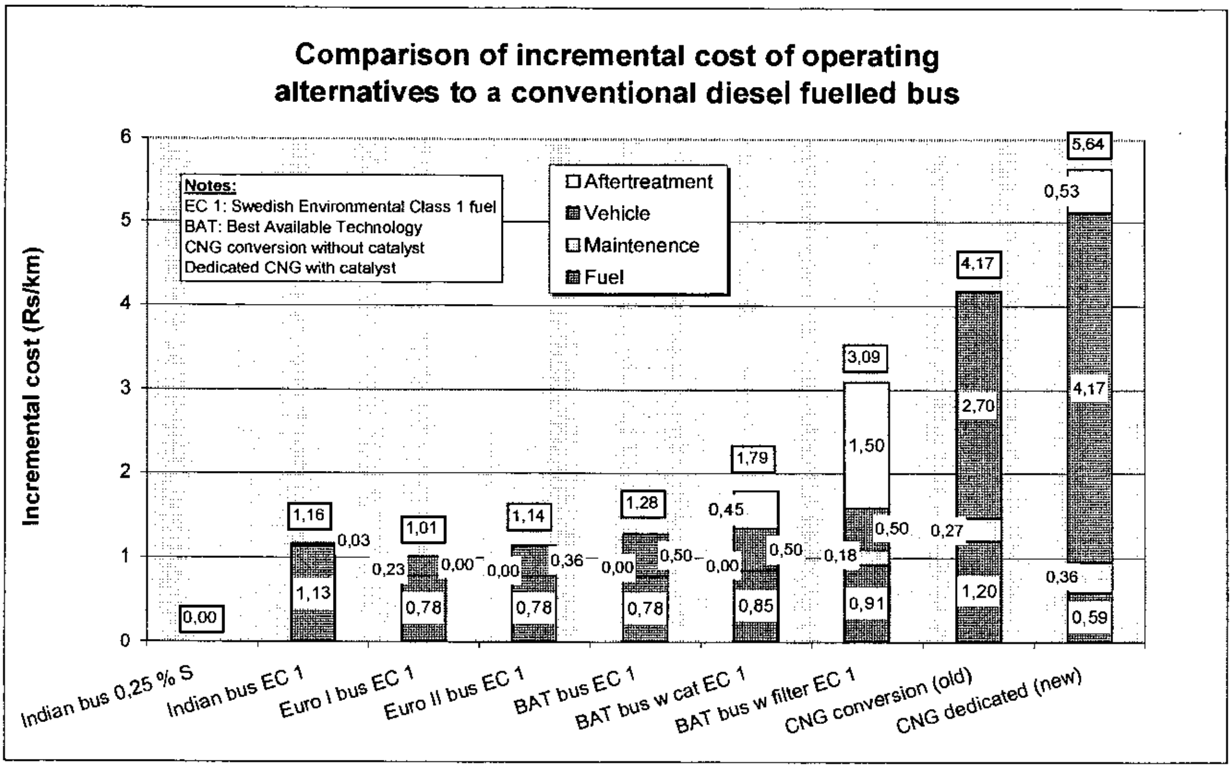

Figure IV-11: *Incremental operating cost for various bus options*

The cost-effectiveness of the different options can be evaluated by subtracting the incremental cost of operation from the environmental gain. This could be called the socio-economic benefit (or loss) of each option. The results from these calculations are shown in Figure IV–12.

Surprisingly, all options show a benefit in comparison to the base case. The explanation is the very high emission level in the base case. Using the EC 1 fuel in an old Indian bus is the option that has the smallest benefit of all options. The simple CNG conversion is significantly better that the previous one. The other options are more or less on the same level. In the choice between options that have the same socio-economic benefit, the options that have the most impact on the emissions should be chosen. It is obvious that these two options are the diesel engine with particulate filter and the dedicated CNG engine.

Another way of showing the cost-benefit of different options is to plot the incremental operational cost versus the environmental cost. This is shown in Figure IV–13. A line showing an envelope of the best options has been added to the Figure. It is obvious that the results in this Figure confirm the previous conclusions.

