Environment

Background Document to the

Workshop on EU Policies to Improve the Contribution of Urban Busses and other Captive Fleets to Air Quality

Brussels, 2005-01-14

LAT

Background Document to the

Workshop on EU Policies to Improve the Contribution of Urban Busses and other Captive Fleets to Air Quality

Brussels, 2005-01-14

Authors

Dr. Leonidas Ntziachristos
Prof. Zissis Samaras

This document was compiled by

LAT – Laboratory of Applied Thermodynamics
Aristotle University Thessaloniki
GR 54124 Thessaloniki GREECE
☎: +30 23 10 99 60 14
🖷: +30 23 10 99 60 19
🌍: http://lat.eng.auth.gr/
✉: zisis@auth.gr

On behalf of the

European Commission
Directorate – General Environment
Directorate C – Air and Chemicals
Rue de Genève, 1-3
B-1049 Brussels
BELGIUM

Contract No. 070501/2004/391521/MAR/C1

More Information on the Workshop may be found at
http://europa.eu.int/comm/environment/air/clean_bus/index.htm

Contents

1 INTRODUCTION

Urban air pollution induced by road transport is a multi dimensional technical and social problem which has been in the agenda already since several decades. The request of improved air quality on one hand, and the increasing need for mobility of people and goods within an urban area on the other hand, are the two directions that need to be served in parallel. The multidimensional character of the problem arises from the fact that road transport air pollution originates from factors lying on several levels of human activity and natural processes which include, among others, the city infrastructure, the vehicle technology, the power mix used (fossil fuels, electricity, etc.) but also particular needs of mobility, the density of the population, the climatic conditions and the geography of each specific urban area. Such a complex problem may have different solutions, each addressing a different part of its origins and obtained at a variable cost.

Even when focussing only on the source of pollutants in the atmosphere, i.e. vehicle emissions, there are still different approaches which can be adopted to reduce their contribution: Development of more stringent emission standards for future vehicles, fuel quality refinement regulations, improved traffic management, inspection and maintenance regulations, promotion of alternative powertrains, etc. The range of options increases for centrally managed (captive) fleets, by name urban busses, taxis, refuse trucks and other utility vehicles. These fleets, despite their small size compared to private cars, operate solely on urban areas with a large annual mileage and have usually a longer mean useful life than passenger cars. They also play a central part of urban transportation planning and are directly controlled by public and municipal authorities. Therefore, measures that do not appear feasible or cost-effective for private cars because of the high volumes and cost associated to monitor and recall each individual vehicle may well suit such controlled fleets. These measures include traffic management issues such as bus lanes or environmentally controlled zones and technology intervention measures such as the use of dedicated fuels or retrofitting of emission control devices. The *Polis* network (www.polis-online.org) provides a good overview of the different thematic areas associated with urban transport policy development.

This last group of options – intervention measures to control captive fleets emissions – is the target of the Workshop organised by DG Environment on January 14, 2005. The workshop aims at exploring the benefit, the cost-effectiveness and ultimately the target of different policies to further control emissions of buses and other captive fleets at a European level. Particular emphasis is given to urban busses which is the largest contributor of urban fleets. This document has been prepared in advance of the Workshop to collect background information and to establish the different directions and dimensions associated with the emission control of urban fleets. The four priority areas considered are:

- The effect of improved maintenance
- The use of advanced diesel and alternative fuels
- Retrofitting of emission control devices
- Accelerated replacement

The environmental, economic and social issues associated with each of these policy options depend on several nation-wide or even city-wide factors. For example, it would not be wise to introduce compressed natural gas busses in a city without natural gas infrastructure because this would correspond to an unrealistic solution. Additionally, cities with extended use of alternatively powered vehicles (e.g. trams, trolleybusses) may well benefit from their infrastructure which might not be applicable in other areas. These particularities, one of which more or less appears in every European city for different geopolitical reasons, are issues that go beyond the focus of this background document and need to be addressed on a municipal authority level within each individual city. Instead, this document aims at a horizontal presentation of the different available options and provides a reference of the benefits and the costs associated with each of them, based on available scientific, technical and demonstration studies. Additionally, rather than including an exhaustive list of possible scenarios and reaching firm conclusions, it presents different typical options to quantify the effect and cost of different measures. The final recommendations and conclusions for each different approach will be discussed in the workshop and will be published after that. For the same reason, a list of questions and issues for discussion is included in each main chapter.

2 CAPTIVE FLEETS TODAY

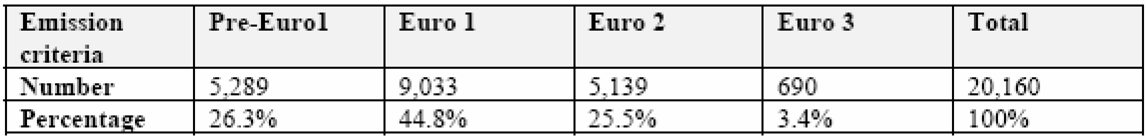
2.1 Contribution of Captive Fleets to Urban Road Transport Emissions

The first issue to be considered for an effective policy development is the estimation of total emissions caused by captive fleets in an urban road network. Although there are several sources – both national and international – on which one may base the calculations, this document presents information drawn from the TREMOVE model (V2.2 – available at www.tremove.org) which is also being used in the CAFÉ activities. Emphasis is given on urban bus fleets, since they correspond to a relatively large share of total urban emissions.

However, the contribution of taxis may be important and should not be neglected, especially in the central areas of a city. The contribution of taxis cannot be deduced from TREMOVE and some examples of national data are presented instead. Table 1 shows the population of taxis operating in central London and their classification to different technologies. In total, 23% of vehicles entering the city centre are licensed taxis and they make up around 40% of traffic in the central hub, due to the congestion charging initiative applied to the city centre. Since the useful life of a taxi can be as long as 15 years, the mean fleet age is rather large and the technology matrix is shifted towards older emission standards. This means that the emission performance of the average taxi is worse than the corresponding average car. The Environment Report by the Mayor of London (2004), estimates that 1/4 of total transport PM_{10} and 12% of NO_x emissions in central London are due to taxis alone.

The contribution of taxis in Athens pollution is also significant, according to a study of the Ministry of Environment of Greece (2002), which reflects the fleet picture in the period 1994-2001. Figure 1 shows the age distribution of taxis in the Athens city area where it is shown that some 20% of the ~15000 taxis in total are over 15 years old. Most of these vehicles (84%) are diesel, 12.5% gasoline/LPG bi-fuel and 3.5% are LPG. Given the age distribution of Figure 1, a large fraction of taxis is still at a Euro 1 level or older. Additionally, the mean annual distance covered by each taxi is estimated at ~89000 km (compared to ~14000 km for each of about 2 mio passenger cars registered in Athens). These data show that the relatively old taxi fleet, the long distances travelled within urban areas and the degraded emission performance are issues that need to be addressed for an effective policy.

Table 1: Population and technology contribution of taxis in central London by June 2002. (Source: Corporation of London Air Quality Action Plan, May 2003).



Emission criteria	Pre-Euro1	Euro 1	Euro 2	Euro 3	Total
Number	5,289	9,033	5,139	690	20,160
Percentage	26.3%	44.8%	25.5%	3.4%	100%

Looking at urban busses, Figure 2 shows the urban bus fleet in operation at EU15 level, classified according to their technology and fuel use (diesel and CNG). Based on more detailed national information from different sources, the CNG and alternative fuels contribution is actually larger at the end of 2004 than what Figure 2 shows. CNG bus fleets should be rather estimated at a couple of thousand units and operate in several European countries (France alone has ~700 and Athens alone ~400 CNG busses). Austria, Denmark and the Netherlands also operate large LPG urban bus fleets (Table 2). Other countries operate ethanol, biogas or retrofitted busses (Sweden, Germany, and others) which are again not present at all in Figure 2. For example, Figure 3 shows the classification of Swedish urban busses to different technologies at the end of 2001. This corresponds to one of the most technologically advanced fleets in Europe and omission of this detailed information may lead to problems when studying, for example, air quality issues in individual cities. The same picture also shows that a large proportion is still conventional busses though. It is therefore assumed that Figure 4 should rather well reflect the total bus activity and is at least consistent with activity estimates for other vehicle categories. Therefore, the relative contribution of busses to total urban emissions from road transport at EU15 level should not be significantly overstated in TREMOVE, despite the non detailed technology classification. Based on these considerations, Figure 4 shows that urban busses correspond to no more than 3% of total urban road transport activity in the EU15 member states, with an average found at ~1.5%. This small contribution is due to the relatively small fleets of busses compared to passenger cars and despite their large annual mileage.

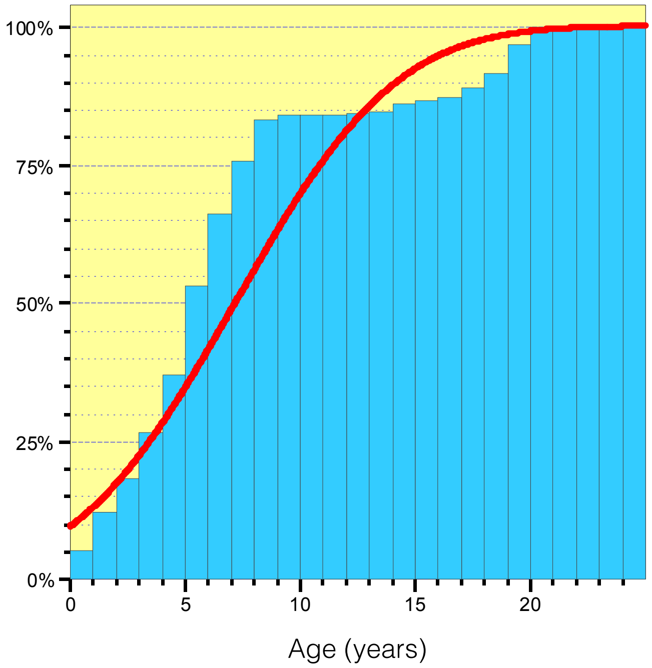


Figure 1: Cumulative frequency distribution of taxis age in the Athens basin.
(Source: Ministry of Environment of Greece, 2002).

Table 2: Population of LPG urban busses operating in European cities at the end 2002.
(Source: web-site of the Association Européenne des Gaz de Pétrole Liquéfiés).

Country	No of LPG busses	Country	No of LPG busses
AUSTRIA (Vienna)	550	FINLAND	7
CZECH REPUBLIC	80	ITALY	25
DENMARK (Copenhagen...)	270	THE NETHERLANDS (Utrecht...)	150
SPAIN (Valladolid. . .)	98	POLAND	85
FRANCE (Paris....)	130		

Figure 5 shows the estimation of total emissions for the four major regulated pollutants produced by urban busses. The contribution of each bus technology per pollutant is also shown in the lower panel. There is obviously an uncertainty in the estimation of total emissions originating from the lack of detail in the technology classification discussed previously. However, the data still indicate that conventional busses seem to be responsible for about 70% of total pollution in all major pollutants. Finally, Figure 6 presents the fraction of total road transport emissions in urban areas produced by busses. The estimations show that urban busses are negligible polluters of CO and HC (below 1% of each pollutant) and significant contributors to NO_x (10.6%) and PM (8.5%). This is more or less similar to the figures quoted by UITP (2004), which estimate urban bus contribution at 9% for NO_x and 7.7% for PM. The difference of the two estimations is rather small and may be solely attributed to the different assumptions and time frame of the calculations. The Mayor of London (2004) mentions that 21% of total NO_x in London is due to urban busses, hence these mean values may deviate significantly in different cities/regions, depending on the fleet and city characteristics.

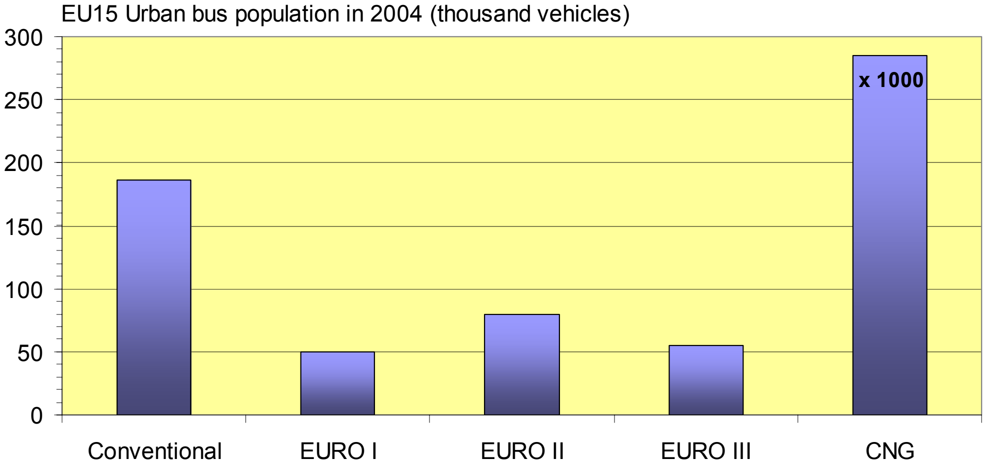


Figure 2: Urban bus population in EU15. CNG busses are multiplied by 1000. Uncertainties are discussed in the text. (Source: TREMOVE 2004).

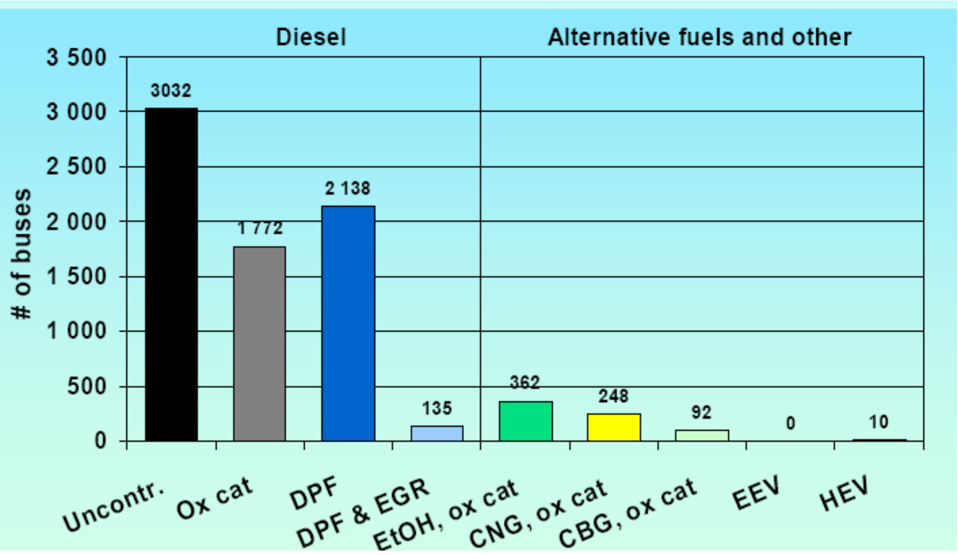


Figure 3: Classification of Swedish urban bus fleet to different technologies. Data correspond to 2001. Acronyms: EtOH (ethanol), CBG (compressed biogas), EEV (electric vehicles), HEV (hybrid electric vehicles). For other acronyms see text. (Source: Ahlvik 2003).

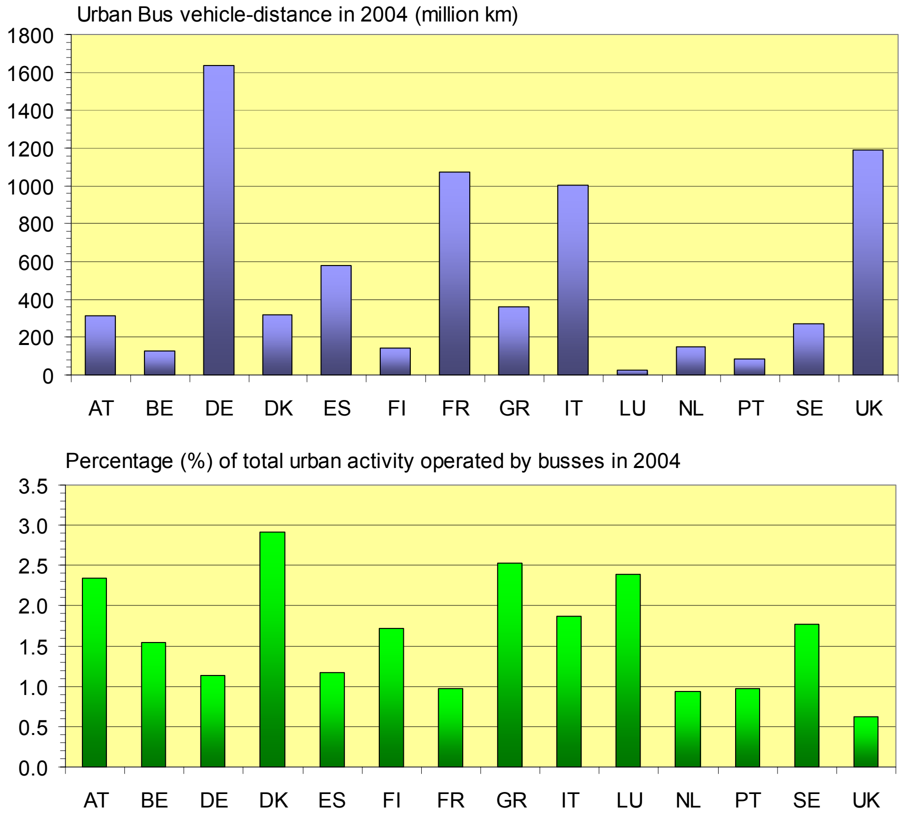


Figure 4: Total activity (veh-km) of busses in absolute scale (upper) and as a percentage of total urban road transport activity (lower).(Source: TREMOVE 2004).

