Best Available Techniques for Mobile Sources

in support of a

Guidance Document to the

Gothenburg Protocol of the

LRTAP Convention

DRAFT

Guidance document on control techniques for mobile sources

Authors:

Leonidas Ntziachristos, Giorgos Mellios, Giannis Papadimitriou (EMISIA)

Jens Borken-Kleefeld (IIASA)

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International Institute for Applied Systems Analysis
IIASA www.iiasa.ac.at

emisia
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Contracting institution

European Commission -
Directorate General Environment
DG ENV.SRD.2,
B-1049 Brussels/Belgium

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Contractor

International Institute for Applied Systems Analysis (IIASA)
Dr. Markus Amann
Schlossplatz 1,
A-2361 Laxenburg/ Austria
Phone: +43 2236 807 432
e-mail: amann@iiasa.ac.at

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List of abbreviations and acronyms

[To be added]

I. Introduction

1. The aim of this document is to provide the Parties to the Convention on Long-Range Transboundary Air Pollution with guidance on identifying best abatement options for mobile sources to enable them to meet the obligations of the Protocol to abate Acidification, Eutrophication, and Ground Level Ozone. Measures addressing particulate matter emissions, including black carbon, are also included.

2. Emphasis is primarily given to technologies that can be implemented on board the vehicles to reduce the emission rates over regular operation of the vehicles ("technical measures"). Other measures falling under the general title of "non-technical measures" are also discussed. These include changes to fuel or fuel specifications, behavioral, operational and infrastructural changes with the potential to reduce emissions. Both technical and non-technical measures are candidates for "best available technology" (BAT).

3. This document identifies several techniques as potential BAT for reducing a specific pollutant. A number of criteria have been taken into account in defining BAT. First, the proposed techniques must have proven their emission reductions in wide scale real-world applications. Experimental or emerging techniques are hence addressed separately. Second, the extra costs for the techniques identified need to be in proportion to the emission reductions. This accounts for the economic viability of the technique(s). In addition, boundary conditions and limiting factors for the implementation of each technique are considered, as well as potential synergies and trade-offs.

4. Mobile sources are comprised of diverse machines that are operated under very variable conditions. Consequently, the resulting emission levels differ greatly between the different machine categories. Latest technologies already offer orders of magnitude of emission reductions compared to older ones. Therefore, this document makes a distinction between BAT applicable for latest and for older vehicle technologies; this allows for national difference between the Parties to the Convention.

5. BAT Associated Emission Levels (AELs) are provided relative to a specific and quantified reference technology for each mobile source category. The criteria for selecting the particular reference technology level included (a) popularity and (b) known environmental impacts. The reference technology does not coincide with the latest technology available in the period of preparing this guidance document (2014).

6. Many different sources have been analyzed in evaluating techniques as BAT candidates, including agency and industrial reports, scientific papers, research reports, as well as direct questionnaire input from industry associations and experts. The results in this document should be considered guidance of what is favorable emission control technology in general. This document is not an exhaustive list of all possible techniques. Under specific local conditions, other technologies might be judged equally good BAT candidates. Therefore, we state for each BAT candidate technology a number of limiting conditions.

Additional limiting factors of technical, financial or infrastructural nature may exist in particular cases.

II. Coverage

7. This guidance document addresses emissions of those pollutants considered in the Gothenburg Protocol, primarily nitrogen oxides (NO_x), volatile organic compounds (VOCs), and particulate matter (PM). Exact definitions for these pollutants are given in the main text of the Protocol. Mobile sources are considered key categories in the emissions of all these pollutants.

8. PM is generally differentiated by its size; PM_{10}, $PM_{2.5}$ and PM_1 are the designated size fractions of particles with aerodynamic diameter of up to 10, 2.5, and 1 micrometers, respectively. Exhaust emissions from mobile sources are primarily within the PM_1 fraction. A large fraction of PM from mobile sources consists of black carbon (BC). Therefore, the techniques considered for PM reduction practically also address BC emissions.

9. Other pollutants considered in the Gothenburg Protocol include sulfur oxides (SO_x), ammonia (NH_3), and further ozone precursors as carbon monoxide (CO). These pollutants are only addressed in this guidance document when deemed relevant. Further reducing CO emissions is in general considered of low priority because of its low ambient levels. Ammonia emissions are relevant from some vehicle technologies only and, hence, addressed there. Finally, SO_x has been satisfactorily addressed with the availability of low sulfur fuels in all inland transport sectors.

10. The majority of vehicles and vessels operate on diesel and gasoline fuels. Because of the different combustion processes and emission profile of gasoline and diesel, this guidance document suggests separate BAT candidates per fuel. In addition, the potential emission reductions from reformulated fuels, as well as alternative fuels, are also discussed. Table 1 summarizes the main categories of vehicles/vessels covered in this document.

Table 1: Categories of mobile sources considered for BAT emission control techniques

Road vehicles	Spark-ignition engines • Powered-two wheelers (mopeds, motorcycles) • Light duty vehicles (passenger cars and light commercial vehicles) Compression ignition engines • Light duty vehicles (passenger cars and light commercial vehicles) • Heavy duty vehicles (trucks, buses)
Non-road mobile machinery	Spark-ignition engines • Handheld and non-handheld equipment (household, gardening, agricultural and forestry machinery) • Snow mobiles • All-terrain vehicles Compression ignition engines • Industrial, construction, agricultural and forestry machinery
Rail	Compression ignition engines (railcars, locomotives)
Vessels	Spark-ignition engines (boats, recreational crafts) Compression ignition engines

III. Emission processes and contributions

11. Mobile machines emit air pollutants primarily as the product of the combustion of fuels in their engines. Engine measures related to combustion efficiency and control of fuel properties can lead to the reduction of these emissions.