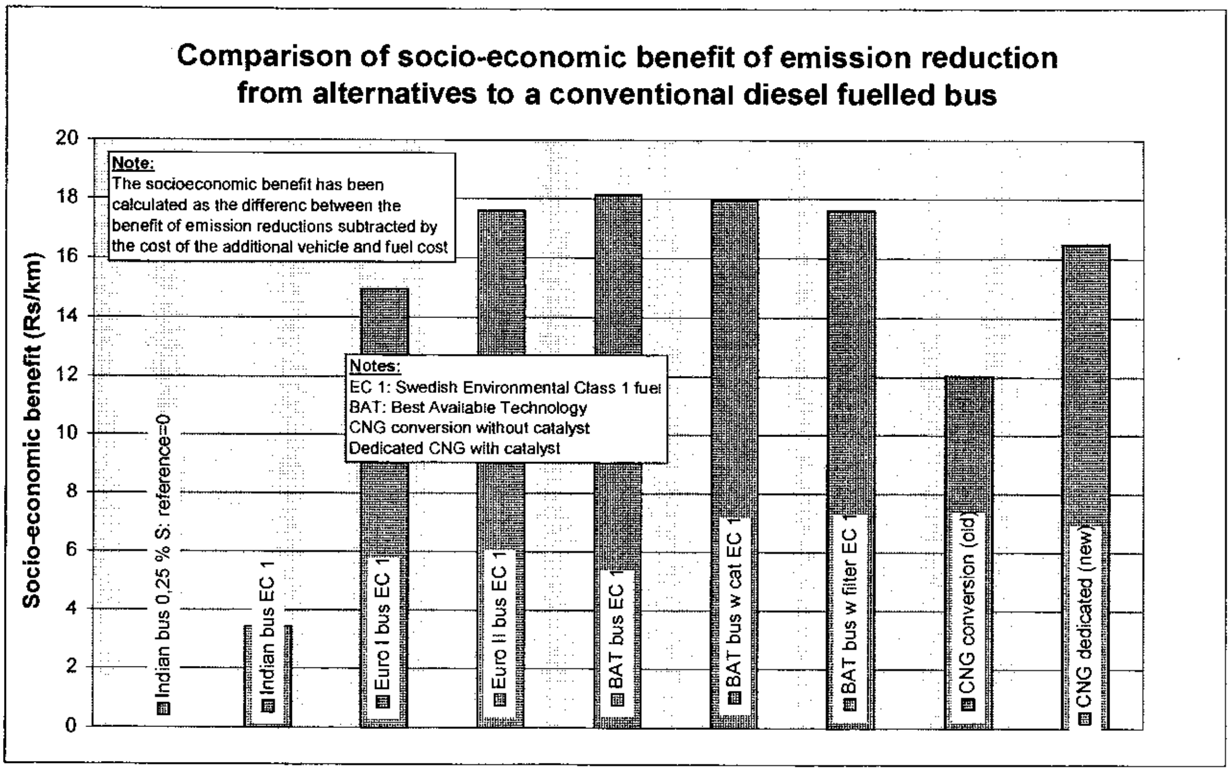

Figure IV-12: *Socio-economic benefit of various bus options*

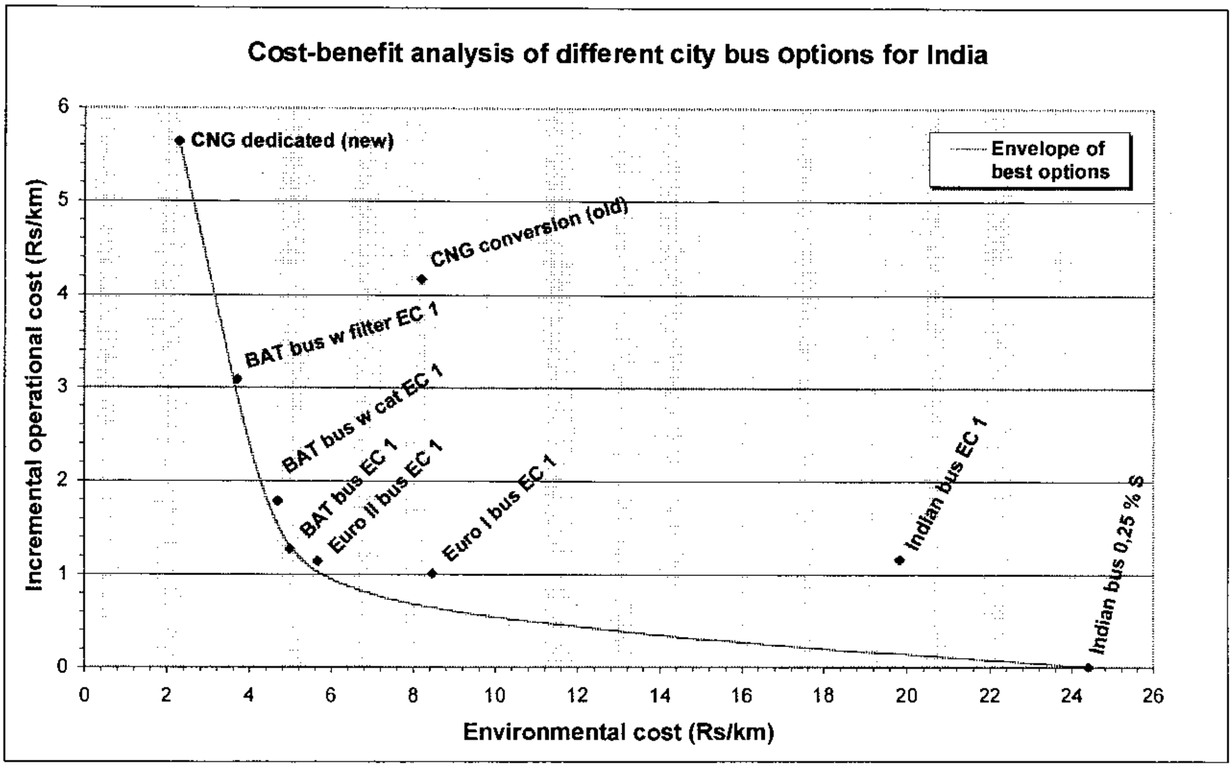

Figure IV-13: *Cost-benefit analysis of various bus options*

V EMISSION REDUCTION POTENTIAL OF CLEAN DIESEL FUEL

1 Introduction

Fuel quality has a significant impact on the emissions from diesel engines. The impact of the fuel quality can be divided into two different areas. The first area is the direct impact on the emissions from an engine. The second area is that a cleaner fuel can enhance the possibilities to use specific emission-reduction technologies. Some of these technologies can be categorised as after-treatment devices (e.g. catalysts, particulate filters etc...) and some of them affect the possible measures to reduce the engine-out emissions (in-cylinder measures). One example of an in-cylinder technology, which is affected by the fuel quality, is the use of exhaust gas recirculation (EGR). The aim of using EGR is to reduce the NO_X emissions. Since the engine is sensitive to wear induced by fuel derived sulphur compounds from the EGR gas stream, a high sulphur fuel often precludes the use of EGR. An example of a sulphur-related problem with exhaust after-treatment is the catalyst sensitivity to the sulphur level in the fuel. In this case, the sulphate emissions, and simultaneously the particulate emissions, increase by the use of a catalyst.

The examples above show that the fuel quality can have both direct and indirect influence on the emissions. In most cases, the fuel quality and the engine technology are closely linked together and both factors must be considered in order to obtain the lowest possible emissions. Likewise, the cost-effectiveness of the total system is affected by both fuel quality and the emission control technology used on the engine. It is obvious that the intention should be to optimise the whole system in order to achieve the most cost-effective solution for a certain emission level.

2 Fuel specifications

A number of different cleaner diesel fuel specifications can be considered as possible candidates for India. Some of those are:

- Indian fuel (Delhi) with 0.2500 % sulphur.
- European "Euro 2" fuel with 0.0500 % sulphur.
- The proposed European "Euro 3" fuel with 0.0350 % sulphur.
- Swedish Environmental Class 2 fuel with 0.0050 % sulphur
- Swedish Environmental Class 1 fuel with 0.0010 % sulphur
- ACEA (European car manufacturers association) "advanced" fuel proposal or similar commercial fuel quality. Sulphur content limited to 0.0050 % but with common market typical data at less than half of that value.

The fuel specifications for the fuels listed above are shown in Table V–1. This table contains most of the emission-related parameters and in the continuation in Table V–2, some parameters that affect the function of the engine, and thus indirectly the emissions, are listed.

Concluding the results shown above, there are several options available that can significantly decrease the emissions and that are advantageous from an socio-economic point of view. The introduction of EC 1 fuel alone, without changing the engine technology in the vehicle fleet, is the option that has the smallest socio-economic benefit. Some options, as the best available diesel engine with after-treatment (catalyst or filter) and the dedicated CNG engine, are the recommended options to be investigated further. If the best diesel engine technology or Euro II is not available, it should also be possible to use exhaust after-treatment on an Euro I engine. Regarding the CNG options, some measures should be taken to assure that the emission level is consistent with time. Unless this is supervised, some emission components could increase significantly by deterioration of some components. Even if the control system is not working properly, the benefit for the particulate emissions will remain and this reduction is estimated to be substantial.

9 Trucks

There are many similarities between trucks and buses regarding the driveline[3]. Smaller trucks in Europe usually have the same engines as the buses, even if there are variations in many cases. In India, the trucks are generally smaller than in Europe, and this implies that the differences between the two vehicle categories are even smaller. Therefore, most of the conclusions drawn for the buses are also valid for the trucks.

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[3] The driveline comprise engine, gearbox, differential, etc...

Table V-1: *Fuel specifications*

Specification	Unit	India 1998	EU Euro II CEN-19 Oct 1996	EU Euro III	Sweden EC2	Sweden EC1	Ecotraffic -96	Greenenergy guarnatee	Greenenergy typical	ACEA wold-wide fuel charter
Cetane no.		45	49	51	47	50	52	50	54	55
Density @15 °C	kg/m^3	820-880	820-860	820-860	800-820	800-820	815-835	820-835	828	820-840
Viscosity @ 40°C	mm^2/s	1.8-5.0	2.0-4.5	2.0-4.5	1.4-4.0	1.4-4.0	-	2.0-4.5	2.35	2.0-4.0
Sulphur content	%wt	0.5000[b]	0.0500	0.0350	0.0050	0.0010	0.0025	0.0050	0.0007	0.0030
Total aromatics[c]	%wt	n.l.	n.l.	n.l.	20	5	15	20	18	10
PAH (di+tri)	%wt	n.l.	n.l.	11	n.l.	n.l.	-	n.l.	n.l.	1.0
PAH (tri+)	%wt	n.l.	n.l.	n.l.	0.1	0.02	0.01	0.1	<0.02	n.l.
Distillation IBP	°C	n.l.	n.l.	n.l.	180	180	180	n.l.	n.l.	n.l.
T90	°C	366	n.l.	n.l.	n.l.	n.l.	-	n.l.	n.l.	320
T95	°C	n.l.	370	360	295	285	325	330	325	340
FBP	°C	n.l.	n.l.	n.l.	n.l.	n.l.	~340	n.l.	n.l.	350

Notes:

[a] n.l.: not limited.

[b] Sulphur content was 1.0000 % in 1996 and will be reduced to 0.2500 % in 2000. In urban areas (as Delhi) it has already been reduced to 0.2500 %.

[c] The value in this row is for mono aromatics for the Greenergy fuel. The number is more or less similar to total aromatics since di+tri aromatics are practically nil.

Table V-2: *Fuel specifications (cont.)*

Specification	Unit	India 1998	EU Euro II CEN-19 Oct 1996	EU Euro III	Sweden EC2	Sweden EC1	Ecotraffic -96	Greenenergy guarnatee	Greenenergy typical	ACEA wold-wide fuel charter
Flash point (min)	°C	32			56	56	⇐	60		55
CFPP (LTFT, CP)	°C	+9/+21			-10/-26	-10/-26	⇐	-10	-15	-15
Water	mg/kg	0.05			0.02	0.02	⇐	0.01	0.001	<Exp. tem[a]
Vegetable esters	g/m^3	-	-	-	-	-	-	-	-	n.d.
Oxygen										No int.add
Total acid no.	mg KOH/g	0.3			n.l.	n.l.	⇐			0.08
Copper corrosion	-	<1			1	1	⇐	2.0	<1	"A"
Ash	%wt	0.01			0.01	0.01	⇐	0.003	<0.001	0.01
Particulates	mg/l	16			24	24	⇐	n.l.	n.l.	24
Injector cleanliness	% air fl. loss	n.l.	n.l.	n.l.	n.l.	n.l.	n.l.	n.l.	n.l.	85
Lubricity (HFRR)	µm (max)	n.l.	n.l.	n.l.	n.l.	n.l.	n.l.	400	260	400

Notes:

[a] Minimum must be equal to or lower than the lowest expected ambient temperature

[b] n.l.: not limited.

In addition to the fuels in the list above, a specification proposed by Ecotraffic some years ago and a commercially available fuel from a fuel distributor in Europe are also shown in Tables V–1 and V–II. By scrutinising the fuel specifications in the Tables, it is obvious that the better fuel qualities have significant advantages concerning the properties that affect the emissions. For example, the sulphur emissions can be virtually eliminated.

3 Impact of different diesel fuel specifications on exhaust emissions

3.1 Background to the activities in Sweden

Sweden is probably the country in the World, which has most experience the commercial introduction of clean diesel fuels. The fuel quality EC 1 now has more than 90 % of the diesel fuel market for on-road vehicles. The effects of the improved fuel qualities on emissions have been extensively investigated by the Swedish EPA (SEPA). These investigations were conducted by the emission lab of SEPA until 1989. After that, the resources of this lab were incorporated in the emission-related activities of the Swedish Motor Vehicle Inspection Co. (ASB) as the independent department "Motortestcenter". In addition, the resources were increased by the move to a new laboratory building. In mid 1998, Motortestcenter was organised as a wholly owned subsidiary company of ASB. During the period since 1989, SEPA has been funding contract research on vehicle and engine emissions at Motortestcenter/MTC (continuing the efforts made in its own lab before 1989). Much of the research has been devoted to heavy-duty vehicles and a large portion of that research has been focused on the impact of diesel fuel quality. Most of the reports from these projects are been published through MTC [1 – 5]. A list of the reports can be obtained at the Internet home page of MTC (www.mtc.se).