This analysis, despite its uncertainties, shows that urban busses have a measurable contribution to total NO_x and PM emissions in urban areas. Assuming that the technology distribution of Figure 5 is more or less valid at a European level, some 70-75% of these emissions come from older busses. These results fully justify the motivation to accelerate technology evolution and improve the emission control of urban bus fleets.

Further to this top-down estimation of bus emissions, a more detailed characterisation needs to take into account the following points:

- The first issue is related with the existing national or municipal initiatives which have been taken to reduce emissions from captive fleets in urban areas. Such incentives have already led to the introduction of CNG, biodiesel and ethanol busses, retrofitting of exhaust aftertreatment devices, demonstrations of electric and fuel-cell busses, low emission zones, etc. which go beyond the minimum requirements for compliance with emission standards. The extent and the impact of these activities at a European level cannot be precisely estimated currently because of the speed with which different projects appear, but also because the actual environmental benefit has not been fully assessed yet. Therefore, a more precise monitoring, management and assessment of individual initiatives may be required to better design an efficient policy in this area.
- Secondly, urban busses operate on specific routes, hence their share may be particularly important as the spatial resolution of the analysis decreases. For example, Simões et al. (2002) calculates that for two typical bus routes in Lisbon, the bus share in PM and NO_x reached 60% and 86% respectively of total emissions in these streets. This means that the contribution of urban busses to hotspots may be more critical than what their share to total urban emissions indicates. The other dimension is that busses operate to transfer passengers, hence their emissions need to be assessed on a per-passenger basis. Figure 7 is adapted from the same study and compares a conventional and a Euro II

diesel bus with the emissions of the average passenger car in Lisbon (hot engine) under two actual bus routes. These indices show that bus transport results to at least 50% lower fuel consumption than passenger cars. NO$_x$ emissions between the Euro II bus and the car are at the same level while bus PM emissions are much higher, because passenger cars in Lisbon are gasoline in their large majority. Such a comparison is valuable for the estimation of effectiveness of measures aiming at the promotion of public transport.

- Finally, the assessment of the actual environmental impact of urban busses requires precise emission factors for their real-world operation. Type approval data today correspond to emissions of heavy duty engines tested under type approval cycles, and may not necessarily be appropriate to estimate real-world emissions. Recent experience (Hausberger et al., 2003) showed that new engines with electronic controls may lead to significant deviations in their emission performance between type-approval tests and their actual operation on a real-world vehicle. This may be expected to hold even more true as emission control techniques become more sophisticated and complicated, as hybrid busses appear and as busses are retrofitted with emission control devices which are sensitive to engine mapping, fuel characteristics or even to environmental conditions. Therefore, for applications where detailed emission inventories are required, such as hotspots, type approval data are not sufficiently detailed or representative. Rather, emission monitoring campaigns will be required to follow technology improvement. These may be conducted either with on-board emission measurement devices, remote sensing techniques or chassis dynamometer tests over actual driving patterns.

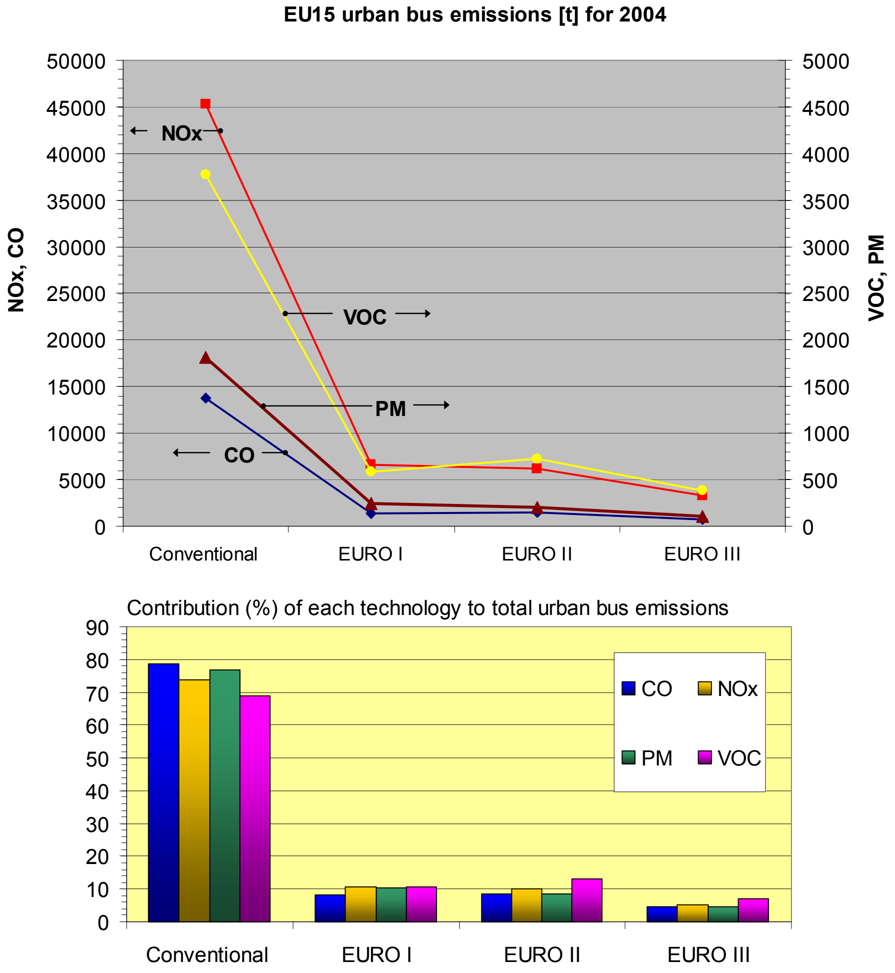


Figure 5: Total emissions per urban bus technology (top) and contribution of each technology to total emissions (bottom). (Source: TREMOVE 2004).

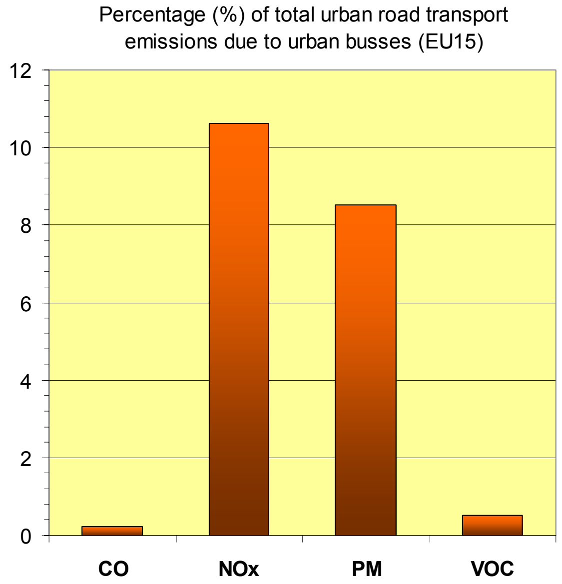


Figure 6: Share of urban busses to total road transport urban emissions. (Source: TREMOVE 2004).

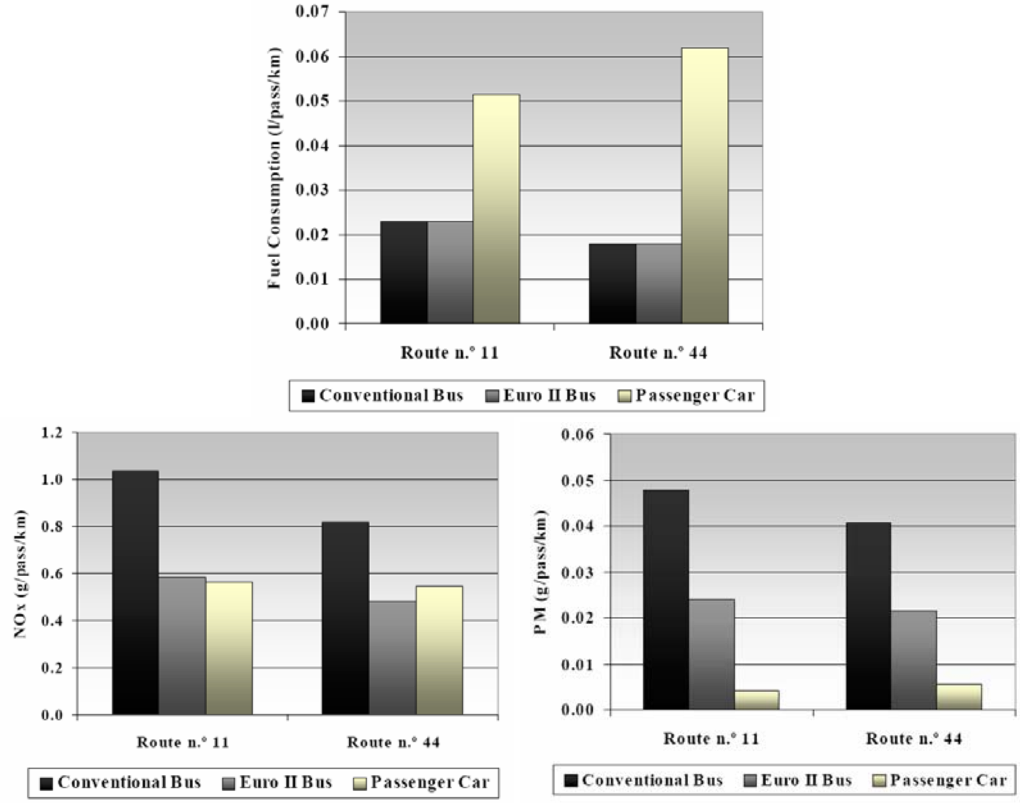


Figure 7: Comparison of fuel consumption (top), NO_x (bottom left) and PM (bottom right) emissions of two busses and the average Lisbon passenger car on two bus routes, expressed on a passenger-km basis. (Source: Simões et al. 2002).

2.2 Background on the European Policies / Legislation

The European Commission has been actively contributing to the efforts towards a cleaner urban environment, by offering technical support to the development of the relevant legislation, by funding best practice and demonstration activities throughout Europe and by launching research projects to promote environmental understanding. In order to examine what is the necessity for new legislative developments, this section provides the framework of the existing relevant legislation.

The Air Quality Framework Directive (96/62/EC) and its Daughter directives (1999/30/EC, 2000/69/EC, 2002/3/EC and the proposal COM(2003)423) set the targets for the ambient concentration of a range of pollutants, including pollutants beyond those measured during vehicle type-approval (benzene, heavy metals, PAHs). In parallel, Directive 2001/81/EC sets nation-wide emission ceilings for the major pollutants responsible for acidification, eutrophication and ground-level ozone pollution. Based on these requirements, Directive 70/220/EEC for light duty vehicles and 88/77EEC for heavy duty vehicles and their amendments set the type approval procedure, the emission standards and the supplementary regulations (OBD, in-use compliance, etc.) for on-road vehicles and their engines. Starting from January 2005 and October 2005 respectively, only Euro IV (98/69/EC) light duty vehicles and heavy duty engines (1999/96/EC) will be allowed for new registration in Europe. Especially for heavy duty engines, a Euro V step is also foreseen in 2008.

Regulations related to the roadworthiness of road vehicles are of particular interest to captive fleets. Taxis and captive fleets of light commercial vehicles need to pass an annual roadworthiness test, starting one year after the first vehicle registration (96/96/EC). With regard to their emissions, gasoline powered vehicles need to pass a low and a high idle test, and diesel vehicles a free acceleration exhaust opacity test. The emission limit values distinguish between a conventional and a three-way catalyst vehicle but there is no distinction for diesel engine technologies. Similar requirements are also prescribed for heavy commercial vehicles (2000/30/EC) with an annual exhaust emission test looking at diesel opacity during a free acceleration test.

Fuel quality is also in the target of focused legislation. Directive 98/70/EC established maximum concentration of sulphur for gasoline and diesel fuels to 50 ppm starting from January 2005. It also set minimum and maximum ranges for other fuel properties. This was complemented by 2003/17/EC which addressed the necessity to allow for an adequate geographic coverage for diesel fuel having a sulphur fuel below 10 ppm, in order to enable the marketing of advanced emission control diesel vehicles which require near-zero sulphur fuel. In the area of widely available alternative fuels (LPG, NG), there is already a directive on the type approval of such engines (2001/27/EC) for heavy duty vehicles. Finally, Directive 2003/30/EC set indicative targets for the promotion of the use of biofuels in transport. The reference values are 2%, 5.75% of total energy sold with gasoline or diesel replaced by biofuels by the end of 2005 and 2010 respectively. This directive makes a particular note on captive fleets and in particular on the potential to fully substitute conventional fuels with biofuels in this sector. Furthermore, directive 2003/96/EC allowed member states to apply a different tax level to mineral fuels and biofuels, in order that the higher cost of biofuel production is not directly passed to the consumer.

Policies that may be used to promote the procurement of environmentally friendly fleets have been recently adopted with the "public procurement" related directives (2004/17/EC, 2004/18/EC). These allow for "green public procurement" on the transport sector which means that contracting authorities may take into account environmental elements when procuring goods. This follows the jurisprudence of the Court of Justice on the Helsinki bus procurement case (1997), where the authorities awarded their tender to the bid which offered the best environmental performance and not the lowest price. This was not foreseen by the earlier relevant directives, but is now an element of the amended ones. There are currently several projects established to monitor and evaluate green procurement practices in Europe (DG Environment, 2004).

With regard to the different policy options to be considered in this workshop, European legislation so far is rather up-to-date with regard to emission standards and fuel regulations and taxation, with the exception of emulsion fuels. The roadworthiness emission tests are relatively old and do not address emissions from current technology vehicles with advanced aftertreatment systems.

Additionally, there is currently no legislation providing technical requirements / targets for retrofitting of emission control devices. Also, there is no policy framework for the establishment or definition of environmental zones in cities. Finally, the public procurement directives could be complemented by a more technical document which would better specify a list of criteria to enable the quantification of a "green" procurement for captive fleets.

2.3 Developments of Environmental Legislation / Future Air Quality Targets

The effectiveness of the air-quality daughter directives and the national emission ceilings directive is today examined in the framework of the Clean Air for Europe (CAFÉ) activity, which is the main technical tool to support the development of air pollution regulations in Europe. CAFÉ also tries to identify cost-effective sectoral measures (not only related to transport) to reach the European air quality targets. As a final outcome, a thematic strategy on air pollution up to 2020 is expected for adoption, with the objective to "achieve levels of air quality that do not give rise to risks to human health and the environment". Although CAFÉ provides a very potent tool to cover the whole of Europe, it is limited in its spatial resolution because the air quality targets are studied over a 50×50 km^2 grid (the so-called EMEP grid). This does not provide enough resolution to study the origin of the hot-spots, e.g. as they are revealed from satellite pictures (Figure 8), especially in urban areas.

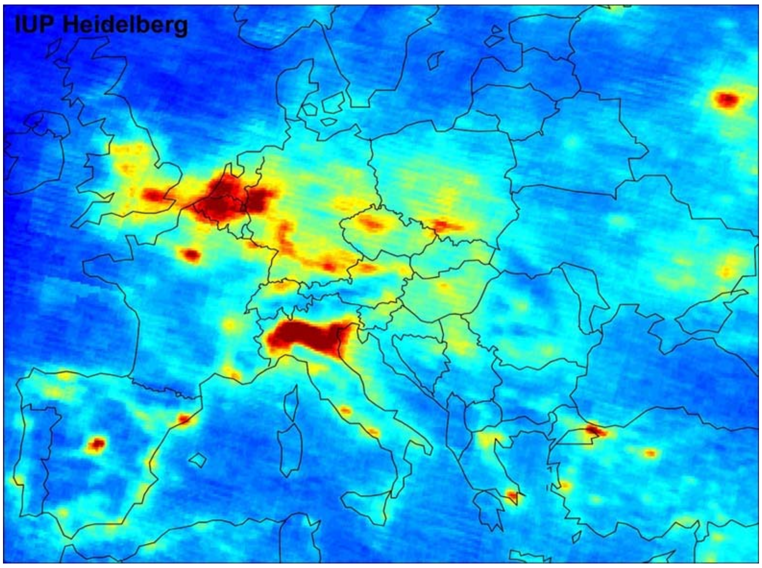


Figure 8: European hotspots of NO_2 concentration as revealed in October 2004 by European Space Agency's Envisat satellite (source: ESA web-site, http://www.esa.int/esaCP/).

In order to better understand air pollution related to hot spots, the CITY-DELTA initiative (rea.ei.jrc.it/netshare/thunis/citydelta) was established looking at 8 cities with a finer spatial resolution (e.g. 5×5 km^2), utilizing a large number of modelling tools. This activity provided some interesting conclusions for the objectives of this workshop. These can be extracted by Cuvelier (2004) and can be summarized as follows:

- With regard to O_3 concentrations:
    - There is an agreement between regional scale and local scale models when aggregated on a regional level, that there is relatively little scope for further improvements of emission controls, beyond the current legislation.
    - There are important sub-grid effects which can be identified only as the modelling resolution becomes finer. This is important, because air quality effects from captive fleet control measures may be rather confined on a street network than the whole urban area. Hence, any potential benefit would increase as the resolution focuses on smaller scales.

