Best Available Techniques for Mobile Sources

in support of a

Guidance Document to the

Gothenburg Protocol of the

LRTAP Convention

Guidance document on control techniques for mobile sources

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List of abbreviations and acronyms

AEL	Associated Emission Level
ASC	Ammonia Slip Catalyst
BAT	Best Available Technique
BC	Black Carbon
BTL	Biomass To Liquid
CCV	Closed Crankcase Ventilation
CH_4	Methane
CI	Compression Ignition
CNG	Compressed Natural Gas
CO	Carbon monoxide
DME	Dimethyl ether
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particle Filter
ECA	Emission Control Area
EEV	Enhanced Environmentally-friendly Vehicle
EGR	Exhaust Gas Recirculation
EU	European Union
GDI	Gasoline Direct Injection
GHG	Greenhouse gas
GPF	Gasoline Particle Filter
GVW	Gross Vehicle Weight
HC	Hydrocarbon
HDV	Heavy Duty Vehicle
HVO	Hydrotreating of Vegetable Oil
I/M	Inspection and Maintenance
LDV	Light Duty Vehicle
LNG	Liquefied Natural Gas
LNT	Lean-NO_x Trap
LPG	Liquefied Petroleum Gas
LRTAP	Long-range Transboundary Air Pollution
LTO	Landing and Take-Off
N_2	Nitrogen
NECA	NO_x Emission Control Area
NG	Natural Gas
NH_3	Ammonia
NMVOC	Non-Methane Volatile Organic Compounds
NO_x	Nitrogen Oxides

NRMM	Non-road Mobile Machinery
OBD	On-Board Diagnostics
OEM	Original Equipment Manufacturer
PAH	Polyaromatic hydrocarbons
PEMS	Portable Emissions Measurement System
PFI	Port Fuel Injection
PM	Particulate Matter
PN	Particle Number
POC	Particle Oxidation Catalyst
RDE	Real Driving Emissions
RSD	Remote Sensing Device
SAI	Secondary Air Injection
SCR	Selective Catalytic Reduction
SECA	SO_x Emission Control Area
SI	Spark-ignition
SO_x	Sulfur Oxides
TCP	Thermal Conversion Process
TWC	Three-way catalyst
UNECE	United Nations Economic Commission for Europe
US	United States
VOC	Volatile Organic Compounds

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 emission sources, in order to assist in meeting 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. This document updates and replaces the guidance document on control techniques for selected mobile sources that was adopted in 1999. The technical background information and analysis that supports this updated guidance document is provided in a comprehensive technical report [20].

3. Emphasis is primarily given to techniques that can be implemented on each single vehicle or engine concerned, to reduce the emission rates over regular operation ("technical measures"). Other measures including changes to fuel type or fuel specifications, as well as "non-technical measures" are also discussed. The latter include behavioral, operational, and infrastructural changes with the potential to reduce emissions. "Best available techniques" (BAT) can be identified amongst both the technical and non-technical measures.

4. This document identifies several techniques as BAT for reducing a specific pollutant. The proposed techniques have proven their potential for emission reductions in wide scale real-world applications. Emerging techniques or techniques only verified on an experimental scale are separately addressed. Identifying a technique as BAT by definition means that the extra costs associated with its implementation are in proportion to its expected emission reductions. This accounts for the economic viability of the proposed technique. In addition, boundary conditions and limiting factors for the implementation of each technique have to be considered, as well as potential synergies and trade-offs on other environmental objectives.

5. Mobile sources including engines used in non-road applications comprise a diverse range of machines based on various concepts, operating under variable conditions and a multitude of environments. Consequently, the technologies implemented and the resulting emission levels may greatly differ between the different machine categories and applications. This document diversifies recommendations per category of vehicle or machinery considered and differentiates between BAT applicable for newer and older types. This allows accounting for differences in the vehicle fleet and mobile machinery stock structures encountered among the Parties to the Convention.

6. BAT Associated Emission Levels (AELs) are provided relative to a specific and established reference technology for each mobile source category. The criteria used for selecting the particular reference technology per mobile source category include (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), but represents current good common practice (a technology still met often in many countries, with known environmental impacts that should be addressed).

7. The recommendations in this document should be considered as general guidance of possible emission control techniques for the different mobile emission source categories. This document is not an exhaustive list of all possible techniques. Under specific local conditions, other techniques might be judged equally good BAT candidates. Therefore, we state for each BAT candidate a number of limiting conditions. Additional limiting factors of technical, financial or infrastructural nature may exist in particular cases.

II. Coverage

8. This document addresses emissions of those pollutants considered in the Gothenburg Protocol, primarily nitrogen oxides (NO_x), volatile organic compounds (VOC), 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 emissions of all these pollutants. A large fraction of PM emissions 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 other ozone precursors, such as carbon monoxide (CO) and methane (CH_4). These pollutants are only addressed here when deemed relevant. For example, SO_x can be controlled with the provision of low sulfur fuels, which is also a prerequisite for the most advanced emission controls.

10. The majority of vehicles, vessels and other equipment operate on diesel and gasoline fuels. This guidance document suggests separate BAT per fuel, providing appropriate distinction between new vehicles and existing stock. It addresses both exhaust and non-exhaust emissions (evaporative, component wear) and includes technical and non-technical measures. Technical measures include powertrain, fuel switching, and after-treatment technologies. Table 1 summarizes the main categories of mobile sources covered in this document.