During the investigations initiated by SEPA, it was found rather early that the sulphur level was very important for the particulate emissions and that the PAH emissions were crucial for the health effects of the exhaust. Therefore, these parameters are specifically strictly limited in the specifications for the environmentally classified EC 1 and EC 2 fuels.

3.2 Emission results

In this section, some results from the reports by SEPA/Motortestcenter/MTC [1 – 5] are first shown and commented. Later the results are generalised for Indian vehicles as well.

Besides the regulated emission components, the PAH/PAC emissions and the biological tests Ames and TCDD are shown in most of the Figures. Brief explanations of these parameters are made below.

PAH is an abbreviation for polycyclic aromatic hydrocarbons and PAC is polycyclic aromatic compounds. PAC contains both PAH and some other compounds that for example contain oxygen or other substances that make the classification as hydrocarbons not strictly correct. Of the 29 different PACs that are normally investigated by MTC, only a few of them are not PAH. According to the nomenclature used here, PAH/PAC are compounds, which have more than two benzene rings[1]. Many of the PAC compounds are carcinogenic and many are mutagenic (possible carcinogenic). Since there is a direct link between the content of PAC in the fuel and the PAC in the exhaust, it is of great importance to limit the content of PAC in the fuel. A typical PAH content for current European fuel is about 1 % but the content is not limited today. In the EC 1 fuel, the PAH content is limited to less than 0.02 %. No data are available for Indian fuel but our assessment of the fuel production processes indicate that the content might be higher than in the current European fuel.

The Ames and the TCDD tests are biological tests that give an indication of the mutagenic activity from the exhaust. In the Ames test, bacteria strains are used as an indicator and the TCDD test reacts on dioxin-like compounds. It has to be stressed that these tests are *not* a direct indicator or the carcinogenic potential of the exhaust, since some compounds can have a mutagenic activity without inducing cancer on humans. However, these tests generally have been accepted as indicator of the mutagenic activity of the exhaust. In the sampling from the exhaust, two different fractions are of interest. The first is the particulate fraction, which is sampled in a similar way as the normal (gravimetric) particulate measurement, apart from the use of a much larger filter to increase the sampled mass. The semivolatile fraction is sampled by using a polyurethane foam plug, where the heavier volatile compounds are trapped. The samples are then divided for further analysis using the Ames and the TCDD tests. To simplify the presentation here, the sum of the results (PAH, Ames and TCDD) from both fractions is shown.

In Figure V–1 the results on a Scania bus representing the model year 1988/1989 is shown. The EC 1 and EC 2 fuel specifications were somewhat preliminary at that time which is indicated by the "~" mark.

By analysing the results in Figure V–1 it is clear that both fuels have an effect on the CO, NO_X and the PM emissions. The impact on the HC emissions is small and unclear. However, it is not the impact on the regulated emissions that is of most importance for the cleaner diesel fuels. The impact on the PAC emissions and in the biological tests is far greater. This is because the harmful compounds in the HC emissions are greatly reduced. The reduction in the biological tests is about 85 %.

In Figure V–2, the same results are shown on a newer Scania bus (this bus engine was introduced in 1991). Note that no tests were carried out on conventional diesel fuel, hence the reference has been set to EC 2 in this case.

[1] Sometimes even 2-ringed aromatic compounds are classified as PAH/PAC but this nomenclature is not correct. Furthermore the biological activity (incl. cancer) from the two-ringed compounds are lower than from the 3+ compounds.

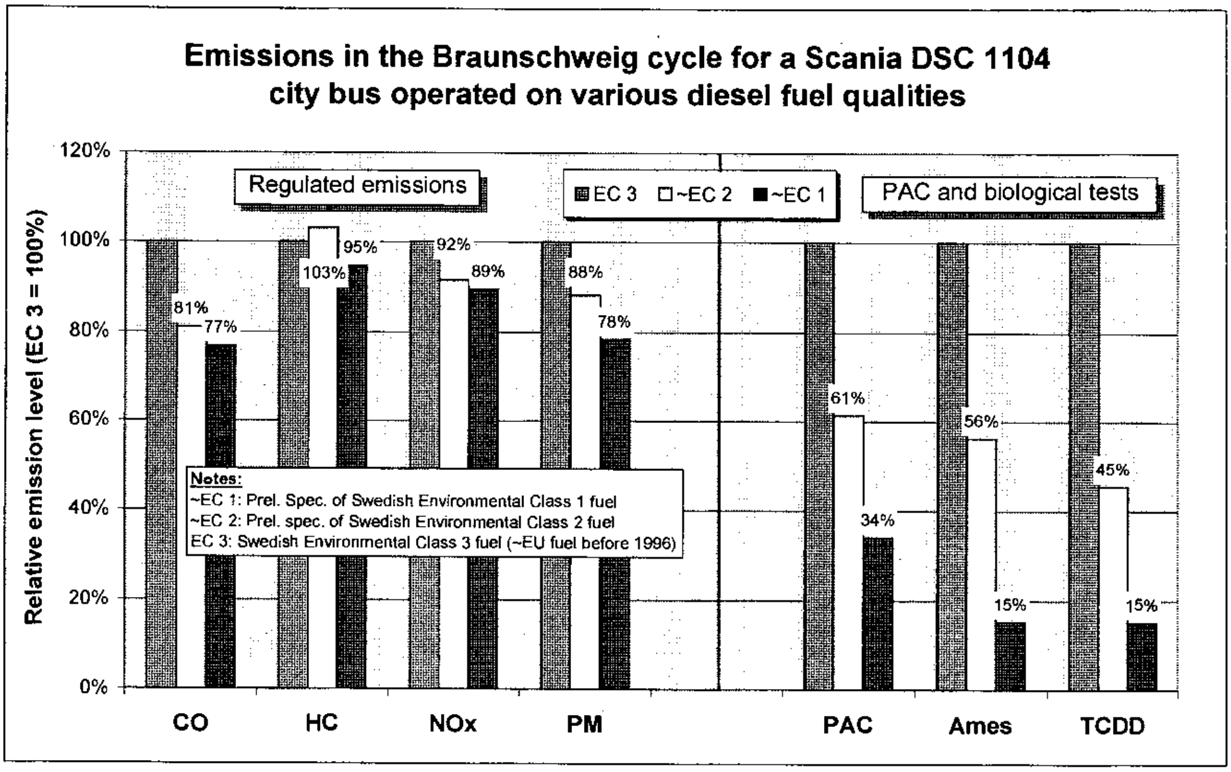

Figure V-1: *Impact of improved fuel quality on emissions from a Scania city bus (engine: DSC 11 04)*

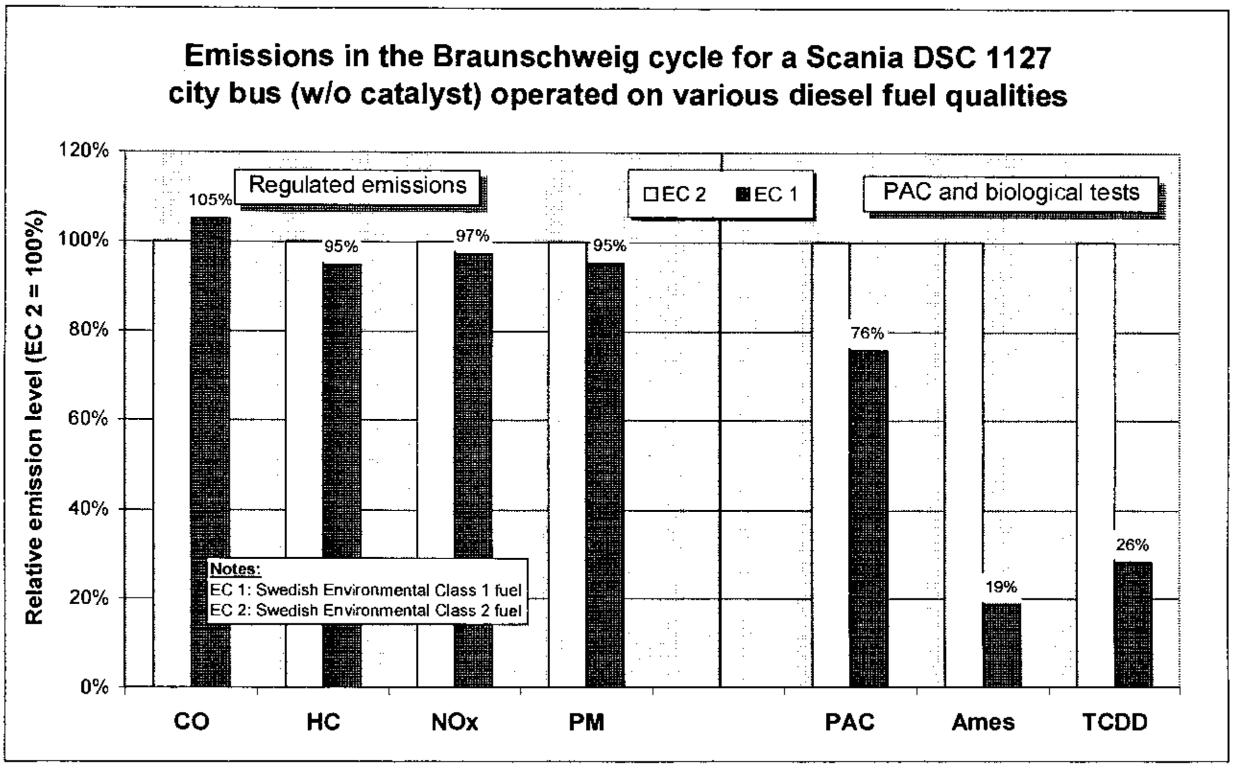

Figure V-2: *Impact of improved fuel quality on the emissions from a Scania city bus (engine: DSC 11 27)*

Figure V–2 shows that the impact of further improving the fuel quality from EC 2 to EC 1 is mostly apparent for the PAC and in the biological tests. Furthermore, this Figure and the former Figure shows that the impact on the biological tests is greater than on PAC emissions.