  - The consistency between model predictions and measurements depends on the city (e.g. Milan showed the larger variations). By extrapolation, this would mean that the effectiveness of any control measure depends on the terrain and meteorology particularities of each city, which needs to be taken into account when considering its cost-effectiveness.
  - Air quality (model) results are highly sensitive to the quality of the emission inventories. Therefore high quality inventories are needed, which can only be based on realistic emission factors and actual activity data.
- With regard to PM concentrations:
  - There is still limited understanding on PM mass because air quality models consistently underestimate ambient concentrations. The uncertainty has significant implications to the cost-effectiveness estimation of different measures.
  - A large part of urban PM comes from the regional background. However, there is a linear correlation between emissions and concentrations beyond this background level.

As the focus is more and more on pollution in hot-spots which may be of size, geometry and orientation not well covered by a conventional modelling grid, the European Environment Agency and its Topic Centre on Air and Climate Change (ETC/ACC) initiated the Street Emission Ceilings (SEC) exercise to identify the origin of pollution hot-spots in different European cities. The main focus of the activity was to develop a typology of cities and streets around Europe, as a function of emissions, meteorology and geometry, to help identifying critical hotspots and then study the origin of air quality standards exceedences. The characterisation of road transport contribution was therefore important. To that end, one of the first things examined was how much ambient concentrations depend on road emissions and this was studied by looking at pollutant ratios instead of absolute values (Figure 9). This approach demonstrated the clear link, even on an hourly basis, between emissions and concentrations. However, actual concentration ratios depend on season and time of day more than emission ratios. This again makes clear that, e.g. in order to predict hourly non-attainment detailed emission factors are absolutely needed.

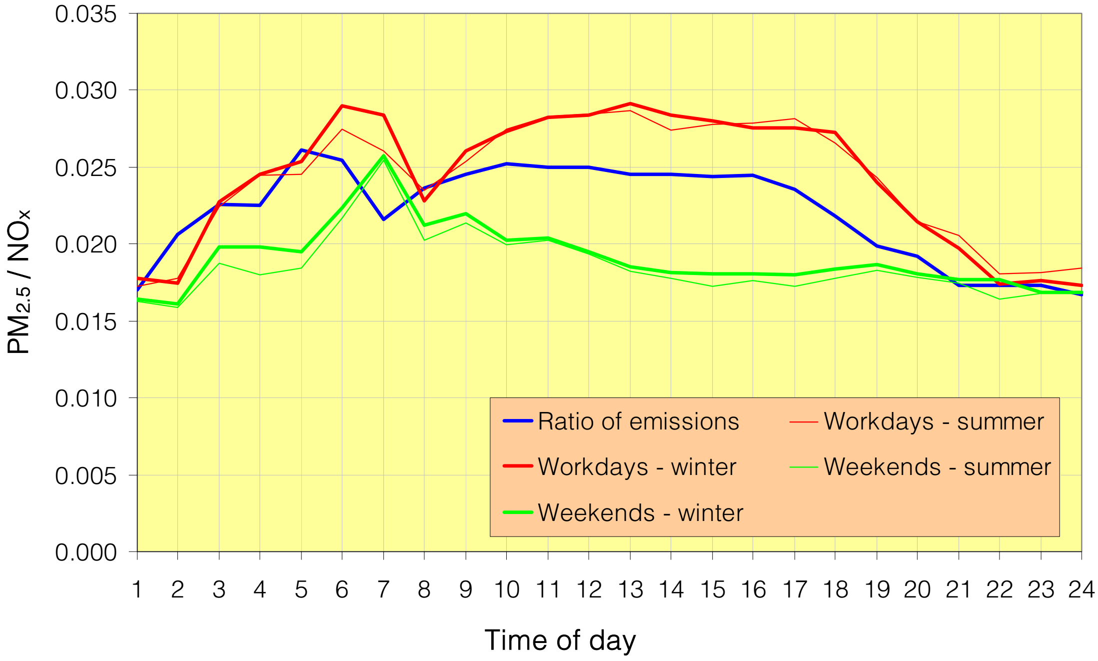


Figure 9: Typical ratio of $PM_{2.5}$/ NO_x emissions and concentration for a road section in Stockholm (Hornsgatan), as a function of the time of the day. Emissions were calculated with the COPERT III (2004) emission factors and concentrations were measured at two roadside stations.

The analysis from the regional level (CAFÉ) to the urban one (CityDelta) and finally to a small scale hotspot (SEC) shows that the quantification of the contribution of different sources depends on the resolution considered. This affects the estimations of the cost-benefit / cost-effectiveness ratios of a control measure. Focusing on captive fleets, potential benefits from any control policy may be weak or non-important on a regional level due to the small share of captive fleets activity, compared to all contributing sources. This is becoming increasingly important as we zoom in a bus route, or a road junction close to a bus station for example. The focus of air quality to hot-spots and local attainment of air-quality targets means that such small scale effects will receive much attention in the future. Control of captive fleet emissions will thus have a role to play in this direction.

2.4 Points for Discussion / Consideration

1. Is the contribution of captive fleet emissions sufficiently detailed in today's emission inventories? Do we need to improve fleet estimates, activity data and emission factors for a more accurate representation, despite their relatively small contribution to total emissions? If yes, what is the best approach?
2. Are there detailed studies for the contribution of captive fleet vehicles in local hot-spots (street canyons, bus stations, etc.)?
3. How is the impact of control measures reflected to local air quality models?
4. Is there a need to develop a central mechanism for monitoring pilot and demonstration studies in different cities in order to be used as examples in other parts of Europe?

3 IMPROVED MAINTENANCE

Improved maintenance is considered as a relatively low-cost measure to control emissions from any fleet. There are several issues related to the realisation of an enhanced maintenance scheme, including the basis for the selection of a vehicle to be maintained, the effectiveness of the diagnosis and finally, the effect of repairs on emission performance. The two sections that follow provide useful information from two different improved maintenance projects, regarding both heavy duty and light duty vehicles.

3.1 Heavy Duty Vehicles

There are some interesting findings on the effect of an I/M scheme on diesel heavy duty vehicles obtained from a US EPA study conducted in Denver, Colorado by the Department of Public Health and Environment (McCormick et al. 2003). The study recruited 26 HDVs based on their visible smoke emissions and measured their smoke opacity with a snap-acceleration (free-acceleration in Europe) test and their regulated pollutants on a chassis dynamometer. Measurements were conducted at least twice, once with the vehicles in the "as received" condition and once after maintenance.

Results from this and earlier studies provide some information on failure rates of busses in the US. Pre-1991 busses had to pass a 55% limit in opacity and 1991 and later vehicles had to pass a 40% limit in most states. Before I/M tests became widespread for older vehicles, failure rates ranged between 25-34%, despite the higher emission levels permitted. Currently, failure rates are in the 4-8% range. This shows both that technology obviously improved in the meantime but also that vehicle owners were taking care to maintain their vehicles before passing the test. This is an indication that such simplified tests may be an effective means of controlling smoke emissions from heavy duty engines. Smoke though is not the target pollutant of the policies considered in this workshop.

Figure 10 shows the effect of maintenance on these smoking HDVs. The repairs conducted during maintenance decreased emissions of all pollutants but increased NO_x levels. The increase in NO_x

originates from fuel efficiency improvement after maintenance and is common to vehicles not equipped with aftertreatment devices. It would be more difficult to predict the effect of maintenance on NO_x emissions for vehicles with emission aftertreatment, but one should rather expect a reduction of all pollutants in general.

The repairs conducted in order to correct the smoke problem were mainly related to the fuelling system. Quoting this study, "Virtually all repairs were to the injectors, fuel pumps, fuel pump calibration, and injection timing". In particular, at least one injector replacement had to be conducted in 11 out of 20 vehicles repaired and some pump maintenance work had to be conducted in 10 out of the 20 vehicles. This may have been caused by fuel sulphur activity or low diesel lubrication characteristics. Hence the rate of failures in Europe could be different due to the different fuel properties. In any case, the need for replacement of crucial engine components increased the mean cost of maintenance to about $1100 per vehicle.

One additional issue that this study raises is whether smoke opacity or Bosch smoke number is associated with vehicle PM emissions. Differently put, the question is whether the reduction in smoke is associated with an equivalent reduction in PM, which then makes sense from an environmental point of view. The correlation between opacity measurement and PM is generally weak in most studies (for a summary see Vouitsis et al. 2003) which is mainly attributed to the volatile PM fraction which does not equally contribute to exhaust opacity. Additionally, PM is measured over a complete transient test while exhaust opacity is measured only during a free acceleration. These two measurements are obviously not equivalent in terms of engine operation. The results of the study suggest that while smoke may not show the best correlation with PM, the repair of visibly smoking vehicles reduced PM levels by 50-60%. Additionally, the repair of malfunctioned vehicles identified with a smoke test increased NO_x emissions by ~20%, obviously due to the improvement of combustion efficiency. This evidence should not be taken the other way around though, i.e. that non smoking vehicles are low PM emitters. More detailed tests would be required to identify PM high emitters.

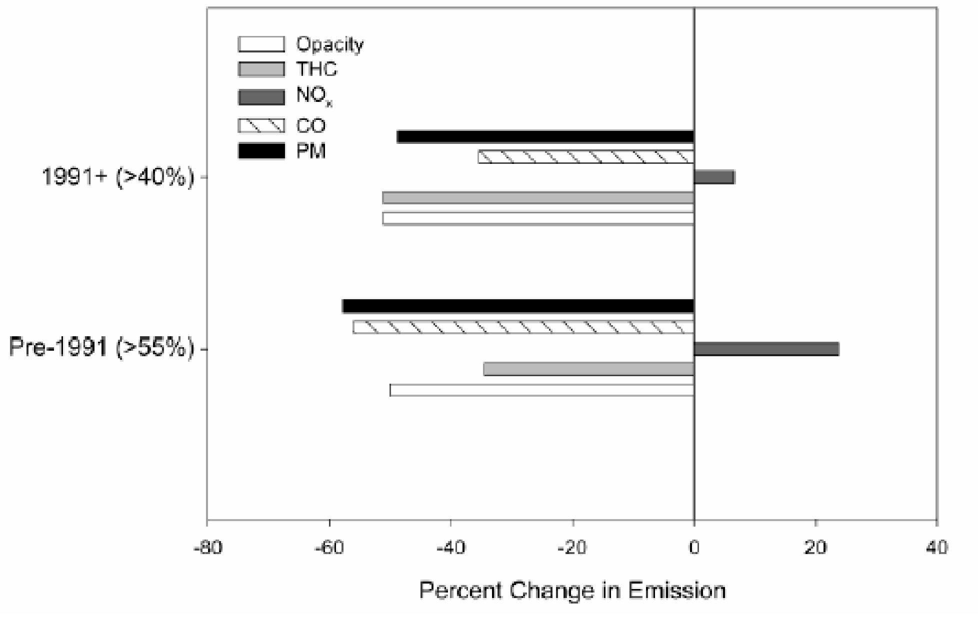


Figure 10: Effect of maintenance on the emissions of 26 smoking HDVs classified in two vehicle age groups. All regulated pollutants and smoke opacity decreased after maintenance but NO_x emissions increased by 10-25%. (Source: McCormick et al. 2003).

3.2 Light Duty Vehicles

An older European Commission (1998) study aimed at identifying alternative tests for an enhanced Inspection and Maintenance (I/M) procedure of light duty vehicles, mainly focusing on gasoline catalyst ones. However, a small sample of diesel vehicles (conventional and Euro I) was also tested and some interesting conclusions may be derived for diesels, which are more relevant for captive fleets. For older technology (up to Euro II) vehicles, which may still be a significant fraction of taxi fleets, it was found that NO_x emissions were rather robust and high polluters were identified only with regard to PM. In other words, this means that improved maintenance, similar to the case of HDVs, is not expected to bring any significant improvements to NO_x mean fleet levels. In order to complete the picture, NO_x benefits from non catalyst gasoline vehicles also showed slight NO_x reductions following maintenance, not exceeding 8%.

The effect of maintenance to PM levels was estimated at an 25% improvement for pre Euro II vehicles and 31-33% for Euro II+ ones. These results were based on a small sample though and are the product of a project which had different main objectives. However, they may still constitute a good estimation of the potential benefits of enhanced I/M procedure. The study went on with the estimation of the cost associated with maintenance. Repair cost figures were estimated in the range of 90-500 €, depending on the extent of the damage. This is also a comparable figure with the repair cost for HDVs, given the size of the different vehicles.

Also similarly to HDVs, a free acceleration opacity test was not fount appropriate to characterize high PM emitters. This is a potential problem only if it is decided to recruit vehicles for maintenance based on an emission test screening procedure, but is not an issue if only enforcement of a regular maintenance scheme is considered.

3.3 Points for Discussion / Consideration

1. (Question with a larger scope than captive fleets) Is the current roadworthiness legislation sufficient for the cost-effective control of diesel vehicle emissions? Is there a need to differentiate between different engine technologies? What about NO_x?
2. (Question with a larger scope than captive fleets) Is smoke measurement a suitable surrogate of PM emissions and is its relevance decreasing for new technologies?
3. Is there evidence that taxis, busses or refuse trucks are badly maintained with respect to their emission controls in order to reduce operation costs? Is there a need to respond with additional measures (i.e. random visits to taxi or bus depots with mobile labs, remote sensing measurements, etc.)?

4 REFUELLING

With the term "refuelling" one may summarize different alternatives to the use of conventional diesel fuel. The first alternative is the use of emulsified diesel, biodiesel blends or synthetic diesel which require no modifications or only minor ones to existing engines. The second option is the use of alternative fossil fuels (natural gas, liquefied petroleum gas and synthetic fuels) which necessitate either major modifications or replacements of existing diesel engines or the procurement of complete new vehicles. The third option is the use of biofuels which require major engine modifications (i.e. not biodiesel) but further to lower engine-out emissions they may also lead to low WTW GHG emissions. Such biofuels include biogas, ethanol, methanol, biomass-to-liquid synthetic fuels and others. The extent of modifications required on existing engines or the need of dedicated engines is an important criterion to select fuels for different applications and initiatives.

It is clear that refuelling comprises a long list of options. To complete the picture one has to include hydrogen related technologies and electric propulsion systems which become increasingly important today and have a clear role to play in the future. However, as the focus of this document is on current fleets and options applicable to present vehicles, the discussion is narrowed to today's viable options, i.e. options that have been demonstrated at least on pilot captive fleets in regular service. This leaves out hydrogen, fuel-cell and battery powered busses.

We also leave out trolleybusses and trams despite their obvious air-quality benefits. This is because their use is associated with significant infrastructure requirements (power lines, rails) which usually result to issues that need to be resolved by local societies, in addition to their significant cost. This is obviously something that needs to be separately considered.

The different fuel options remaining are examined in the following sections using their feedstock as a classification parameter. First, emulsified fuels are discussed which are produced only from water and conventional diesel. Then natural gas and synthetic derivatives are discussed, followed by liquefied petroleum gas. Finally, biomass products (biofuels) are considered.

4.1 Emulsified Fuels

Emulsions are liquid systems consisting of two mixed but discrete phases. Emulsified diesel is a diesel fuel blended with water droplets of a few micrometers diameter (water to fuel blend). The mix of oil and water is achieved with the use of additives which aim at stabilizing the water droplet dispersion in the oil. There are currently no exact specifications for emulsified fuels in the world. CEN launched a standardization in Europe, the kick-off workshop of which was organized on March 15, 2004 (CEN, 2004). Despite the lack of standardization, commercial emulsion fuels at an average content of ~83% oil, ~14% water and ~3% additives are today offered in different member states by four commercial companies. These may be used directly to diesel engines without modifications.

Emulsions have lately received interest because of laboratory and field studies which showed that use of emulsified fuels may reduce emissions of both PM and NO_x and may lead to substantial reduction of exhaust opacity. Based on UITP (2004), emulsions may reduce opacity by 30-80%, PM by 10-40% and NO_x by 5-30%. These findings are in-line with information presented by the emulsions manufacturers (Lubrizol, 2004). Scientific literature also confirms the positive effect of emulsions primarily to smoke and PM and then NO_x (Musculus et al. 2002; Desantes et al. 1999), although independent lab tests usually result to lower improvement figures than field tests conducted by the emulsion manufacturers. Additionally, the actual effect depends on a number of parameters, including water content, engine characteristics and operation condition, etc. From a different perspective, there are no cases known where emulsions have a negative effect on emission performance of diesel engines.

From an emissions point of view, emulsified fuel use seems potentially beneficial in two fronts: NO_x and PM. For this reason, there are some 8-10 thousand busses in Europe operating on emulsified diesel according to UITP (2004) and ADEPT (2003). At least 7 thousand of them operate in Italian cities and the rest operate in France, Germany, UK and Switzerland. The wide acceptance of emulsified fuel in Italy is due to a 36% tax reduction incentive on the fuel. The taxation of such a fuel is a sensitive issue because one has to recognise that some 15% of the mass of the fuel sold is water, hence it is important to realise that a tax rate applied per litre of fuel consumed is also applied on its water content.

The effect of emulsions on reducing emissions is because, according to Musculus et al. (2002), water addition in the fuel increases the fuel-air premixing during both the premixed burn and mixing-controlled combustion phases. This leads to lower soot formation, hence lower smoke and PM emissions. However the reduction of soot formation is engine and operation condition specific. NO_x emissions decrease because water addition in the fuel decreases the flame temperature. Hence, it acts the same way as engine EGR.