12. Further reductions of emissions can be achieved by the use of after-treatment devices in the exhaust line. After-treatment devices have been historically used with great success and continue to be fundamental pillars of emission control systems. However, catalytic processes in after-treatment devices may themselves also produce secondary pollutants. These are exhaust emissions which are not directly linked to the combustion process.

13. Other processes may also be contributing to pollutant emissions from mobile sources. PM produced from component wear (tyres, brakes) from road vehicles and gasoline fuel evaporation from the tank of road vehicles are the most common sources of so called non-exhaust emissions. These contribute to the total emission budget of transport and are also addressed in this guidance document.

14. When the engine and the control system are warmed up, then hot emission levels are reached. Before this, cold-start emissions can be orders of magnitude higher than hot emission levels. With age emission levels usually increase as the effectiveness of emission control degrades with time. Finally, malfunctions which can be due to misuse, fatigue, or stochastic faults may also degrade emission levels. This guidance document tries to refer to emission levels which are affected by all these conditions and assess BAT that can have an impact on any of these processes.

15. Mobile sources contribute about 40% to 60% of NO_x emissions from all sources in the different UNECE regions in the year 2010. The biggest single sources are diesel powered cars and trucks, followed by agricultural tractors. Diesel powered rail traction can be a significant source in some countries, as well as ships. Transmission stations in long pipeline networks may also be a significant source. Mobile sources contribute about 10% to 30% of all $PM_{2.5}$ emissions in the different UNECE regions in the year 2010. The biggest single sources are again diesel powered cars and trucks, followed by agricultural tractors and construction machinery. In individual countries rail, ships and pipeline transmission stations can also be significant sources. Mobile sources contribute about 20% of all VOC emissions in the different UNECE regions in the year 2010. The biggest single sources are gasoline powered cars, mopeds and motorcycles, followed by smaller machinery, and agriculture machines, and in some countries aircrafts and pleasure crafts. Land based mobile sources contribute less than 1% to total SO_2 emissions and 1% to 4% of total NH_3 emissions in the different UNECE regions in the year 2010.

16. Due to their importance, most attention is given to control technologies for NO_x and PM emissions from mobile sources, and road vehicles in particular. In addition, controls of VOC emissions are treated with some detail in this document.

IV. Assessment of Best Available Technology (BAT)

17. The definition of Best Available Technology (BAT) for emission control from mobile sources is modeled according to the respective definition for stationary sources. BAT is defined as “the most effective and advanced stage to prevent and to reduce emissions and the impact on the environment as a whole”.

18. The term ‘available’ refers to technical and economic conditions; the technique in question needs to be “developed to a scale that allows implementation in the relevant … sector, under economically and technically viable conditions…” Whether a technique is economically viable for the operator or customer is hard to judge a priori. The term ‘best’ means most effective in achieving a high general level of protection of the environment as a whole.

19. The BAT definition is not differentiated by operating environment (e.g. normal and sensitive conditions) or by territory (or country), although the technique actually chosen as BAT in a specific country may well depend on its economic, environmental and technological circumstances, and probably additional social, legal and administrative aspects that are far beyond the technical scope considered here.

20. Technologies for both, existing as well as new vehicles are assessed. A reference technology is defined for each source category; this reference is usually not the latest emission control technology, but good common practice.

21. The assessment of a technique as BAT is based on a two-step approach. First, the various options are rank ordered in a qualitative way according to emission reduction potential on the one hand, and extra lifetime costs on the other hand, each relative to reference technology.

22. Those technologies with best appearance on emission reduction potential versus extra costs are checked for further compliance or exclusion with respect to the possible limiting factors. These include emissions of other pollutants, energy efficiency or consumption, requirements in terms of space, operability or infrastructure, etc. Possible solutions to limitations of a wide implementation of the techniques are identified where appropriate for these BAT candidates.

23. BAT may mean several and not a single technique, and this in turn depends on vehicle and pollutant. Different techniques may be comparable in terms of their environmental effects and their economical dimension. In such cases, various techniques can be qualified as BAT. Then, parties to the Protocol will have a wider choice to select and adapt the most suitable technique according to their specific needs and circumstances.

V. Technologies for emission control from mobile sources

A. Road vehicles [to be added later]

i. Spark-ignition engines [to be added later]

Powered-two wheelers [to be added later]

Light duty vehicles [to be added later]

Alternative fuels [to be added later]

Fuel evaporation [to be added later]

ii. Compression ignition engines

24. In a compression ignition engine, fuel is self-ignited after pressure and temperature inside the combustion chamber exceed a certain limit. Fossil diesel is the main fuel combusted in these engines. The compression ignition (diesel) engine is the main technology for heavy duty and non-road machinery. In the past decade, smaller compression ignition engines have also become widely used in cars in Europe, replacing spark-ignition engines.

Pollutant emission controls for compression ignition engines focus on NO_x and PM emissions, including black carbon and PN (particle number emissions).

NO_x control

25. The main NO_x-abatement options (engine measures and after-treatment control) for diesel road vehicles are:

- *Exhaust Gas Recirculation (EGR)*

Short description	EGR redirects a portion of engine exhaust back into the engine to cool and reduce peak combustion temperatures and pressures. In most systems, an intercooler lowers the temperature of the re-circulated gases, which then have higher heat capacity and contain less oxygen than air; hence, combustion temperature in the engine is lowered, thus inhibiting NO_x formation.
Environmental side effects and synergies	EGR may slightly reduce engine power and result in PM recirculation if not combined with a particle filter (DPF).
Limitations in applicability, implementation and other issues	- Ultra low sulfur diesel (<50ppm) and electronic control strategy are required to ensure efficient operation. - Exhaust cooling may result in engine wear due to excess water vapor. - Limited use as retrofit (major engine integration required).