Similar results as in the two previous cases are shown for two Volvo heavy-duty vehicles (trucks) in Figures V–3 and V–4. The first truck represents mid 1985 engine technology and the second truck is an advanced truck having an engine that complies with the Euro II emission regulation. It is obvious that the reduction of the emissions is on the same order of magnitude as in the previous cases.

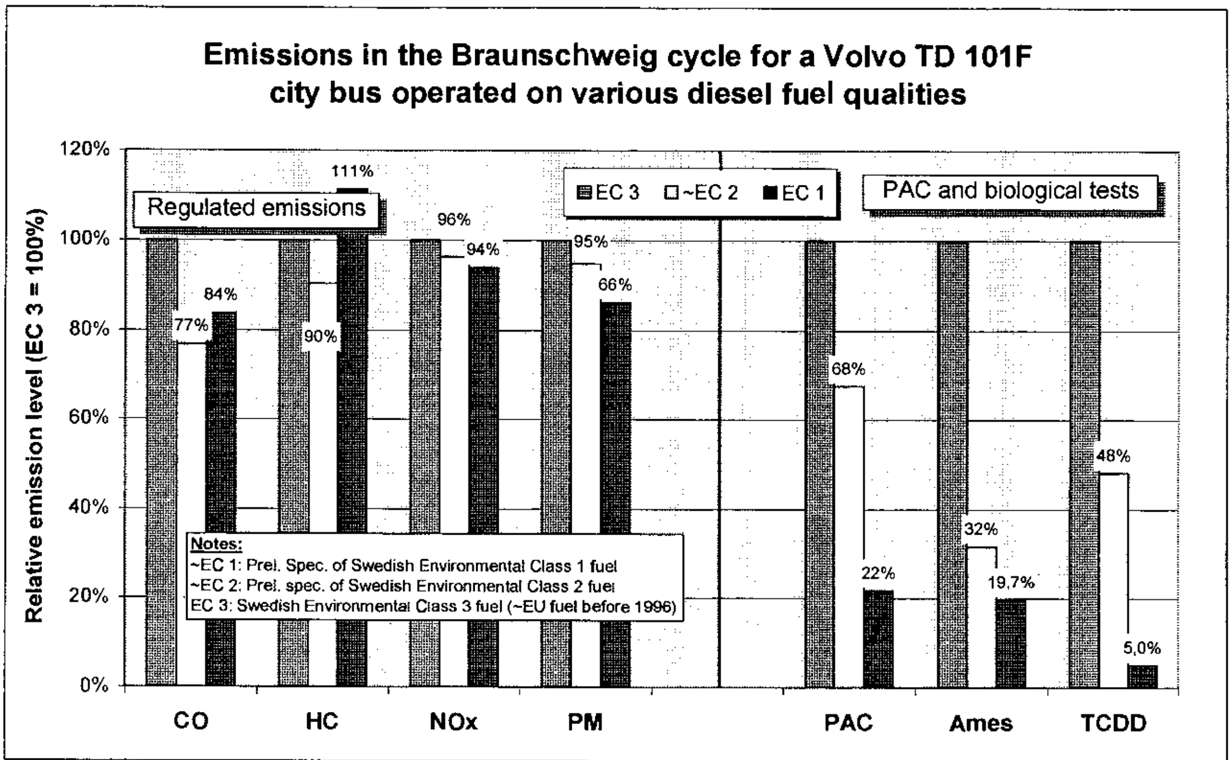

Figure V-3: *Impact of improved fuel quality on the emissions from a Volvo truck (engine: TD 101F)*

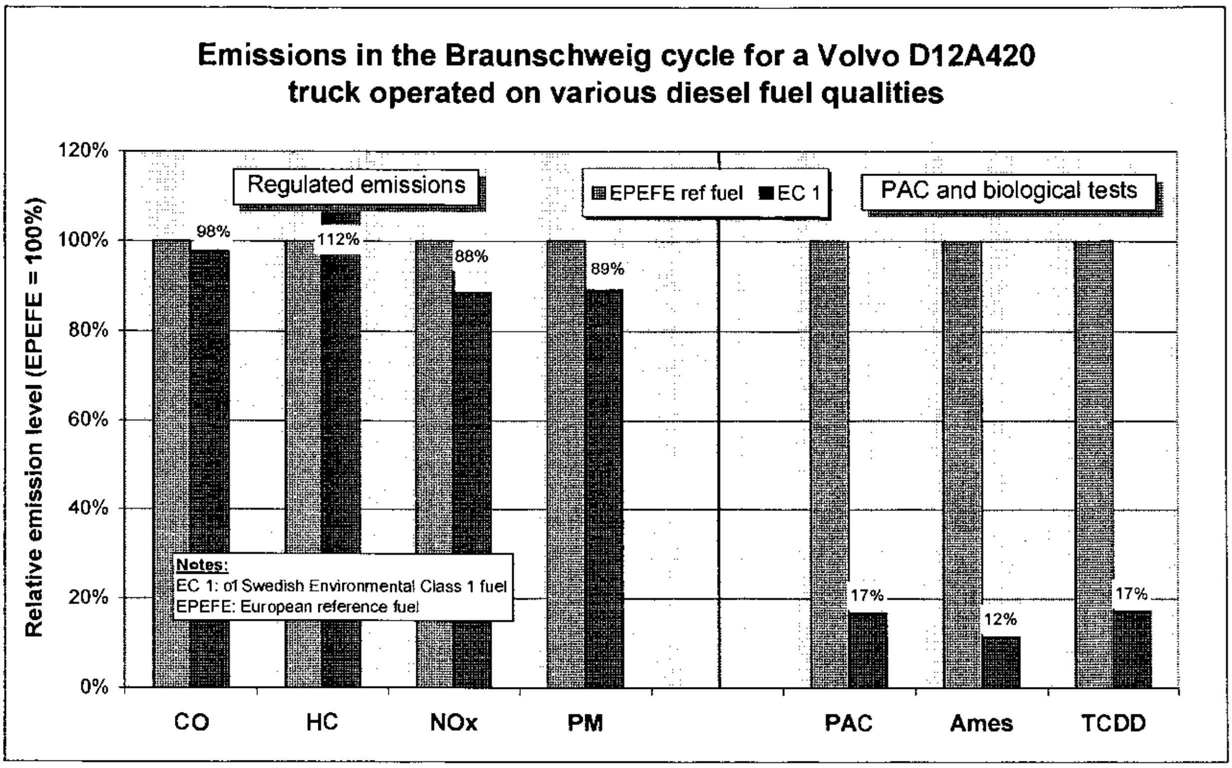

Figure V-4: *Impact of improved fuel quality on the emissions from a Volvo truck (engine: D12A420)*

It must be noted that the measurement scatter is relatively high for the unregulated emissions in comparison to the regulated emissions. The trends for much greater reductions of the PAC emissions and in the biological tests are however, clear. In comparison to the reference fuels in the tests above (EC 3 and EPEFE[2]) Swedish EC 1 fuel can reduce the level in the biological tests by more than 80 %. The reduction in comparison to typical Indian fuel would probably be much greater, implying that this reduction could be equal to one order of magnitude.

One interesting question is how great the impact of an improved fuel quality would be on the emissions from Indian heavy-duty vehicles. To show this trend it has to be recognised that the emissions from vehicles in India generally are much higher than from the new European vehicles covered above. The emission factors by TERI, with some corrections made by Ecotraffic according to Appendix IV, have been used as the base emission level. The calculations in the subsequent Figures are shown only for the regulated emissions. However, it is clear that the difference between the best option in comparison to the base level from an Indian bus would be far greater than the differences shown above.

[2] EPEFE is a reference fuel that has been used in the European fuel investigation projects.