One issue concerning the use of emulsified fuels is the increase in engine noise, due to the increased ignition delay (Musculus et al. 2002; Park et al. 2003). Again, the amplitude of this increase depends on engine and driving conditions. Most importantly, water addition in the fuel decreases the energy content of the fuel delivered to the engine. This means that there is either engine power and torque loss if no engine modification is conducted, or fuel consumption increase by engine modifications to keep the same performance. Obviously, both these options have their pros and cons. Furthermore, the stability of the emulsion is a sensitive parameter. An emulsified fuel left in tanks for a few days starts to develop a separate water phase and requires remixing (which can be performed on-site though). The same may occur in the vehicle fuel tank. Depending on the duration of the vehicle parking period, water separation may lead to longer cranking times before the engine starts-up. In particularly low temperatures, one should also expect water freezing in the tank, if the vehicle is left parked for long periods. Finally, and probably most importantly, the effect of emulsified fuels in new optimized engines is not verified. In particular, engines with extensive EGR to control NO_x may not benefit from the addition of water in the fuel, or this could even cause combustion instability. Furthermore, the increase in spray length may not be beneficial for short stroke engines.

The Texas Department of Transportation initiated a project in July 2002 to evaluate the benefits of emulsified fuel use to heavy duty vehicles of different technology (Matthews et al., 2004). Using the emulsified fuel in 8 trucks and 2 engines, they found a NO_x benefit of 13% for electronically controlled engines and 21% for mechanically controlled ones. PM benefits were on average 17% and 24% for the two diesel control systems respectively. Three cases were found where the use of emulsion increased PM levels. Additionally, the use of emulsion increased fuel consumption by 17% on average for all vehicles/engines tested. These results confirm that emulsion fuels are more appropriate for older technologies and that their actual effect depends a lot on engine technology and operation condition.

4.2 Natural Gas

Natural gas vehicles (NGVs) have started to become more and more a reality in current urban fleets. France has already some 700 NG busses in operation, out of a total of ~12000 while 416 NG busses are in operation in Athens, in a fleet of ~1800 vehicles. NG as a fuel can neither be used on a diesel engine nor on a gasoline one without modifications because it has a high octane number (120-130) and a lower than 50 cetane number which makes it unsuitable for diesel combustion. Most commercial systems therefore utilize a spark plug to initiate natural gas combustion and a higher compression ratio than conventional gasoline engines to take advantage of the high octane rate and to increase efficiency. NGVs may also operate either on stoichiometric mode for low emissions or on lean-mode for higher efficiency. In addition, high pressure storage bottles are required to store Compressed NG (CNG) while liquid NG (LNG) stored at low temperature is not that common, mainly due to the higher complexity of storage on the bus. CNG powertrains are hence associated with more cost elements and higher maintenance costs than diesel engines. A CNG bus is estimated to be ~35-40 k€ more expensive to purchase than a diesel one of similar technology, with the range of cost accounting for different tank sizes, engine concept (lean-burn, stoichiometric), and different options of aftertreatment devices (oxidation or three-way catalyst).

NGVs are closer to gasoline than diesel from a combustion and emissions point of view, thus emitting significantly lower PM and NO_x emissions than uncontrolled diesel vehicles. Figure 11 shows the emission level of a conventional (MY 1998) diesel bus (Diesel OxiCat), the same bus fitted with a particle filter (CRT) and a MY 2000 (lean burn) CNG bus, tested over different urban driving situations. The CNG bus is below 50% of diesel NO_x for all driving situations and regardless of the use of DPF on the diesel bus. It is also found at 20% or below of diesel PM levels – more or less similar to the DPF case. On the other hand, CO and NMHC emissions from CNG may be several times higher than diesel, in particular when a DPF is fitted on the diesel. The use of an oxidation catalyst may significantly reduce HC emissions and CO but they still remain higher than the diesel. CNG may also expected to result to higher particle number emission than DPF diesel (Holmén et al., 2002).

The baseline diesel and the CNG technologies considered are also important for the comparison of these different fuels. Figure 12 shows a comparison of real-world emission data collected with the VITO on-board measurement system in the framework of different research projects (unfortunately no PM measurement was available). The figure compares two CNG busses, a stoichiometric and a lean-burn against the Euro 2 diesel baseline. The number of passengers carried by the bus is also a parameter for the comparison. This figure shows that a stoichiometric CNG bus with a three-way catalyst (TWC) is the cleanest alternative for regulated pollutants but also from a CO_2 point of view and with very low CH_4 emissions.

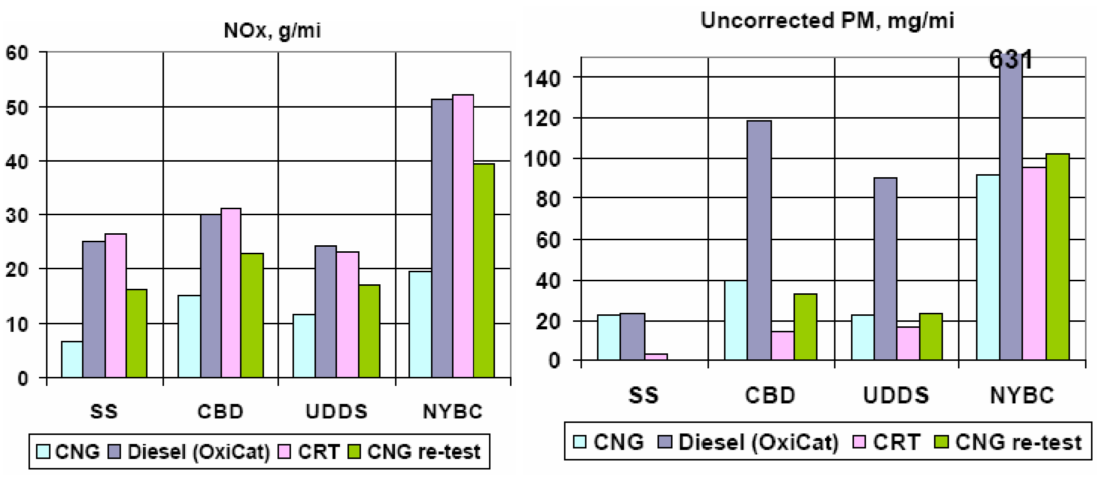


Figure 11: Typical emission behaviour of lean-burn CNG and diesel busses. Categories in x-axis are different driving conditions. (Source: Ayala et al. 2002).

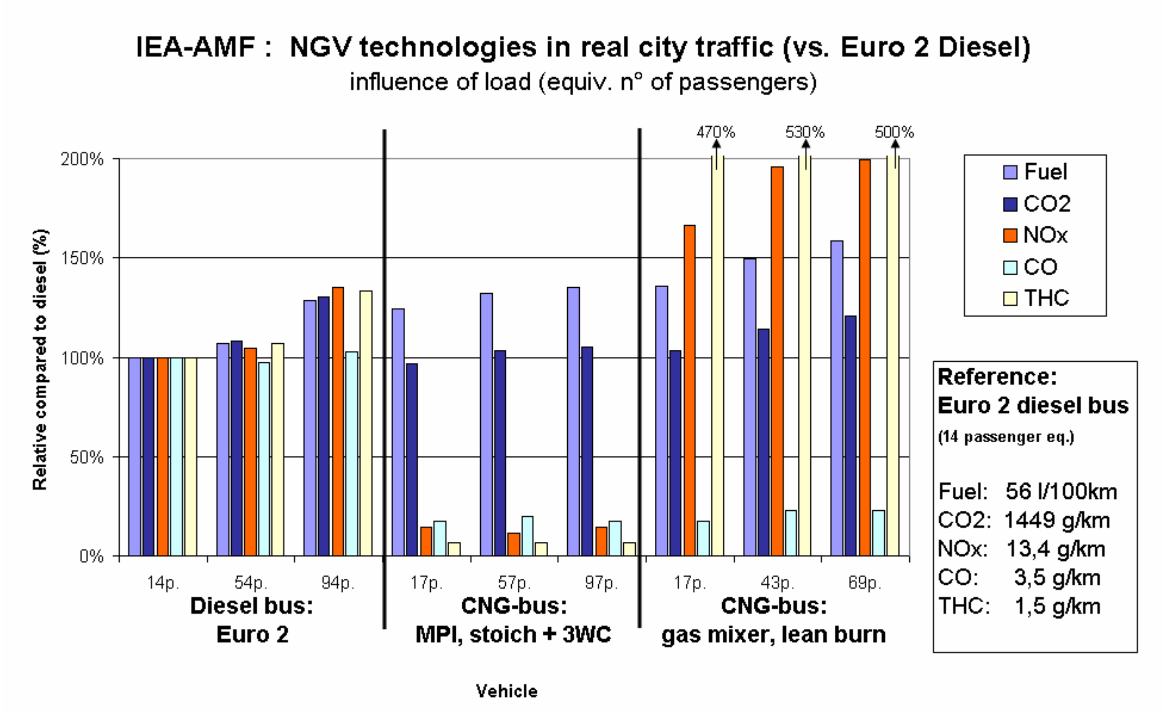


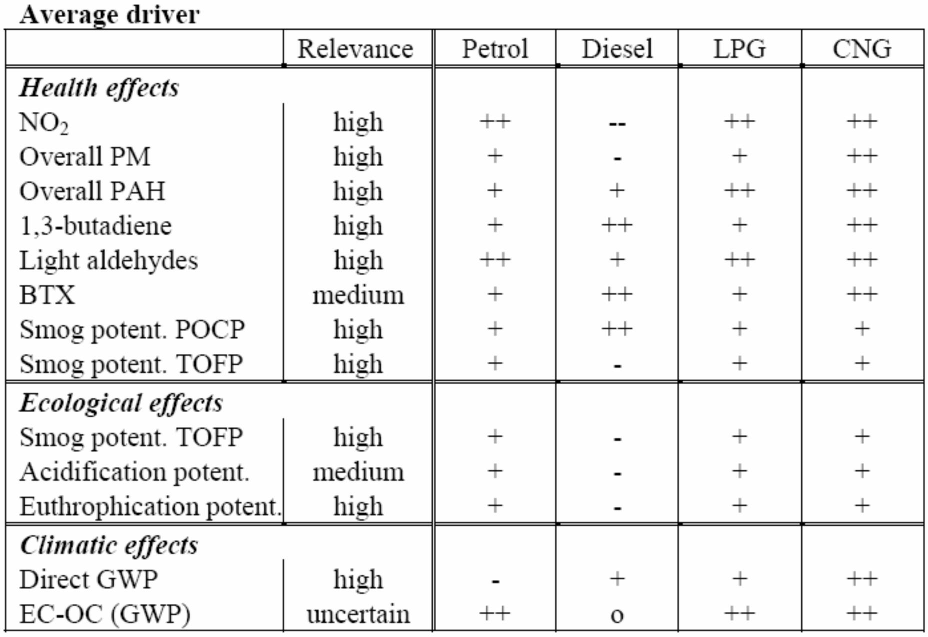
Figure 12: Comparison of CNG technologies over a Euro 2 diesel bus. (Source: Pelkmans et al., 2002).

Greenhouse gas (GHG) emissions is the second priority to examine when shifting to a new fuel technology. CNG as a fuel has 90% of the diesel energy content in mass terms and operates on a thermodynamically less efficient cycle (Otto vs. Diesel). Therefore, energy consumption of NG can be 20-40% higher than diesels (Pelkmans et al. 2002) . On the other hand, the H/C ratio is almost double in NG than in diesel, leading to lower carbon emission per mass of fuel consumed. Therefore, the net balance is difficult to quantify and depends on the application. There are two additional things to take into account though: the contribution of CH_4 emitted by CNG in total GHG balance and the upstream CO_2 emission for both gases for a well-to-wheel (WTW) analysis. Methane emissions from CNG busses may be as high as 14 g/km, even for busses equipped with oxidation catalysts (Ayala et al. 2003) which is the equivalent to ~12% of total GHG emissions from such a bus. Upstream CO_2 is more or less similar for both fuels (Plassat et al. 2004). Therefore, the global warming potential (GWP) of CNGs is today taken ~15-20% higher than diesels (Plassat et al. 2004; Cohen et al. 2003) because of the lower efficiency and methane emissions.

NG may also be used as a feedstock to produce synthetic liquid fuels such as methanol, Dimethyl Ether (DME) or Fischer-Tropsch Diesel (FTD). These fuels are easy to transport and deliver because they are liquid and can be used with either no engine modifications (FTD) or with some modifications (DME, Methanol). They result to cleaner combustion because they have a more simple chemical character than diesel and no sulphur and DME is naturally oxygenated which results to low PM and rather smokeless combustion. Their main problem is that they are produced at a higher cost than conventional diesel and this delays their wide penetration to the market. Pilot fleets may be supported to demonstrate the environmental benefits of their use.

4.3 Liquefied Petroleum Gas (LPG)

LPG is a fuel which has already an almost 60-year history as an automotive fuel and there are multiple uses around the world. As an example, 90% of taxis in Japan are LPG-powered, Italy has an LPG fleet of over 1 mio vehicles, while LPG busses are in operation in Copenhagen and Vienna. Currently, LPG is considered as an alternative fuel in the relevant European legislation and this has renewed the interest in its application.



Average driver

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

Figure 12: Environmental performance of current technology passenger cars operating on different fuels (only vehicle exhaust emissions considered and not fuel production). Plus signs denote positive effect and minus signs denote a negative one. (Source: Hendriksen et al. 2003).

Evaluating the environmental benefits of LPG is not straightforward because it depends on vehicle technology and emission standard considered. Similarly to NG, it requires a spark plug to initiate combustion, hence emissions are rather gasoline-like, this means lower PM and NO_x compared to diesel. Compared to gasoline, the simple molecular structure and the gaseous nature of LPG also lead to low engine-out CO and HC emissions. Figure 12 shows the environmental performance of four different fuels on current Euro III passenger cars where it is shown that LPG outperforms both gasoline and diesel and is second best only to CNG (Hendriksen et al. 2003). The same authors note that differences between CNG and LPG were not significant in several cases. Inclusion of the upstream fuel chain emissions does not substantially change the picture, but it further increases the CNG benefit compared to the rest of the fuels. With regard to the greenhouse gas WTW emissions, LPG and diesel appear 16% lower than petrol in this study.

A summary of evaluations from several studies (UITP 2004; EST 2003; ADEME 2004), shows that LPG has a role to play – albeit a secondary one – as an alternative automotive fuel and there are some markets where it already possesses a measurable fraction (Italy, Netherlands). However, LPG only corresponds to a small fraction of crude oil and natural gas production, hence its small availability limits the fleet sizes it may serve in the long run. The promotion of LPG as a fuel for fleets operating by oil production facilities will reduce the environmental damage caused by LPG flaring.

4.4 Biofuels

The biofuel category includes gaseous and liquid fuels (ethanol, biodiesel, Fatty Acid Methyl Ester – FAME, Synfuel) which originate from living flora and biogas which may be produced by waste and manure processing. All biofuels take part in a much shorter carbon cycle than fossil fuels hence, they are considered as CO_2-neutral in their use. However, their processing from their natural state (e.g. plant fat) to a fuel for use in an internal combustion engine requires additional energy which leads to positive CO_2 emissions. Biofuels in Europe are widely promoted because they are considered as a means to promote energy sustainability and reduce the dependence on energy imports. Therefore, their use to captive fleets and beyond is promoted independently of their potential in reducing air quality

A recent joint study from CONCAWE, EUCAR and JRC (2004) provided some useful conclusions about the WTW GHG benefit of using biofuels, which can be summarised as follows:

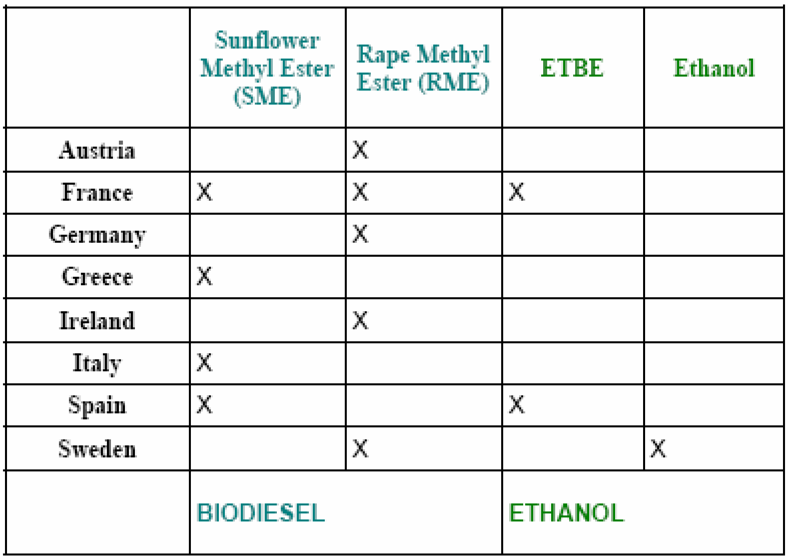
- A number of routes are available to produce alternative liquid fuels that can be used neat or in blends with conventional fuels in the existing infrastructure and vehicles.
- Conventionally produced bio-fuels such as ethanol and FAME provide some GHG benefits but are energy-intensive compared to conventional crude oil based fuels.
- The GHG balance of conventional biofuels is particularly uncertain because of nitrous oxide emissions from agriculture.
- Potential volumes of ethanol and FAME are limited. The cost/benefit crucially depends on the specific pathway, by-product usage and N_2O emissions.
- GTL (Gas-to-Liquids) processes enable high quality diesel fuel to be produced from natural gas. However, the WTW GHG emissions are somewhat higher than for conventional diesel fuel. Only limited GTL volumes can be expected to be available by 2010 and beyond.
- New BTL (Biomass-to-Liquids) processes are being developed to produce synthetic fuels with lower overall GHG emissions, though still high energy use. BTL processes have the potential to save substantially more GHG emissions than current bio-fuel options at comparable cost and merit further study. Issues such as land and biomass resources, material collection, plant size, efficiency and costs, may limit the application of these processes.