- *Selective Catalytic Reduction (SCR)*

Short description	- SCR uses ammonia as selective reducing agent, in the presence of excess oxygen, to convert NO and NO_2 to elemental nitrogen and water (two natural components of the air) over a special catalyst system. Different precursors of ammonia can be used and one of the most common options is a solution of urea in water carefully metered from a separate tank and sprayed into the exhaust system ahead of the SCR catalyst. The consumption of urea depends on the amount of NO_x that needs to be converted and on driving, load, and road conditions (an indicative range is approximately 3-6% compared to the fuel consumption). - SCR is ideal for OEM applications, but retrofit systems are also available and effective.
Environmental side effects and synergies	- Additional reduction of VOC, CO, PM. - 3-5% possible fuel consumption and CO_2 benefits (OEM applications). - Reduction of smoke and characteristic odor produced by a diesel engine. - Risk for ammonia slip.
Limitations in applicability, implementation and other issues	- Periodic refilling with urea is required (on-board dosing unit) and infrastructure to make urea additive easily available must be expanded. - The catalytic reaction requires certain temperature criteria for NO_x reduction to occur; data logging must be performed to determine if the exhaust gas temperatures meet the specific SCR system requirements. - Low efficiency may be observed in low-load city driving (low exhaust gas temperatures). - SCR units are usually large, heavy, complex, and bulky systems, and, therefore, may not be suitable e.g. for small diesel cars (<1.4l). - Application of SCR may not be appropriate for all vehicles; care must be taken to design a system for the specific vehicle involved.

- *Lean-NO_x Trap (LNT)*

Short description	- LNT functions by trapping NO_x in the form of a metal nitrate during lean operation of the engine. The most common compound used to capture NO_x is barium hydroxide or barium carbonate. Under lean air to fuel operation, NO_x reacts to form NO_2 over a platinum catalyst followed by reaction with the barium compound to form $BaNO_3$. Following a certain amount of lean operation, the trapping function will become saturated and must be regenerated. This is commonly done by operating the engine in a fuel rich mode for a brief period of time (one or two seconds is enough) to facilitate the conversion of the barium compound back to a hydrated or carbonated form and giving up NO_x in the form of N_2 or NH_3. - LNT is especially of interest in applications with limited space or in which urea usage for SCR is difficult. Hence, more appropriate for new passenger cars and light commercial vehicles. For heavy duty vehicles, it does not seem to be a preferable option (SCR dominates in these vehicles). Retrofit is possible, but may have some technical difficulties.
Environmental side effects and synergies	- Fuel economy penalty (1-2%) because of required brief periods of rich operation to regenerate. - NH_3 is generated during the rich regeneration phase (give up trapped NO_x).
Limitations in applicability, implementation and other issues	- Ultra low sulfur diesel (<10ppm) required because LNT also adsorbs SO_x resulting from the fuel sulfur content. - Periodic 'desulfation' cycle required to remove any adsorbed sulfur compounds (regeneration at high temperatures ~700^oC, 15-20 minutes required to be completed).

<u>PM control</u>

26. The main after-treatment options to reduce PM from diesel road vehicles are:

- *Diesel Oxidation Catalyst (DOC)*

Short description	- DOC converts CO and HC to CO_2 and water; it also decreases the mass of diesel particulate emissions (but not their number) by oxidizing some of the hydrocarbons that are adsorbed onto the carbon particles. The level of PM reduction is influenced in part by the percentage of Soluble Organic Fraction (SOF) in the particulate. - DOC remains a key technology for diesel engines where the high oxygen content of the exhaust precludes the use of TWC. It is ideal both for OEM and retrofit applications, having little or no maintenance requirements and easy installation.
Environmental side effects and synergies	- Additional reduction of VOC, CO (no positive effect on NO_x). - Concerns that it may increase the NO_2 fraction of total NO_x emissions. - No significant impact on fuel consumption.
Limitations in applicability, implementation and other issues	Ultra low sulfur diesel (<50ppm) required.

- *Diesel Particle Filter (DPF)*

Short description	- DPF removes PM in diesel exhaust by filtering exhaust from the engine. Particulate-laden exhaust enters the filter from one side, passes through the porous walls of filter cells, where PM is deposited, and cleaned exhaust gas exits from the other side. Since a filter can fill up over time, a means of burning off or removing accumulated PM is necessary, e.g. burn or oxidize it on the filter when exhaust temperatures are adequate. By burning off trapped material, the filter is cleaned or 'regenerated'. - DPF is ideal for OEM applications, but retrofit systems are also available and effective.
Environmental side effects and synergies	- Additional reduction of VOC, CO, BC (no positive effect on NO_x). - NO_2 formation, in particular for catalyzed DPFs. - Fuel economy penalty (1-2%).
Limitations in applicability, implementation and other issues	- Ultra low sulfur diesel (<50ppm) required. - Regeneration and cleaning system needed (periodic maintenance to clean out non-combustible materials). - High temperatures required for regeneration (exhaust gas temperature data logging).