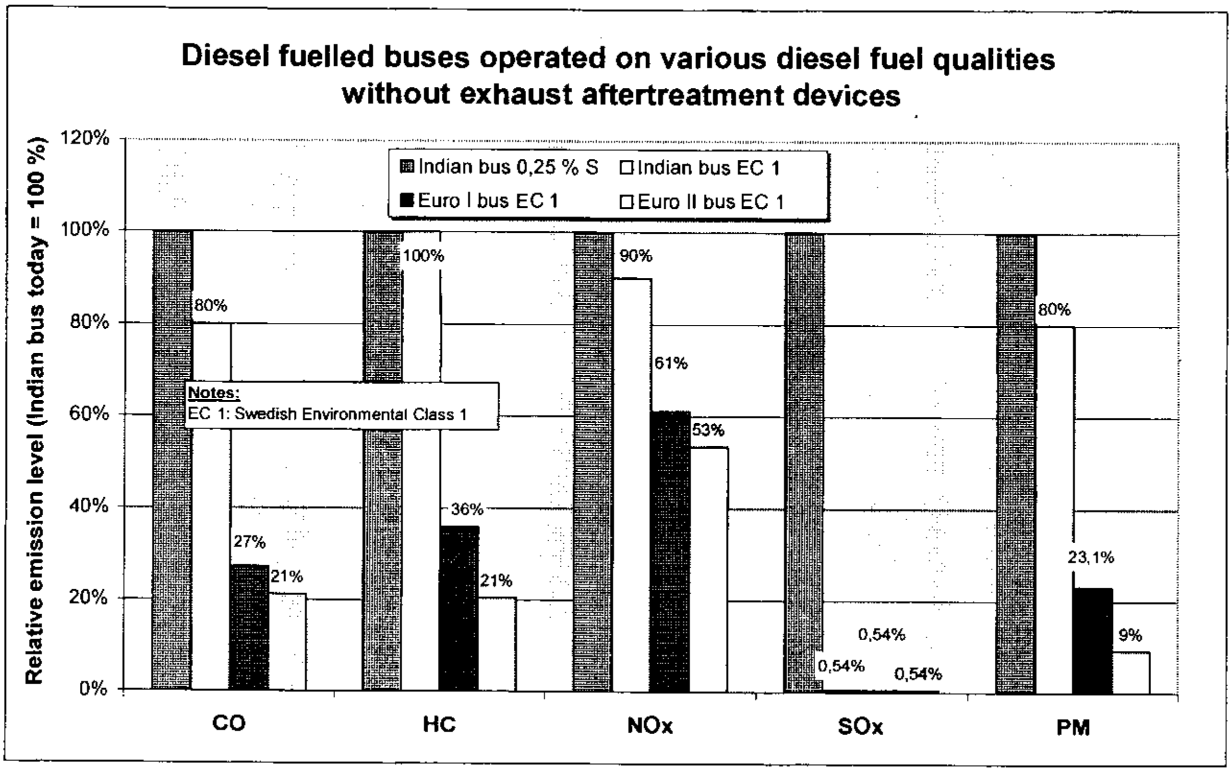

Figure V-5: *Impact of improved fuel quality and engine technology on Indian buses; today and in the future*

In Figure V–5, four different options are shown. The impact of the EC 1 fuel on an Indian bus has been calculated using a weighted average impact on emissions derived from the tests at MTC. Euro I in the Figure is a hypothetical engine complying with this regulation (and India 2000). In comparison to the Scania DSC 1104 shown above, the CO, HC and particulate emissions have been set somewhat higher. Likewise, the hypothetical Euro II bus emissions data have been derived from the newer Scania DSC 1127.

It is clear that the use of EC 1 fuel in an Indian bus has some impact on the CO, NO_X and particulate emissions. The HC emissions remain unchanged while the SO_X emissions are virtually eliminated. The impact on the health-related emissions (PAC, Ames & TCDD) should be at least 80 %. It should also be noted that the engine technology generally has a greater impact on the regulated emissions than the fuel quality. However, as shown earlier, the impact of the fuel quality on the health-related emissions is substantial. Use of the rule of thumb on these emissions would yield an improvement by almost two orders of magnitude in comparison to the base level.

The options shown in Figure V–5 represent actions that can be taken immediately. The fuel can be imported and Euro I and II vehicles can be either imported or produced by the Indian manufactures shortly – at least in the former case. Euro II buses could presumably be produced by Indian manufacturers in co-operation with foreign manufacturers.

The use of a clean diesel fuel gives other options than shown above. It is well known that a catalyst can be used on heavy-duty vehicles, provided that the sulphur level of the fuel is below a certain level. The first generation of catalysts resulted in an inket (similar to the Scania engine shown above). It should be recognised that there are engines on the US market that have even lower HC and PM emissions. The results for the catalyst and the particulate filter have been derived from emission tests at MTC [6 and 7][3]. Some corrections have been made, though, to take some deterioration of the after-treatment devices into account.

The results in Figure V–7 clearly show that further substantial improvements of the emissions could be made in comparison to the best engine by applying a catalyst and/or a particulate filter to it. The catalyst and the filter virtually eliminate the CO and HC emissions. PM emissions are not reduced much by the catalyst but the impact of a particulate filter is at least an order of magnitude. The reduction in this case is more than two orders of magnitude in comparison to the base level. The only remaining regulated emission component is the NO_X emissions. At the moment there is no commercially available after-treatment technology that can reduce the NO_X emissions from diesel engines.

The emissions of the compounds that pose potential health hazards (PAH, etc.) should also be reduced considerably by using a catalyst and a particulate filter. There have been some attempts to measure these compounds and to carry out biological tests on a catalyst equipped bus at MTC [8]. The biological tests were still in an early test phase at that time and the levels were so low that they approached the detection levels of the analysis methods. Therefore, it is somewhat difficult to assess the potential of a catalyst and a particulate filter by using these results. Investigations carried out later on different fuel qualities have always been carried out without a catalyst, even if the vehicle was equipped with such devices, in order to increase the emission levels. One could anticipate that the impact on the harmful substances is about the same as the impact on the HC emissions (both volatile and particle bound). Therefore the impact of a catalyst and a particulate filter on the PAH emissions and in the biological tests could be one order of magnitude. Adding all the possible measures – best engine technology, EC 1 fuel and a particulate filter – could decrease the harmful substances by up to three orders of magnitude, in comparison to the vehicle/fuel combination on the roads in India today. This potential certainly needs to be investigated further.

[3] Unfortunately these reports have only been published in Swedish.

crease of sulphate emissions due to the oxidation of SO_2 to SO_3. SO_3 is hygroscopic and the bonding of water gives sulphuric acid and water, which is measured as particulate emissions on the sample filter. Thus, a catalyst can increase the particulate emissions under these circumstances. In the atmosphere, the described reactions occur anyway but since the reactions are not instant, the local particle concentrations are not affected as much as with a catalyst. Newer catalysts are somewhat more tolerant to sulphur level than the first generation of catalysts but the adaptation generally decreases the activity on the other emissions. It is generally accepted that the sulphur level should be less than 0.0500 % to avoid too much sulphate formation in a catalyst, but a lower level is preferable.

A particulate trap is another technology that has a great potential to further reduce the emissions. There are not many commercially available particulate traps on the market today. Most of the traps are still on a development stage. One exception is a trap called CRT (Continuously Regenerating Trap) from the catalyst manufacturer Johnson Matthey (JM). This trap has been sold in more than 3 000 units on the European market and many of them have been sold in Sweden. The strong sales in Sweden were probably a result of that the trap was initially developed by the JM subsidiary "Svenska Emissionsteknik" (Swedish Emission Technology) in Gothenburg. Initially the CRT was intended for a sulphur level of 0.0010 % but later versions seem to tolerate up to 0.0050 % sulphur. The CRT particulate filter is shown in Figure V–6.

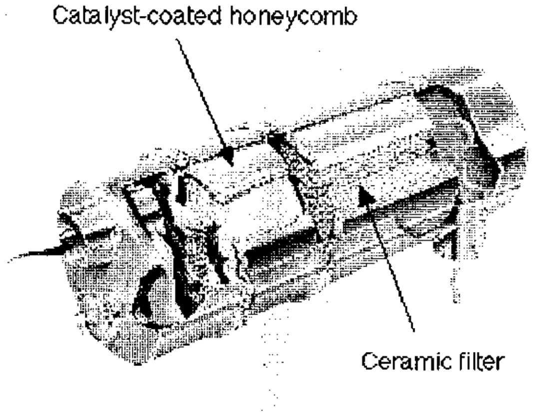

Figure V-6: *The CRT particulate filter*

The CRT filter uses a catalyst before the filter in order to convert NO to NO_2. In the filter, NO_2 works as a catalyst for the oxidation of the particulate emissions. In this reaction, NO_2 is reduced to NO again. However, an increase in the NO_2 share of the total NO_X emissions cannot be totally avoided and this is the major drawback of the CRT system. NO_2 is the more harmful substance of the two, but eventually all NO is oxidised to NO_2 in the air. It is anticipated, though, that the oxidation of NO to NO_2 in the atmosphere in India is very rapid anyway, so an increase in the NO_2 emissions from the vehicle should not increase the local NO_2 concentrations too much. The CRT particulate filter can be applied to most engines that are relatively new, i.e. engines that do not have too high particulate levels. It is difficult to determine (without knowledge of the particulate emission level) the categories of vehicles in India that could be fitted with this equipment but, in general, those vehicles should hardly be any older than five years. The recommendations from the equipment manufacturer should be followed in this respect. It is also anticipated that the best solution for the oldest and dirtiest vehicles is to scrap them rather than to try to modify them (by using exhaust after-treatment).