Point 2, with regard to energy intensiveness, is taken up in more detail by the study of the Swedish National Road Administration (Ahlvik et al. 2001) which shows that alternative fuels are always produced more efficiently by a fossil feedstock than a biomass feedstock because fossil fuels are already partly processed. For example, for a diesel conventional vehicle shifting to DME, the WTW efficiency decreases by 21% when DME is produced from natural gas and by 39% when DME is produced from biogas. On the other hand, when DME originates from biogas, the total WTW energy attributed to non-renewable (fossil) fuels is only 7% of the fossil energy consumption in case DME is produced from fossil fuels. A similar conclusion is also true for WTW GHG emissions.

It needs to be made clear that even if biofuels were the exclusive fuel for captive fleets, this would not be enough to fulfil the indicative European targets of 5.75% biofuel energy in the road transport sector by 2010, due to the small share of such fleets to total road transport energy consumption. According to TREMOVE, urban busses are responsible for only 0.62% of total CO_2 emissions from road transportation. However, captive fleets are very good platforms and showcases for demonstrating and making public the use of biofuels, evaluating their benefits, addressing potential problems and improving the methods and the infrastructure for their production and distribution. It is therefore considered that the use of biofuels in captive fleets needs to be supported. Hence, this background document does not further address what is the best fuel with regard to energy efficiency / fossil energy savings or WTW GHG but shortly discusses what is the present experience with the use of biofuels and what are the potential effects on urban air quality.

A report from the TRENDSETTER (2003a) provides a summary of European activities with regard to biogas as an alternative to NGVs or dual fuelled petrol vehicles and Table 3 shows the use of different biofuels in difference countries. Stockholm currently operates ~500 dual-fuel municipal vehicles on biogas produced from wastewater treatment (in addition to 250 ethanol powered busses), with a target to reach 3000 vehicles. In Lille, 128 busses operate on biogas produced again by wastewater treatment with no particular problems, according to the study. Target of TRENDSETTER is to replace 35% of Lille urban busses with biogas ones. In Linköping, Sweden, 68 busses and 150 cars are in operation with biogas produced by organic material from slaughterhouses and animal manure. Biogas vehicles are also in operation in Göteborg. The City of Göteborg offers priority taxi lanes at four locations in the town centre for environmentally friendly taxis. Similar biogas projects are in operation in other towns of Sweden, Norway and in Zürich. The total fleet of biogas in Europe is therefore estimated to a few hundreds of vehicles mostly operating in Sweden. Biogas is considered to have similar performance to natural gas with much improved WTW GHG emissions.

Table 3: Use of biofuels in different countries (Source: TRENDSETTER, 2003b)



	Sunflower Methyl Ester (SME)	Rape Methyl Ester (RME)	ETBE	Ethanol
Austria		X		
France	X	X	X	
Germany		X		
Greece	X			
Ireland		X		
Italy	X			
Spain	X		X	
Sweden		X		X
	BIODIESEL		ETHANOL	

The second interesting option for biofuel use in captive fleets is biodiesel which is mainly produced from vegetable oils that can be derived from oil crops, such as rapeseed, soybean (mainly US), palm and sunflower. Biodiesel production technology and its use is today mature in countries like Austria, France, Germany, Sweden, etc. Biodiesel blended up to 5% with diesel fuel may be used with no modification to all diesel engines. Pure biodiesel may only be used in dedicated engines which allow compatibility with some of its particularities (high oxygen content, solvent activity). A few examples: In Graz, Austria some 40% of the 140 urban busses already operate solely on biodiesel with a target to reach 100% busses plus a fraction of taxis (~120 vehicles) by mid-2005. In France, the "Partenaires Diester" has been established as a support and information exchange body between communities, the oil industry, research institutes and agencies with the objective to promote the "Diester" biodiesel fuel. This is today used up to 5% by passenger cars and up to 30% to urban fleets. Last but not least, Germany is the largest biodiesel producer in Europe (1.1 MT in 2004) with a biodiesel fuelling station every ~25 km. However, biodiesel only corresponds to 0.8% of total energy consumption in the road transport sector.

Is there a need to further promote biofuels from an air quality point of view? Looking first at biodiesel, a 5% blend to conventional diesel is not expected to bring any emission difference. However, at higher ratios, PM emissions start to decrease due to the oxygen content of biofuels and can reach ~50% for almost pure biodiesel. NO_x on the other hand is expected to increase by 10-20%, because of secondary in-cylinder NO formation mechanisms. The exact change in emission performance depends on engine technology, potential engine tuning to account for the lower energy density of biofuel, etc. Additionally, biodiesel has an almost zero sulphur content which enables the operation of advanced diesel aftertreatment devices. This shows that use of biodiesel, especially as a blend in current vehicles, will have minimal effects on air quality. Table 4 summarizes the effects of biodiesel on conventional diesel emissions. Biogas, on the other hand is basically methane and can be used by NGVs. Therefore air quality benefits are mainly those also achieved with natural gas.

Table 4: Effect of pure biodiesel on regulated and unregulated exhaust components
(Source: MEET Deliverable 26)

EMISSION	TREND	Biodiesel/Petrodiesel
Carbon monoxide	decrease	0.75 - 0.8
Hydrocarbons	decrease	0.2 - 0.8
Nitrogen oxides (NO_x)	increase	1.1 - 1.2
Total Particulate Matter (PM)	Change depends on SOF ratio	0.6 - 1.2
Organic fraction of particulates (SOF)	increase	
Sulphate fraction of particulates	decrease	
Carbon fraction of particulates	decrease	
Visible smoke	decrease	
PAH	decrease	
Aldehydes	increase	

The estimation of the costs and the WTW environmental performance of biofuels is a multidimensional problem. Any estimation is naturally confronted with the large range of options for the production and processing of biofuels, together with the uncertainty in the estimation of the effect of certain associated processes (i.e. N_2O emissions of rapeseed cultivation). This is clearly shown in Figure 13, which shows, first, that there is a positive cost in most cases; secondly, that with some oils there is a potential for lower operational costs than conventional diesel; and, thirdly, that the range of cost estimations is very large to reach any firm conclusions. The cost of converting an existing diesel bus to run purely on biodiesel is in the order of a few thousand Euros. With regard to biogas, an additional cost of ~35 k€ needs to be considered for each new bus, compared to a diesel equivalent.

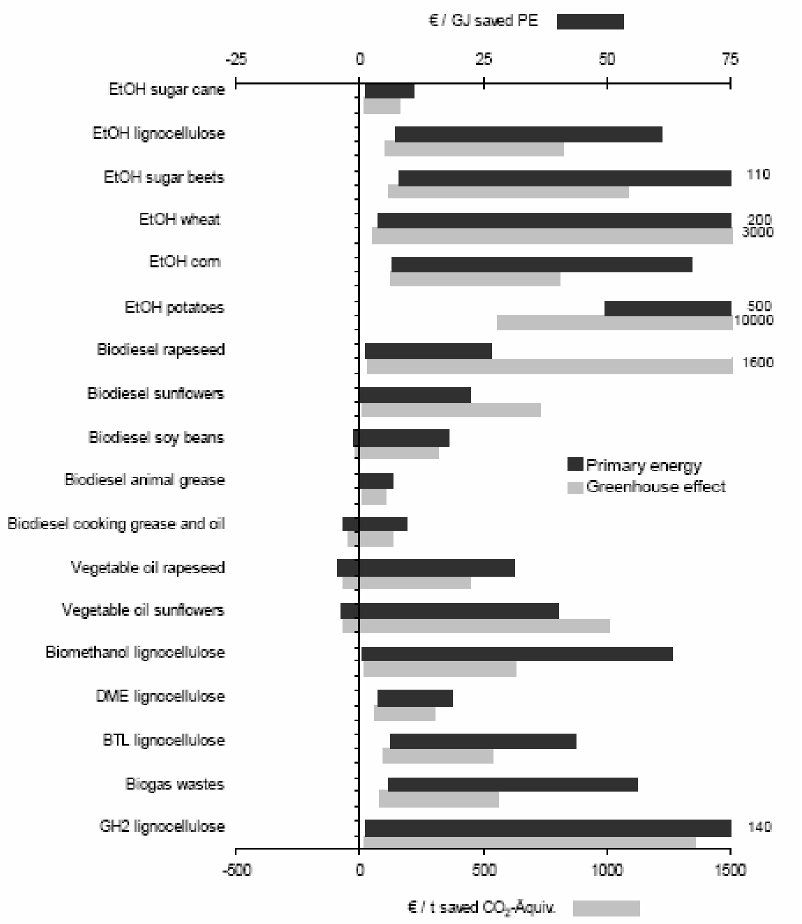


Figure 13: Cost per GJ of fossil fuel energy saved (black bars) and per tonne CO_2 equivalent saved, associated with the WTW use of different biofuels. (Source: IFEU, 2004).

4.5 Points for Discussion / Consideration

1. Is there realistic and updated information on emission benefits from the use of emulsions at European level (e.g. Italy)? What is the status of their standardization within the CEN group? What is the best approach for their taxation?
2. What is the present status of NG bus emission levels? Are there realistic emission factors for their operation in cities, also for non-regulated pollutants? Is methane emission still a problem with current technology? Effects should be seen separately for stoichiometric and lean-burn engines.
3. Is NG only an option for new vehicles or is it also available as a retrofit option? What is the status of NG in other vehicle categories? Are there any concepts for LNG vehicles in Europe?
4. Is LPG a better option for taxis and light duty trucks than diesel both with regard to air quality and operation costs? Is there a need to promote its use?
5. Biodiesel and biogas may be used with none or minor engine modifications to existing fleets but offer limited air quality benefits over low sulphur diesel and NG respectively and are produced at a higher cost. What are the options for other biofuels like ethanol or DME today from an air quality point of view?

5 RETROFITTING

5.1 Available Technology for Retrofitting

5.1.1 Diesel Oxidation Catalyst

Diesel Oxidation Catalysts (DOCs) are simple, passive devices that may be installed in the exhaust line of diesel vehicles and oxidize products of incomplete combustion, given the high oxygen content of the exhaust gas. Several DOCs are today available for retrofitting. Oxidation catalysts are very effective in reducing CO and HC by ~80% and ~60% respectively, or even higher. However, retrofitting of DOCs would primarily target to reduce PM. DOCs are not effective in reducing solid particle emissions but they do reduce the soluble organic fraction (SOF) of PM by oxidizing the hydrocarbons that constitute it. The efficiency depends on the SOF content of PM and may range from 10-20% for new engines up to 50% for old engines with high SOF emission. Additionally, white smoke emissions which originate from unburnt hydrocarbons may be substantially reduced. Recently, some new oxidation catalyst systems started to appear for retrofitting, under the name "particle oxidation catalysts" which are supposed to also oxidize solid particles by diffusing them into the catalytically active wall sites. Experience with these systems is still limited but their efficiency is considered to be in the order of 50% PM reduction. The Association of manufacturers of emission control (MECA) estimates that ~20 000 DOCs have been retrofitted in USA and Europe since 1995 (MECA, 2004).

There are two issues associated with DOC applications. The first is associated with the increase in the NO_2/NO ratio because DOCs are also effective in oxidizing NO to NO_2. Hence, the NO_2/NO ratio which for a typical uncontrolled diesel vehicle is in the range of 5-10% may reach or exceed 50% when using a DOC (this last value is more common for DOCs combined with CRDPFs, see §5.1.2). Different catalyst formulations may be used to reduce the extent of (but not to eliminate) the oxidation. The second issue is the oxidation of SO_2 to SO_3 (sulphate) which may lead to an increase of the volatile fraction of PM. However, this is more an issue of the past and is not expected to be a significant problem with sub-50 ppm S fuels.

5.1.2 Diesel Particle Filter

Diesel Particle Filters (DPFs) are installed in the exhaust line and usually have a honeycomb construction (similar to conventional catalysts) and operate by forcing the exhaust gas to pass through the porous walls of the monolith. Particles carried by the exhaust gas stream accumulate on the walls by mechanisms involved in deep-bed filtration (diffusion, interception, impaction) and form soot layers in the filter. The filtration efficiency of DPFs usually exceeds 99% in number count, making it a very attractive option for diesel PM reduction. Depending on the trap configuration, NO_x emissions may increase, decrease or stay at the same levels. CO and HC emissions usually decrease.

The critical point in DPF application is how to efficiently oxidize the soot accumulated in the filter, in order for the backpressure to remain at moderate levels, not to induce a large fuel penalty on the application. The controlled oxidation process is called "regeneration" and there are several techniques that may be potentially applied. Given that soot ignites at ~550°C with O_2, one way is to increase the soot temperature at this level and allow it to combust with the oxygen carried by the exhaust gas stream. The increase in temperature may be achieved with electric heaters or post combustion fuel oxidation. A different way is to decrease the soot ignition temperature by using a fuel-borne (FB) catalytic additive (Ce, Cu, Fe,…) or to apply a catalytic washcoat on the DPF walls. These may initiate regeneration even at 250°C below the soot ignition temperature. Finally, a third direction is to oxidize soot by means of NO_2 which may occur at much lower temperature than with O_2. In this last option, an oxidation catalyst is required (either upstream of the DPF or on a catalytic washcoat), in order to achieve a high NO_2 concentration to facilitate regeneration. Such applications are called Continuous Regeneration DPFs (CRDPFs) because oxidation may continuously occur as long as NO_2 concentration and exhaust gas temperature are within certain limits.

There are today commercially available diesel particle filter (DPF) systems based on the NO_2 regeneration principle, for the retrofitting of heavy duty vehicles from at least two automotive component suppliers (Johnson Matthey, Engelhard). Three manufacturers (STT Emtec, Donaldson, Cleaire) produce a retrofit system based on post-fuel oxidation, one of them also combining an SCR system (Edgar et al., 2003). Additionally, passenger cars fitted with DPFs in the market, operate on the FB catalyst principle. A new system based on the CRDPF principle was recently revealed for retrofitting of passenger cars at a cost of 600-700 € per vehicle (HJS Fahrzeugtechnik). The presentation of retrofitting activities in the world later in this paper, show that all options are promising but are also associated with complications that need to be overcome before retrofitting to large volumes. Issues involved in retrofitting include:

- The necessity to use ultra-low sulphur fuel, especially with the use of CRDPF systems. Sulphur reduces the catalytically active sites requiring higher exhaust gas temperatures for regeneration to occur. FBDPFs are more flexible in the fuel sulphur content. This becomes less and less of an issue nowadays due to the 50 ppm S fuel enforcement and the wide availability of near zero sulphur fuel (<10 ppm) in most EU15 countries.
- DPFs filter all particles emitted, including ash originating from the fuel but mainly the lube oil metal content, engine attrition and any intake air inert particles. Ash is not combusted and gradually clogs the filter leading to lower soot loading capacity and a higher mean backpressure. DPFs need to be periodically removed and washed with high pressure water. This is not a real technical problem but increases the maintenance cost and the possibility for filter mishandling in the process.
- CRDPFs require some kind of calibration before installation because their operation characteristics depend on their input (exhaust gas composition, temperature, soot concentration). This means that not all busses may be fitted with such a system, especially when a very high soot concentration is emitted. Additionally, due to the efficient oxidation catalyst, tailpipe NO_2/NO ratios may even exceed 50% under specific driving conditions. On the other hand, FBDPFs require either some kind of infrastructure to add the catalyst in the fuel or more substantial engine modifications to blend the fuel on-board. DPF dimension and characteristics need also to be adjusted per bus type.

5.1.3 Exhaust Gas Recirculation

Exhaust Gas Recirculation (EGR) is a means of reducing in-cylinder NO_x concentration by recirculation of exhaust gas into the cylinder which acts as an inert gas. This absorbs part of the heat generated on the flame front thus reducing the maximum temperatures generated during combustion and suppressing NO formation. EGR is widely used in diesel engines of different sizes by their original manufacturers as a NO_x control technology.

An aftertreatment components manufacturer builds a retrofit EGR system for retrofitting in urban busses (STT Emtec). According to this manufacturer's press releases, this is considered to achieve up to 50% reduction in NO_x emissions and has been tested in London busses and in Asia and will be now installed in busses in Houston, Texas. There is no publicly available information on the actual performance of the system.

5.1.4 Selective Catalytic Reduction

In the Selective Catalytic Reduction (SCR) process, NO_x reacts with ammonia, which is injected into the exhaust gas stream before the catalyst. Ammonia reacts with NO_x at temperatures above 200°C to produce harmless nitrogen and water. This is a very common application for NO_x control in stationary applications but it is also foreseen as the most effective solution to reach future emission standards for heavy duty applications (Schittler, 2003).

Mobile application of SCR technology involves a water solution of urea as an ammonia carrier for safety reasons. Depending on the SCR system development and characteristics, NO_x reduction rates may reach up to 80-90%. A separate storage tank for urea is required which is consumed at a rate 1-4% of fuel. Additionally, an urea infrastructure is required to make urea available at fuelling stations. Such a network has started to form in Europe already (AdBlue urea solution production available in Germany, France, Spain, Ireland, Austria and elsewhere). Figure 14 presents the network and cost for urea infrastructure.