<u>Crankcase emissions control (VOCs)</u>

27. The main option (engine measure) to reduce crankcase emissions from diesel heavy duty road vehicles is:

- *Closed Crankcase Ventilation (CCV)*

Short description	- Crankcase emissions are not typically a significant source of direct UFPs, but they can contribute to the formation of secondary aerosols when oxidized in the atmosphere. Therefore, diesel UFP control strategies should consider both the tailpipe and crankcase emissions, especially from older vehicles (e.g. pre-Euro V). - Crankcase emissions are released directly from the engine into the atmosphere through a vent or the 'road draft tube'. CCV systems capture the oil in blow-by gas, return it to the crankcase, then redirect these gaseous emissions back to the intake system for combustion instead of emitting them into the air. A multi-stage filter is used which is designed to collect, coalesce, and return the emitted lube oil to the engine's sump. - Retrofit is possible. Can be paired with a DOC or DPF for further emission reduction.
Environmental side effects and synergies	- Reduction of VOC (and PM) from crankcase emissions. - CCV systems eliminate odor and toxins from vehicle interior and reduce engine oil consumption.
Limitations in applicability, implementation and other issues	- No specific limitations in applicability, easy to implement. - Periodic replacement of incorporated filter elements.

Alternative fuels

28. The fuels that can be considered as main alternatives to diesel for road vehicles and with possible emission reductions are:

- *Natural gas (NG), either in compressed (CNG) or liquid (LNG) form*

Short description	Natural gas consists mainly of methane (CH_4). It can be used in OEM applications, as a retrofit, and in dual fuel engines (bi-fuel vehicles). LNG differs from CNG only to the way that the fuels are stored on board the vehicle. The combustion of the two forms of natural gas is identical; this results to identical emission profiles. Smaller volume for storage of LNG (vs. CNG) makes it a better choice for long distance transportation.
Environmental benefit, side effects and synergies	Environment benefit of natural gas is different e.g. for OEM/retrofit applications, light/heavy duty vehicles, etc. Some general points: - Significant reduction of PM (and BC) can be achieved in any case; the benefit is even higher comparing NG to an old diesel engine without after-treatment control. - OEM applications can also reduce NO_x, CO, NMVOC; however, retrofit may lead to uncontrollably high NO_x emissions in some cases. - Volumetric energy content of natural gas (especially CNG) is ~4-5 times lower than diesel, hence requiring appropriate filling infrastructure. - Less CO_2 emissions compared to a similar diesel powered vehicle (due to lower carbon content). - NG may not be so effective in PN and increases CH_4 emissions.
Limitations in applicability, implementation and other issues	- Availability of fuel. - Significant changes to fueling infrastructure and maintenance facilities may be required. - Gas tank limits storage space and increases vehicle weight (problem more intense especially in smaller vehicles). - Driving range may decrease (better for urban applications). - Limited experience in retrofitting and in long term truck performance.

- *Dimethyl Ether (DME)*

Short description	DME is a NG liquid derivative. It can be produced from NG, biomass or coal. It offers much higher volumetric energy content than NG; hence, easier handling for refueling and storage on board the vehicle. Its general use is difficult, it may be more appropriate for dedicated fleets (heavy duty trucks, buses), where fuel distribution is easier. Retrofit is possible.
Environmental benefit, side effects and synergies	- PM (and BC): DME combustion results to soot levels that can meet Euro VI limits without the need of a DPF. - NO_x benefits can be achieved compared to an old diesel engine. - Higher fuel consumption due to lower energy density per unit volume. - Possible higher formaldehyde (CH_2O) emissions than diesel.
Limitations in applicability, implementation and other issues	- Limited experience in DME-fuelled vehicles. May be more appropriate for use in fuel cells. - Availability of fuel (distribution network is limited). - Its low viscosity is responsible for leakage problems from the fuel supply system and for poor lubricity.

- *Biodiesel*

Short description	A mix of fatty-acid methylesters produced by the transesterification of vegetable oils (1st generation biofuel). Used as blend with conventional diesel. 2nd generation biofuels currently under research, produced from non food-competitive biomass, utilizing advanced sustainability production techniques. Retrofit is possible.
Environmental benefit, side effects and synergies	- Only small reduction of PM, BC, VOC, CO can be achieved. - NO_x and fuel consumption may slightly increase (2-3%), proportionally to the blend considered. - Possible increase of aldehyde emissions and polyaromatic components.
Limitations in applicability, implementation and other issues	- Availability of fuel. - Current regulations in Europe limit blends to B7 and only gradually move towards higher blending ratios. Higher blends are allowed in controlled captive fleets where maintenance intervals and practices, as well as engine materials, can be adjusted to the fuel properties. - More often maintenance is necessary, incompatibility with some older engines, reduced fuel economy.

- *Renewable diesel*

Short description	Produced a) by hydrotreating (and not esterification) of vegetable oil (HVO), b) thermal conversion process (TCP), c) biomass to liquid (BTL). Neat renewable diesel has several advantages over fuels produced with the transesterification process, such as reduced waste and by-products, higher energy density and better cold flow properties. It can also be used as an additive to increase cetane number. Retrofit is possible.
Environmental benefit, side effects and synergies	- Some NO_x, PM, BC, VOC, CO reductions can be achieved (e.g. comparing neat HVO to an old heavy duty diesel engine). The benefits are lower when used as an additive. - Free of aromatics, low aldehyde, mutagenic emissions, engine smoke. - Additional CO_2 benefits.
Limitations in applicability, implementation and other issues	- Availability of fuel. - Additives may be needed to address the lubricity issues. - Adjustments in the electronic control of the engine may be required. - Existing farm-based feedstocks compete with food production.