In Figure V–7, the results from using a catalyst and a particulate trap are shown in complement to the results from Figure V–5. The notation BAT stands for Best Available Technology, which corresponds to one of the best engine on the Swedish mar-

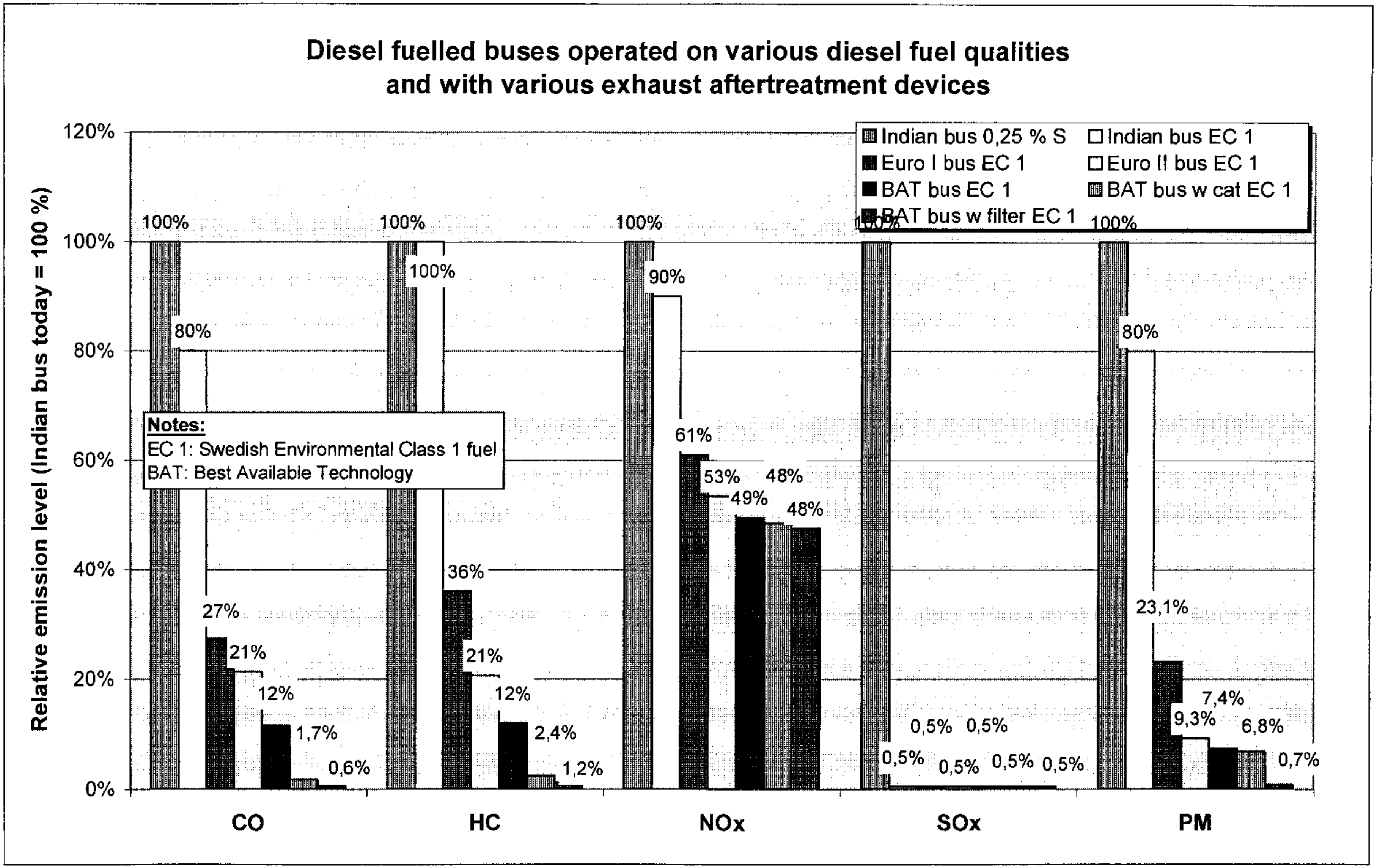

Figure V-7: Impact of improved fuel quality and emission control technology on Indian buses; today and in the future

5 Recommended fuel qualities

The Swedish EC 1 fuel is the best commercially available fuel (on a relatively large scale) in the world today. The most notable impact is on the unregulated emissions causing adverse health effect. A further advantage is the possibility to use after-treatment devices such as catalysts and particulate filters. One problem for the refineries is that the upper boiling range of the fuel is limited. Therefore, the yield from the crude oil is reduced and consequently there is a competition between diesel fuel and aviation fuel. The situation works in Sweden since there is trade of fuel between the nearby countries. However, it seems impossible, with the knowledge today, to duplicate this situation for the whole world market. Since the environmental impact of a fuel on a world-wide basis is also dependent on the market penetration, there might be a better total compromise if a fuel with a slightly higher boiling range is used. This was proposed by Ecotraffic some years ago and some rough calculations showed that the economic gain by changing the fuel specification could be more than 1 billion Rs per year for Sweden. There are fuels available on the market that have specifications very close to the specification proposed by Ecotraffic and the ACEA proposal is also very close. The ACEA proposed fuel specification could probably be introduced in Europe in 2005. Therefore, it might be both more cost-effective and increase the harmonisation if this fuel was chosen for India as well.

Ecotraffic has posed the question to a Swedish oil distributor of the cost of different fuel qualities and the transportation cost from Europe to India and the results are shown in Table V–4. Since no fuel according to the Indian specification was available from this distributor, the cost for European heating oil was used as the base level instead. The fuel called "City Diesel" is the Swedish EC 2, which is very close to the ACEA specification. The transportation cost has been calculated from Sweden to an oil depot in a harbour in India. Provided that a supplier closer to India could be found, the transportation cost would decrease somewhat.

Table V-3: *Incremental cost of clean diesel fuel and transport cost (per liter)*

	Incremental cost		Transp. cost	
Fuel type	US $	Rs	US $	Rs
EU heating 0.2 % S	0	0	0,03	1.2
City Diesel (EC 2)	0.0166	0.69	0.03	1.2
EC 1	0.0448	1.87	0.03	1.2

It is obvious that the incremental cost is much lower for the EC 2 fuel than for the EC 1 fuel. The impact on the emissions from a single vehicle for the EC 2 are not as great as for the EC 1, but since the former could be supplied in greater quantities, the total impact on the pollution could be similar. Our proposal is therefore to investigate the possibilities of introducing a fuel according to the ACEA specification instead. In an initial phase, the EC 1 fuel could be introduced, but later the specification could be changed. One condition for choosing the ACEA specification is that the manufacturers of the after-treatment devices approve of the use of this fuel.

6 Potential problems with clean diesel fuels

When the EC 1 fuel first was introduced in Sweden several problems were encountered. One problem was that the lubricity was poor, which caused severe wear in the injection pumps. It was first thought that the cause could be the lower viscosity or the removal of the sulphur. Later it was found that the cause was that several polar compounds (molecules) in the fuel were removed in the process that reduced the PAH and sulphur content. The problem was eventually solved by using an additive. Lubricity tests now indicate that the lubricity of the EC 1 fuel is at least as good as conventional low sulphur European fuel (0.0500 % S). The fuel also meets all future ACEA specifications for lubricity.

The solvent nature of EC 1 fuel can cause problems with the removal of deposits in the fuel system of old vehicles. Therefore, the fuel filters must be changed several times in the fuel-switching process.

If a very high aromatic content fuel has been used, the aromatic compounds migrate into elastomers and polymers and replace the plasticisers in these materials. When the fuel is switched to a low aromatic fuel, the aromatic compounds are dissolved in the fuel and the material is hardened. This might lead to potential leaks from o-rings or gaskets. However, not many problems of this kind have been reported from the Swedish market.

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VI QUALITY ASSURANCE METHODS FOR THE SUPPLY OF ULTRA LOW SULPHUR DIESEL FUELS

Introduction

In order to guarantee the quality of low-sulphur diesel fuel in the fuel supply chain from the refinery to the consumer, the purchaser must secure that a number of measures are taken in addition to the normal procedures for standard diesel fuel. This is of particular importance for the ultra-low sulphur diesel fuels, such as the Swedish Environmental Class 1 (EC1) and Class 2 (EC2) diesel fuels or equivalent fuel specifications. The recommendations in this appendix have been focused on the mentioned two fuel qualities but the recommendations are valid for other low-sulphur (<50 ppmw) fuels as well.

The EC1 fuel has solvent properties, implying that special care has to be taken considering tanks and pipes that have oil deposits. In this appendix, the necessary steps to be taken in each link of the fuel supply chain are highlighted.

1 Choice of fuel supplier

1.1. Several fuel suppliers in Europe can deliver high quality low-sulphur diesel fuel today. For example, all oil companies on the Swedish market can supply the EC1 diesel fuel. Today this fuel has more than 90 % of the Swedish market for on-road diesel fuel.

1.2. In the United Kingdom Greenergy is the leading supplier of reformulated diesel and petrol fuels. The reformulated diesel oil delivered to the UK market is somewhat similar in specification to the Swedish EC2 diesel fuel (see spec. in Appendix V) in that respect that the sulphur content is limited to 50 ppmw. The market penetration of this fuel is expected to increase rapidly due to the introduction of economic incentives in 1999. The Finnish oil company Neste, the Norwegian Statoil and the Swedish Preem are large suppliers of EC1 and EC2 diesel fuels.