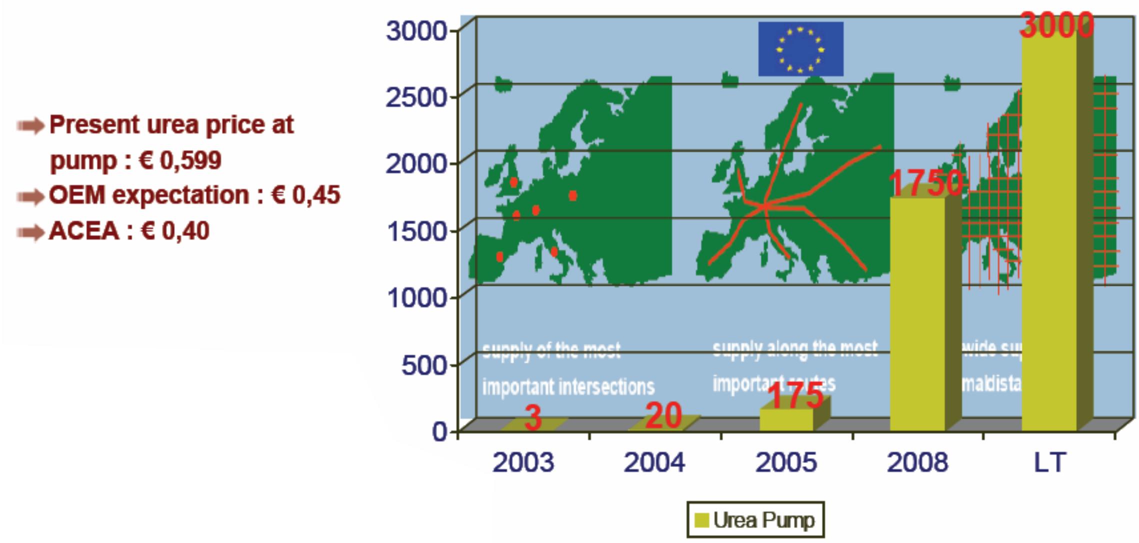


Figure 14: Urea infrastructure network and associated cost per litre. LT stands for "long term". (Source: adapted from Joubert et al., 2004).

There are today at least four commercial SCR systems for retrofitting from European and American manufacturers (mobiCLEAN by the Environmental Technology Institute in Rapperswil, Longview by Cleaire, Elim-NOx from Combustion Components Associates and the SCR system from Emission Technology Group in Sweden). Three of these systems also include a DPF and an oxidation catalyst in the same package for concurrent reduction of PM, NO, CO and HC. The oxidation catalyst also helps in reducing NH_3 slip from the SCR. Typical cost for a complete system is in the range of 20-25 k€. Further to the high cost, additional issues may be the complexity of the system which negatively affects reliability and durability and the need for initial calibration depending on the engine application. SCR is the most recent exhaust retrofit component and demonstration activities have just started to appear in New York, Southern California, Germany and elsewhere.

5.2 Demonstration Activities

5.2.1 USEPA/CARB activities

The US Environmental Protection Agency (USEPA) has launched a Voluntary Diesel Retrofit Programme to accelerate the marketing and implementation of diesel aftertreatment devices for the control of exhaust emissions from captive fleets. This program brings together retrofit manufacturers and fleet operators and tries to assist in the selection of an appropriate retrofit solution depending on the fleet characteristics. This is mainly done in two directions: First, USEPA has established an approval/verification procedure for retrofit devices. With this procedure, all retrofit commercial solutions offered are examined with regard to their applicability to different vehicle/engine technologies, their durability and their environmental benefit (within pre-determined operating conditions). Once the device has passed the test, a verification is granted and the device may then be used in retrofit campaigns. In such cases, an in-use testing is conducted to verify the performance of the device in actual use. Table 5 provides a list of devices verified under the USEPA programme. The second direction is to assist local authorities and fleet owners retrofit their fleets by sharing part of the financial burden, since this is a voluntary programme. Funding is offered either by EPA grants or by Federal or local funds, or it takes the form of tax credits for retrofitted fleets. A second large voluntary project on school-bus emission reduction ("Clean School Bus, USA") is assisting in the direction of raising money for retrofitting of school busses. Recently, even court settlements have provided the money for school bus retrofit initiatives.

Table 5: USEPA verified retrofit devices, range of applicability and pollutant reduction percentages achieved. List reflects verifications granted by Dec. 2004.
(Source: http://www.epa.gov/otaq/retrofit/retroverifiedlist.htm).

Manuf.	**Technology**	**Applicability**	**Reductions (%)**			
			PM	CO	NOx	HC
Caterpillar, Inc.	Catalyzed Converter/Muffler (CCM)	Highway, heavy-heavy and medium-heavy duty, 4-cycle, non-EGR, model year 1998 -	20	20	na	40
Clean Diesel Technologies, Inc.	Platinum Plus Purifier System (fuel borne catalyst plus DOC)	Highway, medium-heavy and heavy-heavy duty, 4 cycle, model year 1988 - 2003, turbocharged or naturally aspirated	25 to 50	16 to 50	0 to 5	40 to 50
Clean Diesel Technologies, Inc.	Platinum Plus Fuel Borne Catalyst/Catalyzed Wire Mesh Filter (FBC/CWMF) System	Highway, medium-heavy duty, 4 cycle, model year 1991 - 2003, non-EGR, turbocharged or naturally aspirated	55 to 76*	50 to 66*	0 to 9*	75 to 89*
Donaldson	Series 6000 DOC & Spiracle (closed crankcase filtration system)	Highway, heavy-heavy and medium-heavy duty, 4 cycle, non-EGR, model year 1991 - 2003, turbocharged or naturally aspirated	25 to 33[a]	13 to 23	n/a	50 to 52
Donaldson	Series 6100 DOC	Highway, heavy-heavy and medium-heavy duty, 4 cycle, non-EGR, model year 1991 - 2003, turbocharged or naturally aspirated	20 to 26	38 to 41	n/a	49 to 66
Donaldson	Series 6100 DOC & Spiracle (closed crankcase filtration system)	Highway, heavy-heavy and medium-heavy duty, 4 cycle, non-EGR, model year 1991 - 2003, turbocharged or naturally aspirated	28 to 32[a]	31 to 34	n/a	42
Engelhard	DPX Catalyzed Diesel Particulate Filter	Highway, heavy-duty, 4 cycle, model year 1994 - 2002, turbocharged or naturally aspirated	60	60	n/a	60
Engelhard	CMX Catalyst Muffler	Heavy Duty, Highway, 2 cycle engines	20	40	n/a	50
Engelhard	CMX Catalyst Muffler	Heavy Duty, Highway, 4 cycle engines	20	40	n/a	50
Engine Control Systems	Purifilter - Diesel Particulate Filter	Highway: Heavy Heavy-Duty, Medium Heavy-Duty; Urban Bus; 4 cycle; model years 1994 - 2003; turbocharged or	90	75	n/a	85
Engine Control Systems	AZ Purimuffler AZ Purifier	Heavy Duty, Highway, 2 cycle engines	20	40	n/a	50
Engine Control Systems	AZ Purimuffler AZ Purifier	Heavy Duty, Highway, 4 cycle engines	20	40	n/a	50
Johnson Matthey	Catalyzed Continuously Regenerating Technology (CCRT) Particulate Filter	Highway, heavy-heavy, medium-heavy, light-heavy duty, urban bus, 4-cycle, non-EGR model year 1994 - 2003, turbocharged or naturally aspirated engines.	60	60	n/a	60
Johnson Matthey	Continuously Regenerating Technology (CRT) Particulate Filter	Heavy Duty, Highway, 2 & 4 cycle, model year 1994 - 2002, turbocharged or naturally aspirated engines	60	60	n/a	60
Johnson Matthey	CEM™ Catalytic Exhaust Muffler and/or DCC™ Catalytic Converter	Highway, heavy-heavy, medium-heavy, light-heavy duty, non-urban bus, 4-cycle, non-EGR model year 1998 - 2003, turbocharged or naturally aspirated engines	20	40	n/a	50
Johnson Matthey	CEM Catalyst Muffler	Heavy Duty, Highway, 2 cycle engines	20	40	n/a	50
Lubrizol	PuriNOx Water emulsion fuel	Heavy Duty, Highway & Non-road, 2 & 4 cycle	16 to 58	-35 to 33	9 to 20	-30 to -120
Various	Biodiesel (1 to 100%)	Heavy Duty, Highway, 2 & 4 cycle	0 to 47	0 to 47	0 to -10	0 to 67
Various	Cetane Enhancers	Heavy Duty, Highway, 4 cycle, non-EGR-equipped	n/a	n/a	0 to 5	n/a

A similar programme is supported by the California Air Resources Board (CARB) under the "Diesel Risk Reduction Plan" activity. A similar to USEPA verification procedure has been established which classifies PM control solutions in three levels, depending on their reduction potential. CARB and USEPA have also signed a memorandum of agreement "for the Coordination and reciprocity in diesel retrofit device verification". This basically commits EPA and ARB to work toward accepting particulate matter (PM) and oxides of nitrogen (NO_x) verification levels assigned by the other's verification programs. Currently, only USEPA recognizes and accepts those retrofit hardware strategies or device-based systems that have been verified by CARB.

In the framework of these initiatives, an indicative, but not exhaustive list of diesel retrofit projects in the US includes:

Clean School Bus Programmes (http://www.epa.gov/otaq/schoolbus/demo_projects.htm)

These are demonstration projects which are included in the USEPA's Clean School Bus Initiative. There are currently 21 demonstration projects running, affecting some 5000 busses in ~30 states. Different solutions from Table 1 are considered for implementation. For example, 1800 busses are already retrofitted in Washington with either DOCs or CRDPFs at a cost ranging between 1.5-8 k$/bus, depending on the device used.

Results on school bus applications of CRDPFs are presented in a few studies. Le Tavec et al. (2002) installed CRDPF systems on two school busses operating on ultra low sulphur fuel and found PM reductions up to 96%. The CRDPFs operation was reliable for 65000 km accumulated on these two busses. Five school busses were retrofitted with CR DPFs in the study of Chatterjee et al. (2001) and each accumulated ~45000 miles in a period of one year. No reliability issues were identified. More experience is expected to be accumulated with these projects in the near future.

The NY State Clean Diesel Air Quality Demonstration Programme

The New York State Department of Environmental Conservation preceded USEPA's initiative by designing and executing a large demonstration activity for urban busses. The New York Metropolitan Transit Authority (NYMTA) is the main urban bus operator in NY, operating a fleet of ~4400 busses on 234 routes. Under this project, initially 25 busses of NYMTA, powered by 1999 diesel engines (equivalent to Euro III), were retrofitted with CRDPFs and were operated on ultra low sulphur fuel (ULSD<30 ppm S). Later on, some 500 busses were retrofitted with CRDPFs.

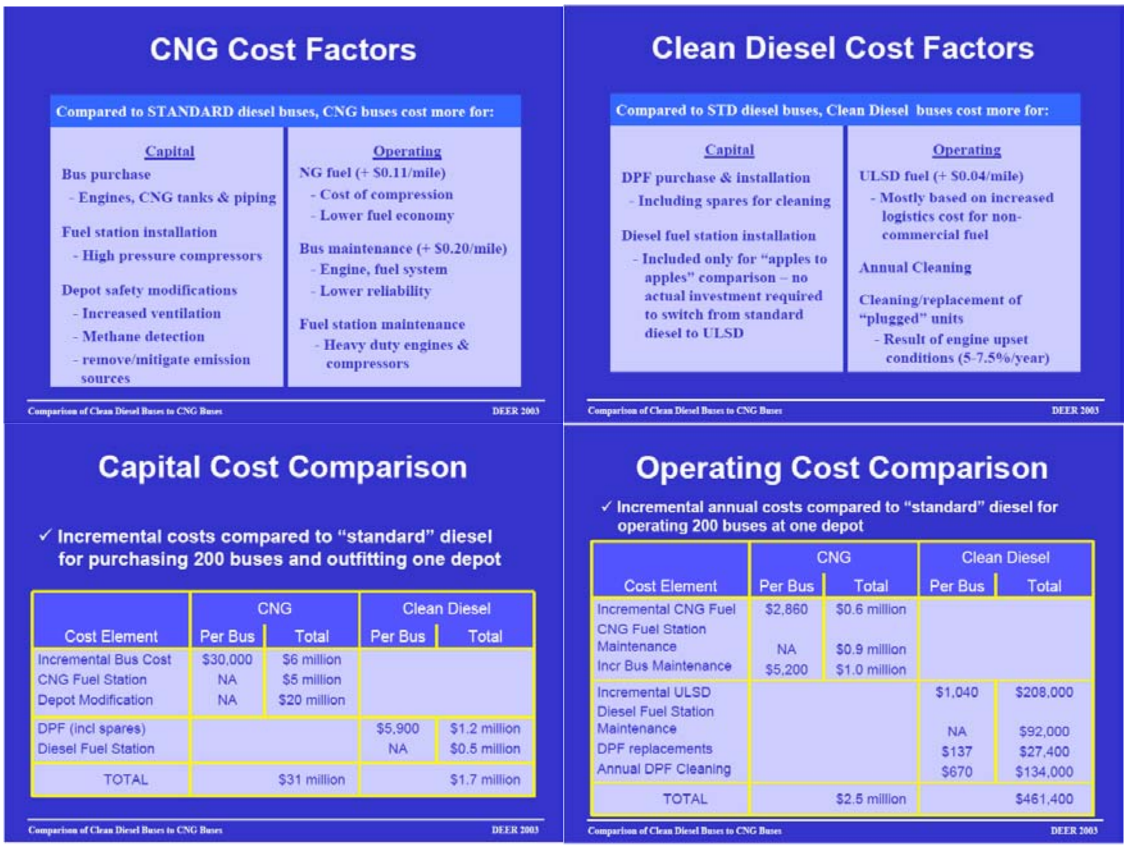
Lanni et al. (2001) and Chatterjee et al. (2002) presented the emission performance and durability results of the CRDPF-fitted busses. With CRDPF retrofit and ULSD, the average emissions were reduced by 92% for THC, 94% for CO and 88% for PM under a cycle similar to UDC. There was no noticeable change in NO_x emissions from baseline. In addition, there was >99% reduction in toxic carbonyls and 78% in PAH. The nitro-PAHs were also reduced by an average of 79%. PM filter analysis for CRDPF tests showed >99% reduction in SOF, >95% reduction in soot (both in elemental and organic carbon forms) and 86% reduction in sulphate. Over a more rigorous cycle, the CRDPF showed an even higher (93-98%) reduction in THC, CO and PM.

With regard to durability issues for busses operating between Feb and Nov 2000, the same authors report in their 2001 update: "8 months of operation on 25 buses without a failure or any significant increase in fuel economy indicates that the CRDPF has no adverse effect on the operation, reliability or maintainability of the vehicles thus retrofitted". In their 2002 update the same authors further assess the CRDPFs systems durability, by reaching the same conclusion over 21 months of CRDPF operation on 25 buses.

The NYMTA study also evaluated the environmental benefits and costs associated with operating a fleet of CNG or DPF-fitted busses. Figure 15 presents a series of slides from the presentation of Lowell in the 2003 DEER conference, discussing the investment and operation cost associated with each option. According to this analysis, the incremental cost for the life cycle (30 years amortization) of the 200 bus fleet amounts to an annual incremental cost of M$2.3 for the CNG and M$0.34 for the DPF scenarios.

The NY Department of Sanitation Study

As an example of retrofitting refuse trucks, Wayne et al. (2003) present results of the retrofit of 25 trucks with DPFs. All trucks were powered by Year 1997 Cummins engines, operated on ultra-low diesel sulphur fuel (30 ppm S) and were fitted with CRDPFs of two different manufacturers. Emission performance tests were conducted over two refuse trucks specific driving cycles. Use of the DPFs led to 83% lower HC and CO emissions, a marginal 3-4% lower NO_x emission rate, and PM reductions ranging from 81-97% depending on driving cycle and DPF manufacturer.



CNG Cost Factors

Compared to STANDARD diesel buses, CNG buses cost more for:

Capital

Bus purchase
- Engines, CNG tanks & piping

Fuel station installation
- High pressure compressors

Depot safety modifications
- Increased ventilation
- Methane detection
- remove/mitigate emission sources

Operating

NG fuel (+ $0.11/mile)
- Cost of compression
- Lower fuel economy

Bus maintenance (+ $0.20/mile)
- Engine, fuel system
- Lower reliability

Fuel station maintenance
- Heavy duty engines & compressors

Comparison of Clean Diesel Buses to CNG Buses DEER 2003

Clean Diesel Cost Factors

Compared to STD diesel buses, Clean Diesel buses cost more for:

Capital

DPF purchase & installation
- Including spares for cleaning

Diesel fuel station installation
- Included only for "apples to apples" comparison – no actual investment required to switch from standard diesel to ULSD

Operating

ULSD fuel (+ $0.04/mile)
- Mostly based on increased logistics cost for non-commercial fuel

Annual Cleaning

Cleaning/replacement of "plugged" units
- Result of engine upset conditions (5-7.5%/year)

Comparison of Clean Diesel Buses to CNG Buses DEER 2003

Capital Cost Comparison

✓ Incremental costs compared to "standard" diesel for purchasing 200 buses and outfitting one depot

	CNG		Clean Diesel	
Cost Element	Per Bus	Total	Per Bus	Total
Incremental Bus Cost	$30,000	$6 million		
CNG Fuel Station	NA	$5 million		
Depot Modification	NA	$20 million		
DPF (incl spares)			$5,900	$1.2 million
Diesel Fuel Station			NA	$0.5 million
TOTAL		$31 million		$1.7 million

Comparison of Clean Diesel Buses to CNG Buses DEER 2003

Operating Cost Comparison

✓ Incremental annual costs compared to "standard" diesel for operating 200 buses at one depot

	CNG		Clean Diesel	
Cost Element	Per Bus	Total	Per Bus	Total
Incremental CNG Fuel	$2,860	$0.6 million		
CNG Fuel Station Maintenance	NA	$0.9 million		
Incr Bus Maintenance	$5,200	$1.0 million		
Incremental ULSD			$1,040	$208,000
Diesel Fuel Station Maintenance			NA	$92,000
DPF replacements			$137	$27,400
Annual DPF Cleaning			$670	$134,000
TOTAL		$2.5 million		$461,400

Comparison of Clean Diesel Buses to CNG Buses DEER 2003

Figure 15: Comparison of costs for operating a fleet of CNG or DPF equipped busses. Costs are given as an incremental cost over the baseline scenario which only involves conventional diesel busses. (Source: Lowell, 2003).