- *Emulsified diesel*

Short description	A blended mixture of diesel fuel, water, and other additives that lowers combustion temperatures. The additives also prevent water from contacting the engine. It can be used in any new or existing diesel engine.
Environmental benefit, side effects and synergies	Noticeable PM reduction can be achieved with some additional (lower) NO_x benefits.
Limitations in applicability, implementation and other issues	- Availability of fuel. - Decrease in power and fuel economy, due to the fact that addition of water reduces fuel energy content; this leads to significant increase of fuel cost in the long run. - Over time the water can settle out of the emulsified fuel and may cause performance problems.

Assessment of NO_x reduction technologies in heavy duty diesel road vehicles (trucks, buses)

29. The reference technology is a turbocharged compression ignition engine with high pressure fuel injection. This is a typical base diesel engine without after-treatment control. This technology may still be met often around the world and is the prominent technology for heavy duty vehicles in least developed countries. Such engines emit typically in the order of 4-16 g/km NO_x with variation due to the size and age of the vehicle, the speed and driving conditions, exact technology configuration, fuel sulfur content, etc.

30. The expected emission reductions and additional costs are assessed for the various NO_x control technologies relative to the reference technology (Table 2). The emission reduction ranges should be seen for each measure individually and not cumulatively if several measures are implemented at the same time. The expected additional costs for emission controls are an order of magnitude estimate per vehicle (in Euro). They include usually installation (e.g. retrofitting SCR), additional fuel and maintenance costs, possible fuel savings, etc. Costs are expressed on a per vehicle basis, assuming widespread application. Unit costs depend on the scale of implementation of the technology and can fluctuate upwards or downwards.

Table 2: Summary of emission reduction potential and additional costs of techniques for NO_x control in heavy duty diesel road vehicles (trucks, buses)

Technology	Expected emission reduction		Cost per vehicle (Euro)
	NO_x	Other	
Reference technology: Turbocharged CI engine with high pressure fuel injection	4-16 g/km	PM (0.15-0.5 g/km)	Reference technology
Engine measures			
Exhaust Gas Recirculation (EGR)	25-45%	-	1,400-1,800 (indicative manufacturer cost)
After-treatment			
Selective Catalytic Reduction (SCR)	70-95%	PM (20-40%) VOC, CO (50-90%)	7,500 installation + 500 for urea + 200 for maintenance - 800 possible fuel savings (OEM) p.a.
Alternative fuels			
Natural Gas (NG)	20-50%	PM, BC (85-95%) NMVOC (75-85%) CO (70-95%)	12,000-15,000 for conversion to NG - 500-1,000 fuel cost benefits p.a.
Dimethyl Ether (DME)	40-60%	PM, BC (85-95%)	Depends on source of production
Emulsified diesel	10-20%	PM (50-60%)	1,200-1,600 p.a.
Renewable diesel	5-10%	PM, BC (15-25%) VOC (20-40%) CO (15-30%)	Usually offered at lower price than conventional diesel

31. The technologies discussed above (Table 2) are organized according to the two key criteria, the expected emission reduction and the additional costs (Figure 1). Then, technologies are discussed for potential limitations, side-effects and synergies, starting with the ones ranked as most probable BAT candidate. Thus the remaining criteria (side effects, limitations in applicability, implementation and other issues) are reviewed to identify potential bottlenecks in applicability of each technique.

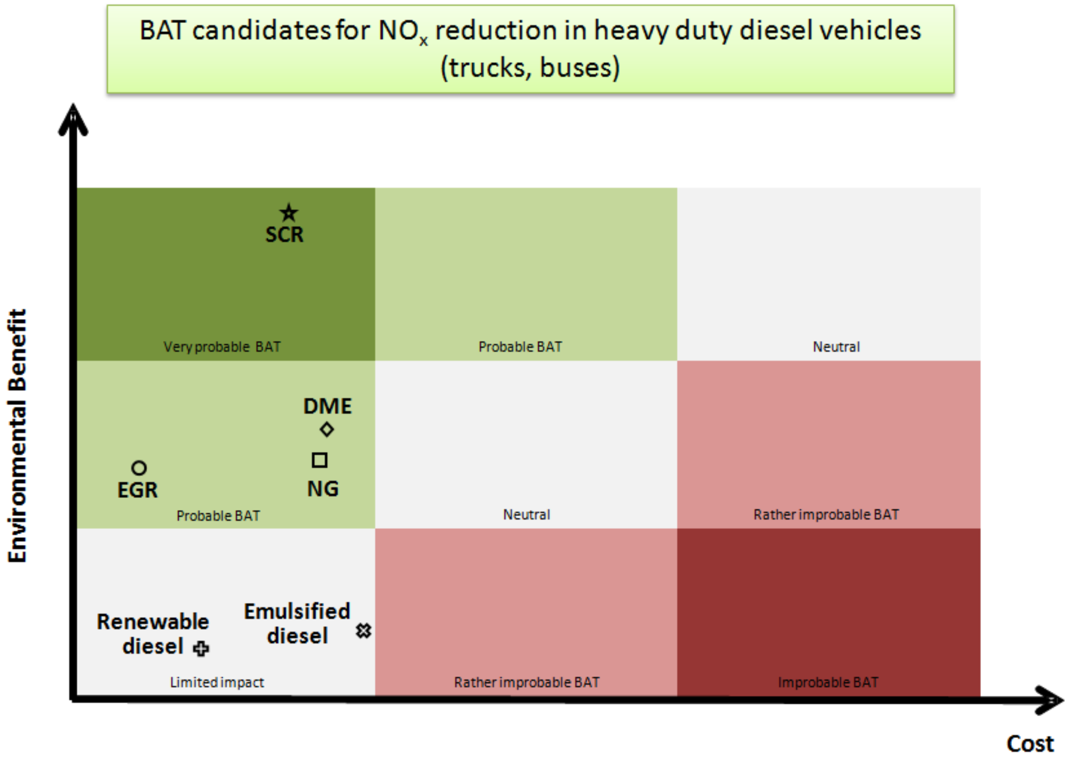

Figure 1: Cost-benefit classification of BAT candidates for NO_x reduction in heavy duty diesel road vehicles (trucks, buses)