1.3. The chosen supplier shall undertake to guarantee that the fuel quality is within the specified min. and max. values. Typical and guaranteed values (by the supplier) are complementary information in addition to the specifications[1].

2 Shipping from the fuel supplier

2.1 EC1 and EC2 fuels should be stored in tanks specially intended for these fuel qualities. Pumping of the fuel to the tanker should – if possible – be carried out in pipes separated from the normal pipes intended for ordinary qualities of diesel fuel and light fuel oils.

[1] It should be noted that some fuel specifications, as for example the ACEA worldwide fuel charter, are not finalised yet. Therefore, the levels guaranteed by the supplier and typical quality results from production data are of great importance.

2.2 Fuel samples should be taken from both from the tank in the harbour and from the ship by an independent inspector before and after loading.

2.3 It could be advantageous to assign the supplier to assume the responsibility of choosing the ship and to initiate shipments on a CIF-basis (Cost, Insurance and Freight).

3 Sea transport on a tanker

3.1. Ships intended for the transport of EC1 and EC2 fuel qualities should be intended for the handling of clean products. An independent inspector should inspect the tanks, pipes and pumps of the ship and in addition make sure that previous shipments cannot cause contamination of the EC1 and EC2 fuels. Samples should be taken before and after the unloading.

3.2. It could be advantageous to assign the supplier to assume the responsibility of the choice of the ship and to initiate shipments on a CIF-basis.

4 Delivery of the fuel from the tanker

4.1. Before the delivery, fuel samples should be taken by an independent inspector.

4.2. The pipelines for unloading the ship should be intended for EC1/EC2 (and/or kerosene) or, as an alternative solution, be cleaned by EC1/EC2 (to be reclassified to ordinary diesel fuel) or be cleaned by water. Special control of the unloading system should prevent that no part of this system could contain any other product than EC1/EC2 before the unloading is initiated.

5 Storage

5.1. Before a tank is utilised for EC1/EC2 fuels, the tank should be cleaned and all oil residues from the walls and the bottom of the tank should be dissolved and removed.

6 Loading of the tank lorry / railway tank wagon

6.1. Loading to a tank lorry, railway tank wagon, ship and the transfer to another tank should be carried out in pipes cleaned and intended for EC1/EC2.

7 Transport in the tank lorry / railway tank wagon

7.1. Tank lorries and railway tank wagons transporting EC1 and EC2 should have cleaned tanks. It should be verified that products from earlier transports do not remain in the vehicle/wagon system for unloading, i.e. pump, pipe and hose systems.

8 Storage at the filling station

8.1. Before the filling tanks are utilised for EC1/EC2 at filling station, transport company and fuel depots, the tanks should be cleaned and fuel filters (if installed) should be replaced.

8.2. Fuel filters in pumps should be replaced or controlled when the transition to EC1/EC2 is made.

9 Vehicle

9.1. Diesel vehicles that are switching from standard diesel fuel to EC1/EC2 should have the fuel filters replaced.

9.2. The fuel filter should be controlled and, if necessary, be replaced at one or several occasions after the switchover to EC1/EC2. The control/replacement necessary depends on the vehicle age and the condition of the fuel tank.

VII FUEL SWITCHING – FROM DIESEL TO LPG/PROPANE/CNG

1 Introduction

Compressed natural gas (CNG) is one of the most interesting fuels on the world-wide fuel market today, even if its use as an automotive fuel is less than 0.1 % today. The reason is that the fuel is very cheap on most markets and that it is available in abundant quantities.

Liquefied petroleum gas (LPG) is used as an alternative fuel on many markets today. The market penetration is about 1 % of the world-wide fuel market, i.e. about the same as the market share for alcohols (mainly ethanol). However, the use of LPG is more evenly distributed around the world than the use of alcohols, which are used mainly on two markets: the USA and Brazil. Propane is the main content of LPG but the propane content varies considerably from market to market. Butane is the other major component in LPG. The specification of LPG differs widely from market to market. The typical specification of LPG in India is very rich of butane. Butane has a much lower octane number than propane and LPG with a high content of butane is a poor fuel for spark-ignition engines. Therefore, LPG is not considered as a viable fuel option in this investigation. Furthermore, LPG is used as a cooking fuel in India and there is a shortage of LPG on the market. The only option left is to import propane.

2 Light-duty vehicles

Although this Appendix is devoted mostly to the use of CNG and propane use in heavy-duty engines, some results are also shown for passenger cars. In Sweden, several field trials are running on gaseous fuels [1 – 2]. Most of the vehicles are running on CNG and biogas (mainly from sewage and waste). The activities in the USA are even more intense than in Sweden due to the greater availability of CNG in USA. The pipeline grid cover most populated areas in USA whereas there is only a short pipeline in Sweden.

In Table VII–1, some results from Kelly et. al [3] are shown. The test series in Table VII–1 are the average results from 75 different vehicles tested in two different laboratories. Of the vehicles in the investigation, 37 were run on CNG and 38 on petrol (reference group). It has to be recognised that the scatters in the data (standard deviation) are great in many cases. Some conclusions can still be made. CO emissions are considerably lower for CNG in one lab, but the other lab shows little difference. NMHC emissions are considerably lower as expected. NO_X emissions are somewhat lower for CNG as well as the CO_2 emissions. The fuel consumption is higher for CNG, probably due to the increased weight of the vehicles.

Table VII-1: *Regulated emissions in the FTP-75 driving cycle for Dodge B250 van*

	Lab1				Lab 2			
	CNG		Petrol		CNG		Petrol	
	g/mile	st. dev.	g/mile	st. dev.	g/mile	st. dev.	g/mile	st. dev.
CO	1.99	1.19	5.83	1.62	3.65	4.29	3.76	0.95
NMHC	0.05	0.02	0.29	0.05	0.06	0.04	0.26	0.03
NO_X	0.54	0.32	0.78	0.16	0.48	0.45	0.70	0.17
CO_2	564	15	667	76	501	23	617	21
FC (mile/gal)	11.54	0.33	13.10	0.51	13.47	0.65	13.91	0.47

In Table VII–2, some unregulated emissions are shown. The emissions of benzene (C_6H_6) and 1,3 butadiene are significantly lower for CNG. This could be expected since CNG contain (practically) no benzene or olefines that can form butadiene. Formaldehyde emissions are higher for CNG but acetaldehyde emissions are lower. The sum of the toxic emissions is significantly lower for CNG and similar results are shown for the ozone forming potential and the specific reactivity.

Table VII-2: *Unregulated emissions in the FTP-75 driving cycle for Dodge B250 van*

	Unregulated emissions (mg/mile)						
	C_6H_6 [a]	C_4H_6 [b]	HCHO [c]	CH_3CHO [d]	Sum tox [e]	OFP [f]	SR [g]
CNG	0.70	0.10	6.28	0.39	7.47	294	2.04
Petrol	10.3	1.93	3.26	1.02	16.31	1 149	4.08

Notes:

[a] Benzene
[b] 1-3 butadiene
[c] Formaldehyde
[d] Acetaldehyde
[e] Sum of air toxics
[f] Ozone forming potential
[g] Specific reactivity

The tests covered above shows that CNG has a great potential to decrease several emission compounds from a spark ignition engine in comparison to petrol fuel. Most of the improvement is seen in the unregulated emissions. The reason for this is that CNG is a very simple fuel concerning its chemical composition. Most of the CNG is methane. This should give an inherent advantage also for small engines (2 and 3-weelers) and heavy-duty engines. Advanced CNG concepts show a great potential for further improvement of the emissions from light-duty CNG vehicles [4, 5].

3 Heavy-duty vehicles

3.1 Emission potential of CNG

There are many results available for heavy-duty CNG engines as well as for light-duty vehicles. The results in the former case are not so complete as in the latter case. Usually the conversion to CNG operation is also much easier for light-duty vehicles since these engines are spark-ignition engines (otto-engines) in the basic configuration. Therefore, the three-way catalyst option is also the most natural choice.

Heavy-duty vehicles generally have compression-ignition engines (diesel engines), which are fuelled by diesel oil. These engines must be converted to spark-ignition to be able to operate on CNG[1]. Simple CNG conversions are usually operated under stoichiometric[2] conditions. Since the thermal load is much higher on an otto engine than on a diesel engine, most turbocharged engines are operated under lean conditions (lean-burn or air excess). In this report, the simple conversion option is a stoichiometric engine and the dedicated engine is a lean-burn engine.

In the literature there are many results showing a very high potential to low emissions for the CNG engines [7]. On the other hand, some reports show problems with the durability of the emission control system [8 – 10]. In Table VII–3, some results by Clark et al. are shown on CNG buses operated in a transient chassis dynamometer driving cycle (CBD) [11].

Table VII-3: *Emissions from CNG city buses according to the CBD driving cycle*

	Emlssions (g/mile)						
	CO	THC	NMHC	NO_X	PM	CO_2	CH_4
CNG (all buses)	2.54	18.91	0.86	23.47	0.030	2454	16.79
⇑ Low NO_X buses	1.80	20.84	0.91	17.40	0.035	2484	18.11
⇑ High NO_X buses	4.27	14.43	0.67	37.62	0.020	2385	12.16
Diesel buses	4.22	1.89	n.m.	28.66	0.69	2429	n.m.