5.2.2 European Experiences

The VERT project and its continuation

VERT (Verminderung der Emissionen Realer Dieselmotoren im Tunnelbau - which translates into Reduction of Diesel-emissions in tunnelling) was a pioneering activity in Europe in the direction of retrofitting diesel construction machinery with DPFs, in order to reduce ultrafine particle concentrations in tunnel worksites. The project was co-funded by the Austrian, German and Swiss authorities. It started in 1993 and finished in 1999 and developed a protocol for the evaluation of durability and emission performance of different DPF solutions. Based on this protocol, a list of verified DPFs systems is periodically published, similar to the USEPA/CARB policy. This list is available from the Swiss Agency for the Environment, Forests and the Landscape (SAEFL - http://www.umwelt-schweiz.ch/buwal/de/fachgebiete/fg_luft/vorschriften/industrie_gewerbe/filter/). However, this verification is indicative and it is not a prerequisite for retrofitting of a commercial system.

Following the project's developments, it is estimated that ~6 500 DPF retrofits were already conducted by mid-2003 in on-road and off-road applications. The summary of the experience so far are summarized by Mayer et al. (2004), into:

- The number counts of particles downstream of DPFs verified by the VERT project are normally reduced by more than 99% compared to the baseline.

- The failure rate of installed traps is in the order of 2% per year with figures up to 6% for earlier years. Typical reasons for malfunctions include use of high sulphur fuel, applications where the exhaust temperature pattern does not facilitate trap regeneration, and mechanical problems of fitting, canistering, etc.

The potential of retrofitting the complete Swiss diesel fleet with DPFs was examined in a report by SAEFL (2000) and cost figures were also estimated. For Euro 2 vehicles, the total investment cost per vehicle was estimated at 6 600-14 500 CHF (4.5-9.5 k€) for a vehicle power range of 100-360 kW. The supplementary operating costs result from the 3% higher fuel consumption as well as the expenses for additional materials (additive, sulphur-free fuel), regeneration energy and maintenance costs (trap replacement after 400 000 km, service interval 100 000 km or 50 000 km for older vehicles). Altogether, additional operating costs of 0.03 to 0.07 CHF (0.02-0.05 €) per driven km are estimated for Euro 2 vehicles. Operating older vehicles may be up to 10% more expensive.

The Swedish Environmental Zones Programme

Since January 2002, the four largest Swedish cities introduced an Environmental Zone Programme in which all heavy duty vehicles operating within the zone should not be more than 8 years old. Older vehicles, depending on their age, can be either exempted from the regulations or banned in the Environmental Zones. A general exemption from the regulation is granted for vehicles aged 8 years. All vehicles older than 15 years are banned. Vehicles aged from 9 to15 years must be retrofitted with an emission control device. The required emission reductions for retrofit equipment are 80% for PM and HC and, an additional 35% NO_x for extending the exemption. It is estimated that some 3 000 vehicles were retrofitted during the first three years of implementation of this programme.

The German Retrofitting activities

Already since 1989, 1 43 trucks and busses were equipped with filters and were tracked for three years over their normal service. There were several difficulties at that time with the filter performance and operation. However, today most of the busses in Berlin have been retrofitted with DPFs. Older busses suffer from high ash content and thus frequent trap cleaning is necessary. Traps on older vehicles must be washed twice a year. Newer vehicles only require traps to be washed every 2 years.

The French Retrofitting activities

Some 12 000 busses are in operation in France today, out of which some 2 000 are fitted with DPFs, 700 are natural gas powered and there are also some LPG and electric ones (Plassat, 2004). A very interesting demonstration programme was launched in 2003 in La Rochelle. In this project, 47 Euro 1 and Euro 2 busses were fitted with DPFs and fuel borne catalyst. The additive was added in the fuel at the pump by an electronically controlled dosage pump. The same pump was also used for conventional busses but the DPF busses were identified by photoelectric devices and only these were fed with additized fuel. The fuel used was diesel with 30% RME and the additive dosage was 30 ppm in the fuel. The sulphur content in the fuel was in the order of 100 ppm or higher. No trouble or failure was reported in more than six months of commercial use of these DPF systems. The stationary dosing system worked well and filter maintenance operations are carried out, in average, every 18 000 km (twice a year). It is worth mentioning that this activity is largely based on previous similar exercises including the early 90s Athens pilot fleet of retrofitted busses with DPF and fuel borne catalyst, the Paris RATP retrofitting and the Lyon experiment.

London Black Cabs Retrofitting

Retrofitting on light duty vehicles is more scarce. A study of a fuel additive manufacturer and an automotive component supplier (Richard et al. 2003) showed the potential of retrofitting DPF systems in the passenger car sector. In this study, four in-use Euro 1 London black cabs were fitted with a DPF system and fuel-borne additive. The PM reduction with DPF in place varied from 80% to 98%, the average reduction being 91%. A NO_x reduction of 3% was also achieved with NO_2 reductions up to 50%. Effect on CO and HC emission was found vehicle specific depending on the existence of EGR or not.

5.2.3 Experiences from the Far-East

The Tokyo Metropolitan Government (TMG) initiative

TMG set into force a very stringent programme with the aim of banning diesel trucks and busses entering the Tokyo Metropolitan area if not equipped with aftertreatment systems, since October 2003, thus affecting at least some 200 thousand vehicles. An exemption period of 7 years from first registration is foreseen, which means that this measure became immediately applicable for trucks and busses registered before 1996. Later on eight local governments of the wider Tokyo area joined forces in this direction. One of the first activities was to verify aftertreatment systems available for installation. As of March 2003, TMG has designated 20 models from 16 manufacturers of DPFs and 30 models from 9 manufacturers of oxidation catalysts. TMG assists in sharing the cost of retrofitting by granting up to 400 thousand Yen (~3 k€) for DPF retrofitting and 200 thousand Yen (~1.5 k€) for DOC retrofitting per vehicle. A loan mediation responsibility has been also taken over to support in this direction. Once retrofitting has successfully taken place, a sticker is affixed to the vehicle for recognition by the authorities.

The programme has been originally met with difficulties with regard to both the cost of retrofitting and initial high failure rates of DPF systems, difficulties in regeneration, etc. No official statistics on these issues could be found.

Hong-Kong retrofitting activities

The Hong Kong Environmental Protection Department initiated a project to reduce respirable particle emissions from vehicles by 80% and NO_x by 30% by 2005 (Hung et al. 2003). One of the major emission control activities of the program was the retrofitting of in-use diesel vehicles with emission reduction devices. By 2003, all pre-1995 (pre-Euro) franchised buses were equipped with diesel oxidation catalysts. Additionally, 24 000 passenger cars were fitted with catalysts. These activities later on continued with the trial application of catalysts on Heavy Duty Trucks. The emission results of these demonstration activities indicated that DOCs resulted into 20-60% smoke reduction for busses, while reductions for heavy duty vehicle emissions were 36% for PM, 48% for CO and 56% for HC on average.

5.3 Points for Discussion / Consideration

1. Is there a need to develop a technical specifications / applicability list of retrofit devices for use in different fleets (similar to USEPA, Switzerland)?
2. What is the actual applicability and maturity of aftertreatment devices for application to fleets of different vehicle technology and characteristics (e.g. Euro I taxis, Euro III buses, etc)?
3. For measures associated with similar environmental benefits and costs (e.g. CNG vs diesel+SCRT retrofitting) how is it possible to evaluate the actual cost-effectiveness of each option as a guidance to public authorities?

6 SUMMARY OF AVAILABLE OPTIONS

There are several criteria to be considered for each available option, depending on its performance and the associated benefits. A report from ADEME tries to qualitatively compare the different options on a horizontal basis, i.e. assuming a conventional diesel vehicle as the baseline and looking how different policy options may affect this baseline (Figure 16). This figure has been completed in the present background document with an option of accelerated replacement for new technology diesel vehicles. The figure shows what is generally accepted for the available current technologies and that there is not a single solution which may be advantageous in all relevant fields, in the sense that it could be regarded as the only policy option to pursue in the future. Natural gas and electric vehicles for example offer significant advantages over diesel technology with regard to air quality issues but they are also associated with a higher cost, both on a vehicle level and due to the significant infrastructure required. Also, hybrids and battery equipped electric busses are currently on a research/development stage, hence they cannot be proposed as today's alternatives.

	Air Quality / Health					GHG		Economic aspect			Public perception	
	CO	HC	NO_x	PM	Unregulated	WTW	Energy diversification	Investment	Operation	Reliability	Noise, Odour Fume	Image
Diesel Euro IV/V (accelerated replacement)	▨	▨	🟩	🟩	▨			🟥	▨	▨	▨	▨
Emulsion			▨	▨							▨	
30% biodiesel blend				▨		▨	▨					▨
DPF	▨	▨		🟩	▨						▨	
SCR/EGR			🟩							?		
NGV (current)	🟨	▨	🟩	🟩	🟩		🟩	🟥	🟨	🟨	🟩	🟩
LPG (Euro2)		▨	🟩	🟩	🟩	🟥		🟥		🟨	🟩	🟩
Hybrid	▨	▨	▨	▨	▨		▨	🟥	🟨	🟥	🟩	🟩
Electric	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥		🟨	🟩	🟩

Worse than Diesel	🟥	🟨	Euro3	▨	🟩	Better than Diesel

Figure 16: Qualitative characterization of different technologies, relative to a conventional (Diesel Euro II/III) diesel bus (Source: Adapted from ADEME, 2004)

Instead, a combination of options should be rather followed in order to meet the multiple energy/environmental targets considered at European level. It should be recalled that the aim of this background document is not to suggest the best candidates for policy development today, but to introduce the potential steps forward for captive fleets, on a European-wide level. The following paragraphs discuss the different issues associated with each technology option. Several cost elements have been taken from the US Dept. of Energy (2003), Energy Saving Trust (2003) and UITP (2004).

6.1 Accelerated Replacement

The cost of a current technology rigid 12 m bus is in the order of 200-250 k€, it has a total lifetime in the order of 15 years and runs about 60-80 thousand km per year. A replacement may therefore be well suited to captive fleets with a mean age of over 10-12 years, otherwise the cost will be high (discarding 1/3 of the useful lifetime costs ~70 k€). Replacement requires no additional costs in infrastructure, only the use of low sulphur fuel, which is already offered in Europe today. New vehicles will also lead to an initial reduction of maintenance costs, which are today estimated in the order of 0.3 €/bus-km.

The environmental benefits induced by a replacement plan depend on the technology replaced. Focussing on NO_x and PM which are more effectively addressed (together with non regulated pollutants), the replacement of a Euro I bus (1992) with a Euro IV one (2005) will bring 65% reduction in NO_x and over 90% reduction in PM and smoke, according to COPERT III. This corresponds to a reduction of about 8.5 [g NO_x/bus-km] and 0.5 [g PM/bus-km] respectively. Reductions of conventional diesel busses will be even more significant, also depending on the maintenance level of the old fleets.

Support for the replacement of fleets may be considered in the case of old, not well maintained bus fleets. This is usually associated with additional positive characteristics introduced with the new busses, such as improved bus safety, assistance functions for the disabled, coverage of new city areas by enlarging the fleet, etc. Such activities may be assisted by direct funding to cities with intense pollution problems.

6.2 Improved Maintenance

Bus fleets usually follow a maintenance schedule prescribed by the bus manufacturer and is part of the contract between the operator and the manufacturer. This is generally followed by the fleet operators in order for any warranty to apply. Presumably, maintenance frequency and practices, at least with regard to the emission performance of vehicles, degrade as the fleet grows older. This may be even more true for taxis and refuse trucks. Emissions from diesel vehicles with no aftertreatment systems should be expected to significantly deteriorate only with respect to PM. Combustion inefficiency which is the main reason for high PM emissions, reduces NO_x. The main diesel malfunctions usually involve faulty injectors and pump components and may increase PM from a few percentage units up to an order of magnitude higher than the corresponding emission standard. Pumps and injectors are the most expensive parts of the diesel engine and the mean repair cost should be estimated in the range of 1000 € for busses and 90-500 € for smaller vehicles.

Badly maintained busses may be ideally identified by an independent inspection. In this respect, an annual inspection and maintenance scheme is already in place in the European legislation. However, this only looks at smoke emissions (opacity) and does not differentiate between different diesel technologies. Smoke and PM on the other hand are only roughly correlated, especially as technology improves and engines become smokeless. There will soon be the necessity to modify the inspection and maintenance procedure, including a better PM emission characterisation. However, this is a wider need, not just focussed to captive fleets and will be even of higher priority with the introduction of On-Board Diagnostics (OBD) in Euro IV/V heavy duty vehicles (COM(2003) 522). The current legislation still seems effective in identifying ultra emitters, only with regard to old and smoky busses or taxis.

6.3 Retrofitting

There are four emission control systems which are offered for retrofitting today: diesel oxidation catalysts (DOCs), diesel particle filters (DPFs), selective catalytic reduction (SCR) systems, and exhaust gas recirculation (EGR). DOCs and DPFs mainly focus on PM emissions, while SCR and EGR mainly reduce NO_x. Recently, combinations of some of the systems have started to appear for retrofitting (e.g. DPF+SCR, DPF+EGR), depending on their commercial application in order to address both PM and NO_x emissions. Since they also reduce HC and CO, these systems are some times called "four-way catalyst systems".

DOCs are easy to fit and may reduce PM up to max 50%, for vehicles with high volatile content of PM. They do not significantly reduce the solid (soot) part of PM though, hence their effectiveness reduces as the solid fraction of exhaust PM increases. They also tend to increase the NO_2 / NO ratio thus increasing the toxicity of exhaust. These may cost in the range of 300-500 € for a light duty vehicle up to 1500 € for busses. There are today large DOC retrofitted fleets in the world, hence this is considered as a mature and established technology. Fitting an oxidation catalyst is neither expected to hamper vehicle reliability nor to increase maintenance costs.

DPFs are very efficient systems in removing all (99%) of the solid part of PM emissions. CRT configurations are also very effective (up to 80-90%) in reducing CO and THC, and in particular the volatile part of PM, carbonyls, PAHs and nitro-PAHs depending on the duty cycle. NO_x emissions are not particularly modified but NO_2/NO ratios again increase. DPFs assisted by a fuel borne additive are more effective in PM than other gaseous pollutants. Commercial applications of CRTs come at a cost of 4.5-9.5 k€. They are also associated with a 0.02-0.05 €/bus-km higher cost due to the somewhat higher fuel consumption and the need to clean the filter from ashes twice per year. Several thousand retrofits of on-road and off-road vehicles have been conducted today in Europe, US and Japan. However, despite there are already several commercial systems for application, DPF retrofit is not as simple as DOCs. The main reasons are that CRTs require relatively high exhaust temperatures (i.e. duty cycles not compatible with refuse trucks for example) and NO/PM ratios that are mostly found in post Euro II vehicles rather than pre-Euro I ones. This does not make them applicable to all vehicles and a careful selection of target fleets is required. Additionally, there is a ~2-3% possibility of a complete failure of an installed system. DPF systems with fuel borne additive have just started to appear as demonstration for retrofitting of busses in France. These may be also used in older busses but they require some infrastructure for filling in additive in the fuel. Some new DPF systems for retrofitting of cars have started to appear in Germany and England.

SCRs use urea to reduce NO_x emissions to nitrogen and water and reduction rates may reach 80-90%. This means that a separate tank for urea is required which is consumed at a 1-4% rate of the fuel consumption and leads to an additional cost of 0.005-0.01 €/km. Three of the four commercial systems for retrofitting are combined with CRT systems for reducing PM and NO_x at the same time. The cost of such a system is in the range 20-25 k€. However, this cannot be considered a mature technology today, at least to a level where experience on large fleet applications has been collected. This is because most of these SCR/SCRT systems have been commercialised in 2004 and any experience has been collected either from pilot studies or research projects. This is actually an active field for demonstration studies and for system development, which is expected for Euro V/VI busses.

Finally, EGR (+CRT) may be used for NO_x (and PM) reductions. This is a relatively new option offered for retrofitting and it may bring reductions up to 50% for NO_x and similar to CRT for PM, at a cost of ~14 k€. However, demonstration applications have only started to appear and there is no experience accumulated on the actual performance, the range of applications and the limitations associated with their use.