32. The placement of the techniques on the evaluation grid is indicative and relative and should not be used for extracting quantitative conclusions. For the cost calculations, an indicative period of 10 years of operation is considered in order to make a fair comparison between options, e.g. conversion to natural gas usually has a high initial investment cost, but a significant part of it may be paid back after 10 years of use by fuel cost savings because of lower fuel price. Although such an approach may have some uncertainties in assessment, it is sufficient for the purpose of this relative cost-benefit evaluation. For example, considering a period of 8 or 12 years (instead of 10) could slightly change the position of some techniques on the grid; however, it would not substantially change the categorization of each technique as 'very probable BAT', 'probable BAT', 'neutral', etc.

33. The conclusions of BAT evaluation and proposals for NO_x reduction in heavy duty diesel road vehicles are summarized below.

34. *SCR:* Selective Catalytic Reduction is the most cost-effective option to reduce NO_x from diesel HDVs (trucks, buses), achieving high % reduction (70-95%) at reasonable cost. It also reduces PM, VOC, CO. It is ideal for original equipment manufacturer (OEM) applications, providing possible fuel consumption benefits, but retrofit systems are also available and effective. Urea additive has to be made widely available, since periodic refilling is required (on-board dosing unit); careful urea injection strategy is necessary to avoid "ammonia slip". In addition, the catalyst requires a minimal operating temperature that may

not be encountered in low-load city driving conditions. Thus either care needs to be given to adjust the control strategy in such cases to the driving pattern, or some extra heating might be necessary. In summary, SCR with urea dosing can be considered BAT with some limitations that need to be taken into account (urea infrastructural needs, lower efficiency in low-load city driving where exhaust gas temperatures are low).

35. *EGR:* Exhaust Gas Recirculation generally exhibits NO_x reduction efficiency of 25-45% which is modest compared to SCR, but it has low installation cost. It slightly reduces engine power, while other technical limitations are: low sulfur fuel (<50ppm) required, major engine integration when retrofitted, and exhaust cooling may result in engine wear due to excess water vapor. EGR (preferably low-pressure) can be considered as BAT when combined with a DPF to ensure that large amounts of particulate matter are not re-circulated to the engine (use of EGR as a standalone retrofit technology for NO_x reduction is limited). Hence it will be discussed in particular when PM control is in the focus and only limited NO_x reductions required.

36. *NG:* Conversion of captive fleets to natural gas can lead to NO_x reduction 20-50% (at higher cost than EGR) and additional PM, BC, NMVOC, CO benefits. CO_2 emissions are lower due to lower carbon content. However, technical complications for conversion to NG, fuel availability, and high initial costs are limiting factors; NG for truck applications is still at experimental scale. PN increase may be a problem is some NG bus applications, while there is also an increase of CH_4 emissions. Based on the above, NG is considered as BAT especially for OEM applications in captive fleets (e.g. buses), providing an alternative energy pathway to oil, that promotes energy security, and offering fuel cost savings because of lower fuel price.

37. *DME:* Dimethyl ether is a natural gas liquid derivative, offering a similar emission reduction profile as natural gas. It offers much higher volumetric energy content than NG, hence, easier handling for refueling and storage on board the vehicle. However, its general use is difficult (fuel production and availability is a major issue) and there is limited experience in DME-fuelled vehicles. It may be more appropriate for dedicated fleets (e.g. buses) where the fuel distribution is easier or for use in fuel cells. In general, DME can be considered as a good alternative for replacement of diesel in the future, but the issues of production and distribution must be addressed first.

38. *Emulsified diesel:* Emulsified diesel exhibits low NO_x reduction efficiency (10-20%) with some additional PM benefits; it can be used in any new or existing diesel engine. However, there is a decrease in power and fuel economy due to the fact that addition of water reduces fuel energy content; this increases the cost of this option in the long run; fuel availability is also an issue. It is evaluated as a technology with ‘limited impact’ because there are better options for significantly higher NO_x reduction.

39. *Renewable diesel:* Renewable diesel offers low emission reduction for NO_x (5-10%) with some additional PM, BC, VOC, and CO benefits. The reduction is even lower when used as an additive. Neat renewable diesel has several advantages over fuels produced with the transesterification process, it is free of aromatics, and it produces low mutagenic emissions and engine smoke. The main issues concerning its use are fuel availability, adjustments in the electronic control of the engine, and additives to address the lubricity issues. It is evaluated as a technology with ‘limited impact’ because there are better options for significantly higher NO_x reduction. There are also potential environmental issues related to its production – as for any fossil fuel as well – but these are by definition outside the scope of assessment here.

Assessment of PM reduction technologies in heavy duty diesel road vehicles (trucks, buses)

40. The reference technology is a turbocharged compression ignition engine with high pressure fuel injection. This is a typical base diesel engine without after-treatment control. This technology may still be met often around the world and is the prominent technology for heavy duty vehicles in least developed countries. Such engines emit typically in the order of 0.15-0.5 g/km PM with variation due to the size and age of the vehicle, the speed and driving conditions, exact technology configuration, fuel sulfur content, etc.