The CNG buses in Table VII–3 have been divided into two groups; the low NO_X and the high NO_X buses. CNG has some advantage concerning the CO emissions although it has to be recognised that the diesel reference has very high CO emissions. Total hydrocarbons (THC) are much higher for CNG but the NMHC emissions are lower than the THC emissions of the diesel buses. The reason for the higher THC emissions from CNG is that a spark ignition engine generally has one order of magnitude higher emissions of unburned fuel due to the air-fuel mixture trapped in the crevices, which escape combustion. The direct injection of the diesel fuel avoids this problem. On the other hand, the HC emissions from a CNG engine contain mostly methane, and thus the NMHC emissions are somewhat lower than the THC emissions from the diesel engine. The average NO_X emissions are lower for the CNG engines but the scatter is very high. The "high NO_X" CNG buses have considerably

[1] There are options available that do not use spark plug but these options are not covered here.
[2] Stoichiometric means that the relative air-fuel ratio is set to unity (1).

higher NO_X emissions than the reference diesel buses even if the NO_X level for the latter have to be considered as a very high level as well. The particulate emission are more than one order of magnitude lower for the CNG buses than for the diesel buses and this has to be considered as the major advantage of CNG operation.

The test results in Table VII–3 shows that CNG has a great potential for low emissions but also that the NO_X emissions can increase considerably if the engine control system is not working properly. It has to be noted that the CNG engines in the study above are advanced engines with a sophisticated emission control system. Still this system is not durable. This problem has to be taken into account when the emission potential of heavy-duty CNG vehicles is assessed. Another problem is that the emissions are much higher in a transient driving cycle than in a steady-state test cycle. This has been observed in the tests on gaseous-fuelled vehicles in Sweden [6 – 10].

There is still a great potential of further decreasing the emissions from heavy-duty CNG engines. One option is to use the TWC emission control system similar to the system used on light-duty vehicles. Some results from a work by Corbo from Iveco on a 9.5 litre engine show this potential [12].

Table VII-4: *Emissions from two different CNG combustion systems (g/kWh)*

	CO	HC	NMHC	NO_X	PM
Euro II – limits	4.0	1.1	- - -	7	0.15
Euro III – limits	2.1	0.66	- - -	5	0.1
Stoichiomet. TWC	0.3	0.3	n.d.	0.1	<0.01
Lean-burn	3.3	5.1	0.3	4.7	<0.02

As can be seen in Table VII–4, the TWC system has a greater potential than the lean-burn system. On the other hand, the TWC system is more sensitive to deterioration and malfunctions in the control system will inevitably increase the emissions more that for the lean-burn system. Another problem is the thermal stress on the engine and its exhaust system. These problems have resulted in limited interest in the TWC system for heavy-duty engines. Therefore, we have considered only the lean-burn option as an advanced solution for India.

As in the former case with the TWC engine, the lean-burn engine can be improves as well. Some results from a work from Kubesch et al. on a John Deere 8,1L engine are shown in Table VII–5 [13]. By scrutinising the results in Table VII–5, it is obvious that the emission level of the lean-burn engine can be improved as well as in the former case. Since this engine investigated by Kubesh et al. was a prototype engine, it is not clear if this level could be achieved on a production engine.

Table VII-5: Emissions from two different CNG combustion systems

Emission regul. / Engine results	CO	THC	NMHC	NO_X	NMHC+NO_X	PM
	US Emission standards (g/bhp–hr)					
US –98 urban bus	15.5	1.3	-	4.0	-	0.05
US 2004 opt. 1	15.5	1.3	-	-	2.4	0.05
US 2004 opt. 2	15.5	-	0.5	-	2.5	0.05
	SwRI emission results (g/bhp-hr)					
SwRI – Deere 8.1L	1.768	4.931	0.420	1.009	1.429	0.025[a]
	SwRI emission results (g/kWh)					
SwRI – Deere 8.1L	2.370	6.610	0.563	1.353	1.798	0.034[a]

Notes:

[a] Particulate data estimated by SwRI due to outlier data on the cold start portion of FTP-75.

3.2 *Projected emission level of HD CNG vehicles for India*

The two options chosen for India are a simple conversion of a few years old naturally aspirated engine and an advanced dedicated engine.

To maintain the power on the converted engine, it must be operated on stoichiometric or near stoichiometric air-fuel ratio. Therefore, the NO_X emissions will be high. No catalyst is used on this engine and therefore the unburned methane emissions will be high. The advanced dedicated engine is a turbocharged lean-burn engine. This engine should have almost the same performance as a new Euro I diesel engine that also has a turbocharger.

The two options described above are compared in Figure VII–1 below. CO emissions are somewhat lower for the converted engine while the dedicated engine has considerably lower CO emissions due to an efficient catalyst[3]. Total HC emissions are much higher for the converted engine whereas the dedicated engine is better again due to the catalyst. Both CNG versions have lower NMHC emissions since the methane is the major part of the HC emissions and due to the catalyst for the dedicated engine. SO_X and particulate emissions are virtually eliminated in comparison to the base level diesel engine. It should also be noted that the particulate emissions should remain on a very low level even if the control system is not working properly. This is an inherent advantage of CNG operation.

[3] The base level diesel engine has no catalyst.

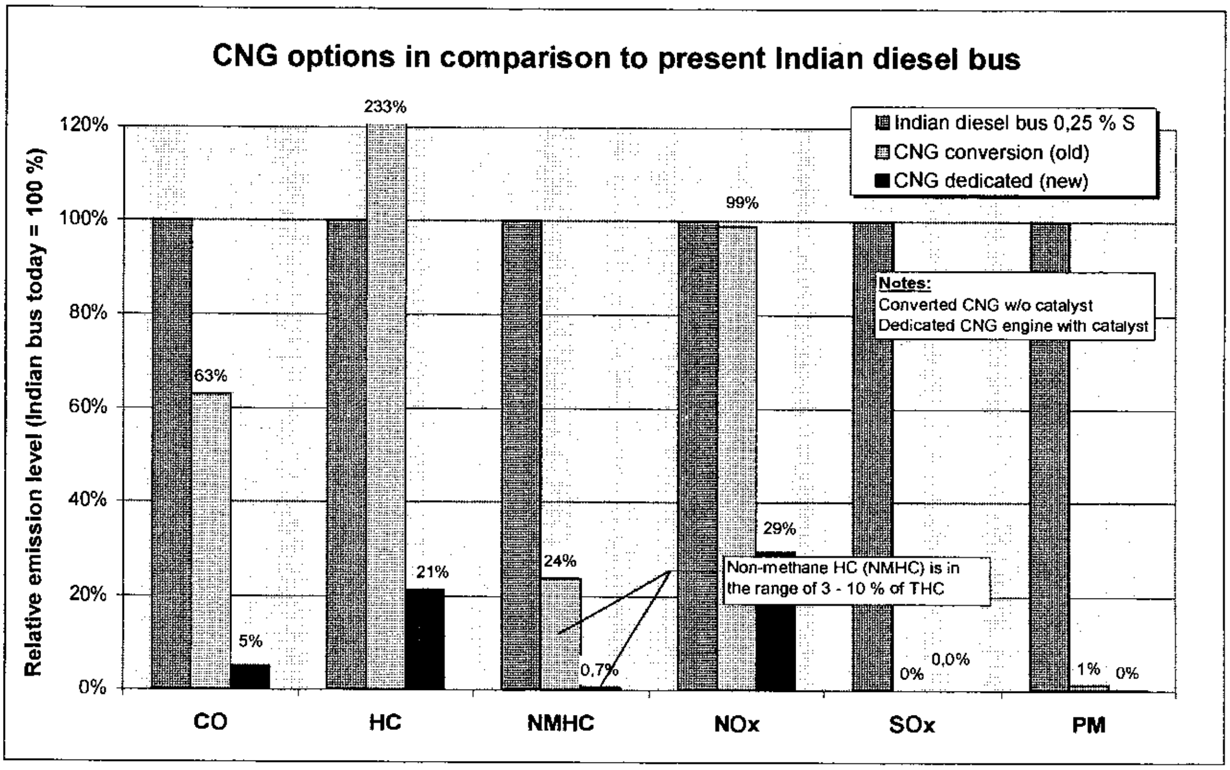

Figure VII-1: *Impact of fuel switch to CNG for Indian buses; today and in the future*

3.3 Emission potential of propane

Propane has many properties in common with CNG regarding the emission potential. The octane rating of LPG is slightly lower than CNG but this affects the fuel consumption only marginally. The lean limit of combustion is also slightly less than CNG and therefore the NO_X emissions can be somewhat higher (some 20 %) than for CNG. Propane is oxidised much easier than methane in a catalyst and therefore the total hydrocarbons are significantly lower for a propane engine. NMHC emissions are higher but the particulate emissions are only marginally higher. Some of the unregulated emissions, such as ethene and propene, are higher from a propane engine. One could also expect that the PAC emissions would be higher. In general, the difference for the unregulated emissions is not great and therefore it could be expected that the results in the biological tests would be on a slightly higher level than for CNG. There are no Swedish data available from these tests on propane for the moment and such results in the international literature are scarce.

In general, it could be concluded that propane would have about the same or only slightly worse emission characteristics as CNG. Since there are not so many reliable data available, calculations for propane has not been included in the results here.

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