Summarising, retrofitting (mainly DPF) may be very effective for captive fleets which consist of relatively new busses (e.g. post Euro II) and may bring up to 90% reductions of PM and non-regulated toxic components, which are of primary concern today. DOCs are effective in reducing the organic PM fraction but do not address the solid PM part, they may increase NO_2 and there is no consensus on their effect on non-regulated pollutants. The efficiency and practical issues associated with new systems that have started to appear for NO_x or simultaneous NO_x and PM control, need to be further evaluated in demonstration studies.

Experience from the US, Japan and Switzerland shows that the promotion of retrofit systems application has been supported with the publication of lists of certified retrofit systems by the national authorities. These are accompanied with efficiency standards and targets and the specification of engine series compatible with particular retrofit systems. Funding is also offered for demonstration activities, mainly for DPF systems in the past and NO_x-control systems at present. Subsidies are offered for the retrofitting of urban busses, school buses, taxis and so on. These may reach up to 75% of the retrofit cost and can be combined with tax exemptions, non restrictions to environmentally controlled zones, etc. Clearly, this is an area where centrally organised and monitored education of bus operators, formulation of a technical specifications list, and technical and financial support will be required for the initiation of large scale retrofit programmes.

6.4 Emulsions

Emulsified fuels have been shown to reduce smoke, PM and NO_x at the same time. The extent of reduction is variable depending on engine type, operation condition and fuel. Old technology engines seem to be associated with larger emission reductions (up to 80% smoke, 40% PM and 30% NO_x). It is not known what the effect of emulsions would be on contemporary engines operating on optimized EGR, but much lower benefits than for older engines are expected. Also, issues regarding emulsion stability need to be addressed, while engine performance decreases proportionally to the reduction of fuel energy content. The Texas Department of Transportation study "revealed that PuriNOx is a relatively high cost to reduce NO_x emissions" according to a cost-effectiveness analysis (Prozzi et al. 2004) and did not recommend it for use in Texas captive fleets. The highest cost element was the engine start-up at least twice weekly, required to avoid water/fuel separation. However, they do stress the fact that for fleets where buses operate more frequently, the cost-effectiveness could be much improved.

6.5 Alternative Fuels

This involves two main light hydrocarbon fuels: Liquefied Petroleum Gas (LPG) and Natural Gas (NG).

LPG is widely known especially for passenger cars. Several car manufacturers offer cars and light trucks already operating on either gasoline or LPG (http://www.lpga.co.uk/Contents_f.htm). It is easier to convert a gasoline than a diesel car to LPG, because LPG requires a spark plug for its combustion. A typical petrol to LPG conversion costs 800-1500 € for a passenger car (taxi) with fuel injection and there is an option of the vehicle operating on either of the two fuels (bi-fuel). The LPG cost per litre of fuel is today at 50-60% of the cost of petrol in most European countries. However, LPG cars have a 20-25% higher fuel consumption than petrol, because of the lower energy content. The net cost per km is though lower for LPG (actual benefit depends on retail fuel prices) and therefore it is suited for taxis and other captive fleets with high annual mileage. Air quality related emissions from LPG vehicles are also similar to gasoline ones and require similar technology for compliance with the latest emission standards. Finally, there is some additional weight and a smaller boot for bi-fuel vehicles due to the LPG tank (but they achieve a longer range than gasoline ones) or similar weight but a shorter range for single LPG ones. WTW GHG emissions of LPG are similar to diesel and in the order of 15% lower than gasoline. This is both due to the lower CO_2 emissions per kg of fuel consumed (higher H/C ratio over petrol) but also due to the less energy intensive processing in the refinery.

Although LPG is also used for busses in Austria and the Netherlands, its use is associated with relatively high conversion costs (or initial purchase cost) in the order of 10-20% of the diesel bus cost (i.e. 25-40 k€), and it is not really widespread in other countries. Due to the much higher (~40%) LPG consumption than diesel, the benefit from the lower LPG retail price is lower than the petrol case. It is also associated with higher maintenance costs, including the maintenance facility modification cost. However, LPG has significant air quality benefits compared to diesel. Conversion of a Euro I bus to LPG may lead to 80% reduction in NO_x and 90% in PM emissions, but exact values depend on the actual application.

NG in its compressed form (CNG) is the most widespread alternative fuel for automotive use in captive fleets, mainly because several cities have a complete NG infrastructure which may be used for vehicle refuelling. However, a special CNG filling station needs to be built, which together with a modified maintenance facility costs 300-600 k€. The incremental cost of a CNG bus over a diesel is in the order of 35-40 k€. Converting a diesel bus to CNG is rather not advisable because in addition to the complete engine change, it requires high pressure tanks and high pressure fuel lines which increase the cost of the transformation. Also, applications of NG to passenger cars exist but are not widely considered because of the significant volume sacrifices required to store NG. There are several technical solutions for CNG busses, including mono-fuel or bi-fuel, lean-burn with oxidation catalysts, or stoichiometric with three-way catalysts which may fulfil different emission standards. Therefore, it is not possible to summarize the emission performance of all such cases. However the lean-burn CNG concept which is the most widespread application for busses has PM emission levels similar to Diesel+DPF and NO_x emissions which are ~50% lower than a Euro III diesel. In that respect, it may already fulfil Euro IV regulations with no advanced aftertreatment but only an oxidation catalyst. With regard to WTW GHG emissions, CNGs are today found 15-20% higher than diesels, mainly because of the higher fuel consumption, the heavier vehicle and high methane emissions. Technology improvements may reduce this difference.

6.6 Biofuels

Manufacturing of liquid and gaseous automotive fuels from biomass constitutes today a very active field of research and development because of the expected significant energy security and GHG benefits. There has been a relative detailed discussion of the different issues involved with the use of biofuels in this background document (§4.4) and the need to support their development and promote their use, which go beyond the aims of this workshop. Summarising the air-quality benefits from the use of biofuels, which can be used in today's captive fleets without major modifications, it can be said that biodiesel may reduce PM emissions due to its oxygen content by up to 50% when used pure, but increases NO_x by up to 20% for the same reason. In most cases, use of pure biodiesel would require some engine modifications to handle the lower energy content and material compatibility with biofuel use. However, typical biodiesel applications involve 5% blend for an average car and up to 30% for a captive fleet and are not considered to bring significant changes to air quality related issues. For CNG busses, biogas may be used which is not considered to change their emission performance.

6.7 Points for Discussion / Consideration

Since the ultimate question of the Workshop is 'which are the priorities for the involvement of the European Commission in the reduction of emissions from captive fleets', the potential answers could include:

1. Funding of pilot studies and demonstration projects in the area of retrofitting and biofuel / alternative fuels use.
2. Support and promotion of studies for the understanding of urban air quality issues (improving and maintaining the link between regional and local scale modelling).
3. Subsidizing the retrofitting, refuelling or replacement of complete fleets, by means of structural funds, the European Investment Bank, State Aids, etc. This needs to be made

following specific criteria, quantifying the urgency for action, the cost-effectiveness of the proposal, etc. Examples from USEPA, Switzerland and Japan may be explored.

4. Development of technical specifications / reduction potentials for retrofit devices which may then be used by fleet operators, authorities, etc. for green public procurement or to achieve specific air quality targets.
5. Develop definitions and publication of examples for particular exemptions of green fleets, e.g. tax exemptions, non restricted access to environmentally controlled zones, use of special lanes, etc.
6. Further development of the legislation in the areas of vehicle (not engine) type approval, maintenance and roadworthiness tests and standardization of emulsion fuels.

The priorities are obviously different for vehicle manufacturers, fuel producers, local authorities, fleet operators or local societies. The workshop should be used as a chance to prioritise these areas, by reaching a consensus between the involved members.

REFERENCES

ADEME, 2004. SOMMAIRE - Le comparatif complet des filières et les perspectives.

ADEPT, 2003. Emulsified fuels in Western Europe: An Overview. Available online at http://www.adeptgroup.net/reports/0308_ARBCECpresentation.pdf.

Ahlvik, P. 2003. Summary of Swedish Experiences on CNG and "Clean" Diesel Buses. 2003 DEER Conference. Available online at http://www.orau.gov/deer/DEER2003/default.htm.

Ahlvik, P., Brandberg, Å, 2001. Well-To Wheel Efficiency for alternative fuels from natural gas or biomass. Swedish National Road Administration, Report 2001: 85, Sweden. Available online at http://www.vv.se/publ_blank/bokhylla/miljo/lista.htm.

Ayala et al., 2002. Diesel and CNG Heavy-duty Transit Bus Emissions over Multiple Driving Schedules: Regulated Pollutants and Project Overview. SAE Technology Paper No. 2002-01-1722.

Ayala et al., 2003. Oxidation Catalyst Effect on CNG Transit Bus Emissions. SAE Technology Paper No. 2003-01-1900.

Biancoto et al., 2004. Retrofit program of a EURO 1 & EURO 2 Urban Bus Fleet in La Rochelle - Status after one year experience. 2004 DEER Conference. Available on-line at http://www.orau.gov/deer/presentations.htm.

CEN, 2004. CEN Workshop Business Plan : "Water in diesel fuel emulsions for use in internal combustion engines". Available online at http://www.cenorm.be/cenorm/businessdomains/technicalcommitteesworkshops/workshops/cen+ws19+emulsion+fuels.asp.

Chatterjee et al., 2001. Emission Reductions and Operational Experiences With Heavy Duty Diesel Fleet Vehicles Retrofitted With Continuously Regenerated Diesel Particulate Filters in Southern California. SAE Technology Paper 2001-01-0512

Chatterjee et al., 2002. Performance and Durability Evaluation of Continuously Regenerating Particulate Filters on Diesel Powered Urban Buses at NY City Transit - Part II. SAE Technology Paper No. 2002-01-0430.

Cohen, J.Y.; Hammitt, J.K.; Levy, J.I. 2003. Fuels for Urban Transit Busses: A Cost-Effectiveness Analysis. Environ. Sci. Technol. 2003, Vol. 37, pp. 1477-1484.

CONCAWE, EUCAR and JRC 2004. Weel-to-Wheels Report. Version 1b January 2004. Available online at http://ies.jrc.cec.eu.int/Download/eh.

COPERT III, 2004. Available online at http://vergina.eng.auth.gr/mech/lat/copert/copert.htm.

Cuvelier, C., 2004. What did we learn from CityDelta? Ispra 14-15/10/2004. Available online at http://rea.ei.jrc.it/netshare/thunis/citydelta/.

DeSantes, J.M., Arregle, J., Ruiz, S., Delage, A., Schmelzle, P., Esmilaire, O., 1999. Characterisation of the injection-combustion process in a common-rail D.I. diesel engine running with fuel-water emulsion. FISITA Technology Paper 99C407.

DG Environment, 2004. Green Public Procurement. Available online at http://europa.eu.int/comm/environment/gpp/studies.htm.

Dieselnet, 2004. Biodiesel. Available online at www.dieselnet.com (subscription required).

Edgar, B., 2003. Development and Deployment of Advanced Emission Controls for the Retrofit Market. 2003 DEER Conference. Available on-line at http://www.orau.gov/deer/DEER2003/presentations.htm.

EST, 2003. The Route to Cleaner Buses. Available online at http://www.transportenergy.org.uk/downloads/CleanBusGuide.pdf.

EPA, 2004. http://www.epa.gov/otaq/retrofit/overview.htm

European Commission, 1998. The inspection of in-use cars in order to attain minimum emissions of pollutants and optimum energy efficiency. Main Report. Directorates General for Environment, Transport and Energy. Available online at http://europa.eu.int/comm/environment/pollutants/inusecars.htm.

Hausberger et al., 2003. Emission factors for heavy-duty vehicles and validation by tunnel measurements. Atmospheric Environment, Vol. 37, pp. 5237-5245

Hendriksen et al., 2003. Summary of the report evaluation of the environmental impact of modern passenger cars on petrol, diesel, automotive LPG and CNG. TNO Report 03.OR.VM.055.1/PHE.

Holmén et al., 2002. Ultrafine PM Emissions from Natural Gas, Oxidation-Catalyst Diesel, and Particle-Trap Diesel Heavy-Duty Transit Buses. Environmental Science and Technology, Vol. 36, pp. 5041-5055.

Hung et al., 2003. Hong Kong Experience in Retrofitting in-use Diesel Vehicles. SAE Technology Paper No. 2003-01-1391.

IFEU, 2004. CO_2 Mitigation through Biofuels in the Transport Sector. Main Report. Heidelberg, Germany. Available online at http://www.biodiesel.org/resources/reportsdatabase/reports/gen/20040801_gen-351.pdf.

Joubert et al., 2004. Review of SCR technologies for Diesel Emission Control :European experience and Worldwide perspectives. 2004 DEER Conference. Available at http://www.orau.gov/deer/presentations.htm.

Lanni, Th. et al., 2001. Performance and Durability Evaluation of Continuously Regenerating Particulate Filters on Diesel Powered Urban Buses at NY City Transit. SAE Technology Paper No. 2001-01-0511.

Le Tavec et al., 2002. Year-Long Evaluation of Trucks and Buses Equipped with Passive Diesel Particulate Filters. SAE Technology Paper 2002-01-0433.

Lowell Dana, 2003. Comparison of Clean Diesel Buses to CNG Buses. Presented at the 2003 DEER Conference. Available online at http://www.orau.gov/deer/DEER2003/presentations.htm.

Lubrizol, 2004. PuriNOx™ Technology Emissions Testing Results. Available on-line at http://www.lubrizol.com/PuriNOx/mktevaluations.asp.

Matthews, R., Hall, M., Anthony, J., Ullman, T., Lewis, D., 2004. The Texas Diesel Fuels Project, Part 2: Comparisons of Fuel Consumption and Emissions for a Fuel/Water Emulsion and Conventional Diesel Fuels. SAE Technology Paper 2004-01-0087.

Mayer et al., 2004. Reliability of DPF-Systems: Experience with 6000 Applications of the Swiss Retrofit Fleet. SAE Technology Paper No. 2004-01-0076.

Mayor of London, 2004. Transport of London Environment Report 2004. Available online at http://www.tfl.gov.uk.

McCormick, R.L., Graboski, M.S., Alleman, T.L.,Alvarez, J., Duleep, K.G., 2003. Quantifying the emission benefits of opacity testing and repair of heavy-duty diesel vehicles. Environmental Science & Technology, Vol. 37,pp. 630-637.

MECA, 2004. Emission Control Retrofit of Existing Diesel Engines. Available online at http://www.meca.org/.

Ministry of Environment of Greece, 2002. 1994-2001 review of the vehicle and external combustion department (in greek). Available online at http://www.minenv.gr/ek_a/g000.html.

Musculus, M.P.B.; Dec, J.E., Tree, D.R., Daly, D., Langer, D., Ryan, T.W., Matheaus, A.C. 2002. Effects of water-fuel emulsions on spray and combustion processes in a heavy-duty DI diesel engine. SAE Technology Paper 2002-01-2892.

Park, K., Lee, W., Kwak, I., Cho, S., Oh, S., Kim, K., 2003. Durability test of a diesel engine using water emulsified fuel. FISITA Technology Paper 12-03D13.

Pelkmans et al., 2002. Evaluation of Emissions and Fuel Consumption of Heavy-Duty Natural gas Vehicles in Real-City Traffic. NGV2002, 8-10 October 2002, Washington, USA. Available online at www.iangv.org/jaytech/files/ ngv2002/Technology/Pelkmans2.pps.

Plassat, G., 2004. Pollutants Emissions - Global warming Potential Effect. First Comparison using External Costs on Urban Buses. 2004 DEER Conference. Available online at http://www.orau.gov/deer/presentations.htm.

Prozzi, J., Machemehl, R., Matthews, R., Baker, R., DeFries, T.H., Lewis, D., 2004. The Texas diesel fuels project, part 3: Cost-effectiveness analyses for an emulsified diesel fuel for highway construction equipment fleets. SAE Technology Paper 2004-01-0086.

Richards et al., 2003. Demonstration of the Benefits of DPF/FBC Systems on London Black Cabs. SAE technology Paper 2003-01-0375.

SAEFL, 2000. Particulate traps for heavy duty vehicles. Environmental documentation No.130, Bern, Switzerland.

Schittler M., 2003. State-of-the-art and emerging truck engine technologies. 2003 DEER Conference. Available online at http://www.orau.gov/deer/DEER2003/presentations.htm.

Simões et al., 2002. Analysis of the environmental impact of urban busses: Application to a case study in Lisbon. Urban Transport 2002 Conference, 13-15 March, Seville.

Tremove, 2004. Tremove model v2.2 – Dec. 2004. Available online at www.tremove.org

TRENDSETTER, 2003a. Biogas as Vehicle Fuel. A European Overview. Report No 2003:3. Stockholm, Sweden. Available online at http://www.trendsetter-europe.org/index.php?ID=1699.

TRENDSETTER, 2003b. Clean Vehicles in Europe. An overview of vehicles, fuels and national strategies. Report No 2003:2. Available online at http://www.trendsetter-europe.org/index.php?ID=1698.

U.S. Department of Energy, 2003. Transit Costs 1.0 Excel Spreadsheet. Available online at http://www.eere.energy.gov/afdc/apps/toolkit/transit_bus_toolkit.html.

UITP, 2004. Clean fuels for road public transport. International Association of Public Transport, Brussels, Belgium.

Vouitsis, E., Ntziachristos, L., Samaras, Z., 2003. Particulate matter mass measurements for low emitting diesel powered vehicles: what's next?. Progress in Energy and Combustion Science, Vol. 29, pp. 635–672.

Wayne et al., 2003. Reduction of Pm Emissions From Refuse Trucks Through Retrofit of Diesel Particulate Filters, SAE Technology Paper 2003-01-1887.