41. The expected emission reductions and additional costs are assessed for the various PM control technologies relative to the reference technology (Table 3). The emission reduction ranges should be seen for each measure individually and not cumulatively if several measures are implemented at the same time.

42. The expected additional costs for emission controls are an order of magnitude estimate per vehicle (in Euro). They include usually installation (e.g. retrofitting DPF), additional fuel and maintenance costs, possible fuel savings, etc. Costs are expressed on a per vehicle basis, assuming widespread application. Unit costs depend on the scale of implementation of the technology and can fluctuate upwards or downwards.

Table 3: Summary of emission reduction potential and additional costs of techniques for PM control in heavy duty diesel road vehicles (trucks, buses)

Technology	Expected emission reduction		Cost per vehicle (Euro)
	PM	Other	
Reference technology: Turbocharged CI engine with high pressure fuel injection	0.15-0.5 g/km	NO_x (4-16 g/km)	Reference technology
Engine measures			
Closed Crankcase Ventilation (CCV)	5-15%	VOC (15-25%)	250-500
After-treatment			
Diesel Particulate Filter (DPF)	80-95%	VOC (85-95%) CO (50-90%) BC	3,000-5,000 installation + 200-700 additional fuel and maintenance costs p.a.
Diesel Oxidation Catalyst (DOC)	20-40%	VOC (40-70%) CO (40-60%)	1,500-1,700 (installation)
Alternative fuels			
Natural Gas (NG)	85-95%	NO_x (20-50%) NMVOC (75-85%) CO (70-95%) BC	12,000-15,000 for conversion to NG - 500-1,000 fuel cost benefits p.a.
Dimethyl Ether (DME)	85-95%	NO_x (40-60%) BC	Depends on source of production
Emulsified diesel	50-60%	NO_x (10-20%)	1,200-1,600 p.a.

Renewable diesel	15-25%	NO_x (5-10%) VOC (20-40%) CO (15-30%) BC	Usually offered at lower price than conventional diesel
Biodiesel	10-15%	VOC, CO (5-10%)	700-900 a.

43. The technologies discussed above (Table 3) are organized according to the two key criteria, the expected emission reduction and the additional costs (Figure 2). Then, technologies are discussed for potential limitations, side-effects and synergies, starting with the ones ranked as most probable BAT candidate. Thus the remaining criteria (side effects, limitations in applicability, implementation and other issues) are reviewed to identify potential bottlenecks in applicability of each technique.

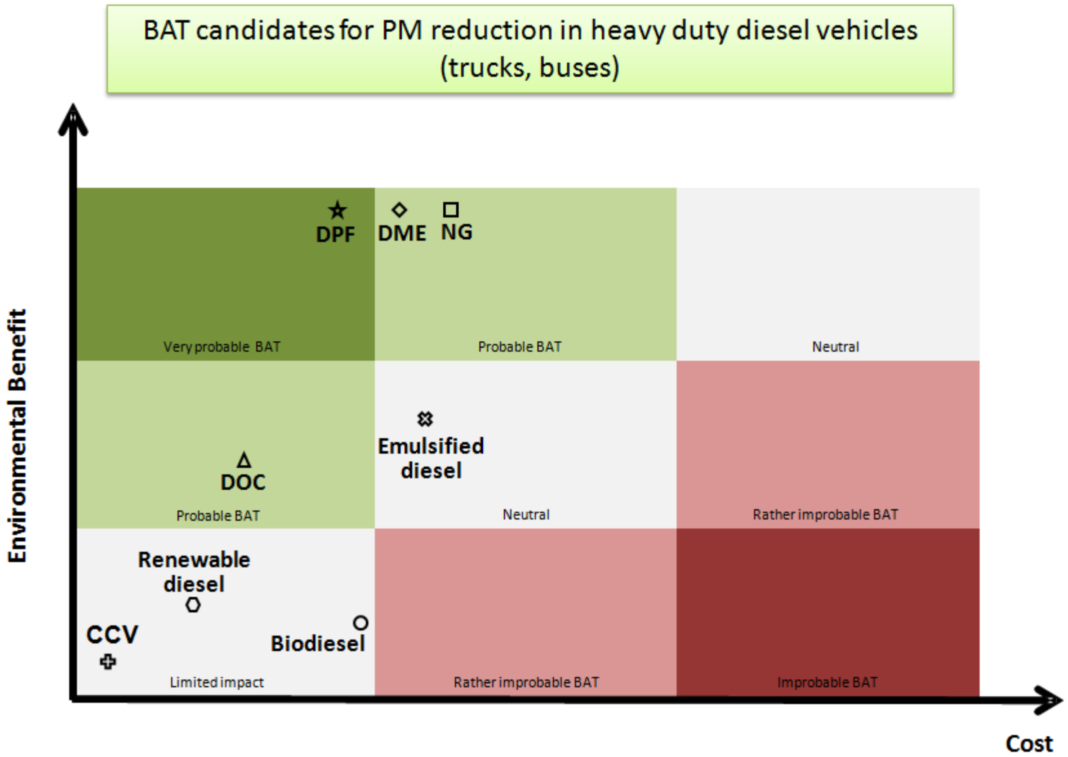

Figure 2: Cost-benefit classification of BAT candidates for PM reduction in heavy duty diesel road vehicles (trucks, buses)

44. The placement of the techniques on the evaluation grid is indicative and relative and should not be used for extracting quantitative conclusions. For the cost calculations, an indicative period of 10 years of operation is considered in order to make a fair comparison between options, e.g. conversion to natural gas usually has a high initial investment cost, but a significant part of it may be paid back after 10 years of use (by the fuel cost savings because of lower fuel price). Although such an approach may have some uncertainties in assessment, it is sufficient for the purpose of this relative cost-benefit evaluation. For example, considering a period of 8 or 12 years (instead of 10) could slightly change the position of some techniques on the grid; however, it would not substantially change the categorization of each technique as ‘very probable BAT’, ‘probable BAT’, ‘neutral’, etc.

45. The conclusions of BAT evaluation and proposals for PM reduction in heavy duty diesel road vehicles are summarized below.

46. *DPF:* Diesel Particulate Filter is the most cost-effective option to reduce PM from diesel HDVs (trucks, buses), achieving high % reduction (80-95%) at reasonable cost. It also reduces BC, VOC, CO. It is ideal for original equipment manufacturer (OEM) applications, but retrofit systems are also available and effective. Attention should be given to the potential increase of NO_2 emissions from some implementations (catalyzed DPFs), while there is also a fuel economy penalty (~1-2%). In general, DPF is a BAT when low sulfur fuel (<50ppm) is available. Other operational issues (regeneration at high temperatures and periodic maintenance with cleaning system) are not considered as severe limitations that may prevent its wide applicability.

47. *NG:* Conversion of captive fleets to natural gas can lead to similar PM (and BC) reductions to the DPF (possibly at higher cost) and additional NO_x, NMVOC, CO benefits. CO_2 emissions are lower due to lower carbon content. However, technical complications for conversion to NG, fuel availability, and high initial costs are limiting factors; NG for truck applications is still at experimental scale. PN increase may be a problem is some bus applications, while there is also an increase of CH_4 emissions. Hence, natural gas is a BAT especially for OEM applications in captive fleets (e.g. buses), providing an alternative energy pathway to oil, that promotes energy security, and offering fuel cost savings because of lower fuel price.

48. *DME:* Dimethyl ether is a natural gas liquid derivative, offering a similar emission reduction profile. It offers much higher volumetric energy content than NG, hence, easier handling for refueling and storage on board the vehicle. However, its general use is difficult (fuel production and availability is a major issue) and there is limited experience in DME-fuelled vehicles. It may be more appropriate for dedicated fleets (e.g. buses) where the fuel distribution is easier or for use in fuel cells. In general, DME can be considered as a good alternative for replacement of diesel in the future, but the issues of production and distribution must be addressed first.

49. *DOC:* Diesel Oxidation Catalyst generally exhibits PM reduction efficiency 20-40%, which is modest, compared to other options; it also reduces VOC, CO, but there are concerns that it may increase the NO_2 fraction of total NO_x emissions. However, this option has very low installation cost and there are no particular installation limitations or maintenance requirements. Hence, DOC retrofits may be considered as BAT (especially in large-scale applications), when high sulfur fuel or other technical factors exclude the applicability of DPFs.

50. *Emulsified diesel:* Emulsified diesel achieves noticeable PM reduction (50-60%) with some additional NO_x benefits; it can be used in any new or existing diesel engine. However, there is a decrease in power and fuel economy due to the fact that addition of water reduces fuel energy content; this increases the cost of this option in the long run; fuel availability is also an issue. It is evaluated as a ‘neutral’ technology in the grid because there are other more cost-effective options for PM reduction in heavy duty diesel vehicles.

51. *Renewable diesel:* Renewable diesel offers quite low emission reduction for PM (15-25%) with some additional BC, NO_x, VOC, and CO benefits. The reduction is even lower when used as an additive. Neat renewable diesel has several advantages over fuels produced with the transesterification process, it is free of aromatics, and it produces low mutagenic emissions and engine smoke. The main issues concerning its use are fuel availability, adjustments in the electronic control of the engine, and additives to address the lubricity issues. It is evaluated as a technology with 'limited impact' because there are better options for higher NO_x reduction.

52. *Biodiesel:* Use of low biodiesel blends reduces PM (10-15%), VOC, and CO, but it may slightly increase NO_x (~2-3%) and fuel consumption, proportionally to the blend considered. Current regulations in Europe limit blends to B7 and only gradually move towards higher blending ratios. Higher blends are allowed in controlled captive fleets where maintenance intervals and practices, as well as engine materials, can be adjusted to the fuel properties. It is evaluated as technology with 'limited impact' because there are many better options for significantly higher PM reduction.

53. *CCV:* Closed Crankcase Ventilation is the best option to reduce mainly VOC (and PM) from crankcase emissions of heavy duty diesel road vehicles. If left open, the crankcase from a pre-2007 diesel engine can contribute up to 25% of total VOC emissions from the vehicle. Therefore, the overall environmental benefit (% reduction of total VOC) is ~20% (80-90% reduction of crankcase emissions * 25% contribution of crankcase to total VOC). PM reduction is estimated ~5-15%. CCV can be implemented in new vehicles or as retrofit, in combination with a DOC or DPF.

iii. Alternative propulsion [to be added later]

General principles [to be added later]

Hydrogen and fuel cell [to be added later]

Electrified vehicles [to be added later]

Hybridization [to be added later]

iv. PM emissions from component wear and abrasion [to be added later]

B. Non-road mobile machinery [to be added later]

i. Spark-ignition engines [to be added later]

ii. Compression ignition engines (including rail) [to be added later]

C. Other mobile emission sources (vessels, aviation) [to be added later]

D. Non-technical measures [to be added later]

E. Promising emerging techniques [to be added later]

VI. Main References

[To be added]