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

Road vehicles	Spark-ignition engines • Mopeds and motorcycles • Light duty vehicles (passenger cars, light commercial vehicles) Compression ignition engines • Light duty vehicles (passenger cars, light commercial vehicles) • Heavy duty vehicles (trucks, buses)
Non-road mobile machinery (NRMM)	Spark-ignition engines • Handheld and non-handheld equipment (household, gardening, agricultural and forestry machinery) Compression ignition engines • Industrial, construction, agricultural and forestry machinery / tractors • Railcars, locomotives
Inland waterways	• Compression ignition engines (passenger ships, freight vessels)

11. *Mobile sources not included in the Gothenburg Protocol:* Annex VIII of the Gothenburg Protocol does not include emissions from the following mobile sources: aircrafts, sea going ships (short sea or deep sea), and (electric) trams, metros, and trolley buses. However, emissions from some of these sources are either included in the national inventories in the framework of LRTAP (aircraft LTO phases, domestic shipping) or there are considerations how to include them (international maritime). As for electric trams, metros, and trolley buses, although they do not have tailpipe emissions, they produce heavy metal emissions due to the wear of their components and, in particular, sparking that occurs in the power lines. For these reasons, all these mobile sources which are not included in the Gothenburg Protocol are shortly covered at the end of this guidance document.

III. Emission processes and contributions

12. 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 reduction of these emissions. Further reductions can be achieved by use of aftertreatment devices in the exhaust line. PM produced from component wear (tyres, brakes) and gasoline fuel evaporation from the tank of road vehicles are the most common sources of non-exhaust emissions. They are also addressed in this guidance document.

13. Mobile sources contribute about 40% to 60% of all NO_x emissions and about 10% to 30% of all $PM_{2.5}$ emissions in the different UNECE regions (year 2010). The largest single emission sources are diesel powered cars and trucks, followed by agricultural tractors. Diesel powered rail and shipping activities also constitute a significant source in some Parties to the Convention. Mobile sources contribute about 20% of all VOC emissions in the different UNECE regions (year 2010). The biggest single mobile sources of VOC are gasoline powered light duty vehicles including two wheelers, followed by smaller machinery, and agricultural machines. 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 (year 2010).

14. Due to the significant contribution of mobile sources to NO_x and PM emissions, these two pollutants receive most of the attention in this guidance document. VOC and NH_3 emissions are dealt with only for those mobile sources that significantly contribute to their total emissions and when well established and economical techniques can be used to achieve substantial emission reductions. Emission levels usually increase with age, as the effectiveness of emission control degrades with time. Furthermore, malfunctions which can be due to misuse, fatigue, or stochastic faults may also degrade emission control. This guidance document tries to refer to emission levels which are affected by all these conditions and assesses BAT that can have an impact on any of these processes.

IV. Methodology for the assessment of Best Available Techniques (BAT)

15. The definition of BAT for emission control of mobile sources is modeled according to the respective definition for stationary sources[a]. In order to retain consistency, this guidance document does not attempt to provide an additional definition of BAT for mobile sources, but only to specify the criteria used for BAT selection in the case of mobile sources. On these grounds, a technique characterized as BAT for mobile sources encompasses the following characteristics:

- Provides measurable real-world emission reductions over a reference technology at a cost which is in proportion to the reductions achieved.
- Is technically feasible and has a proven record of implementation in actual wide scale real-world applications.
- Any environmental or other side effects as a consequence of its implementation are of a much lesser scale than the benefits obtained by the reduction of the pollutant(s) emissions this has been introduced for.

16. In general, it was recommended that in order to assess the potential of a technique to be characterized as BAT, a two-step approach should be followed. According to this, in a first

[a] UNECE, "Guidance document on control techniques for emissions of sulphur, NO_x, VOC, dust (including PM_{10}, $PM_{2.5}$ and black carbon) from stationary sources", as adopted by the Executive Body at its thirty-first session (December 2012).

step, the various options are evaluated in terms of their emission reduction potential on one hand, and extra lifetime costs on the other, each relative to the reference technology (which is defined per vehicle type considered). Techniques with a relatively high ratio of emission reduction potential over extra costs are then further examined in a second step with respect to possible limiting factors. These include environmental side effects such as GHG emissions, energy efficiency or fuel consumption impacts, technical limitations, infrastructural needs, etc. Possible solutions to limitations against a wide implementation of the techniques are identified where appropriate.

17. This detailed two-step methodology for BAT assessment (with cost-benefit comparisons, etc.) is analytically presented in this guidance document for diesel HDVs and NRMM. For diesel LDVs and vessels, a simplified descriptive assessment of various emission reduction techniques is provided here, but this has been based on the same two-step methodology (more details can be found in the associated technical report [20]). For the remaining categories, i.e., gasoline road vehicles and gasoline non-road engines, such a 'strictly defined' evaluation scheme was difficult to follow or even without practical meaning due to a variety of reasons (e.g. limited number of available options, measures targeted to a very specific category, incomparable measures, etc). For these remaining categories, the assessment has been made in a more simplified descriptive manner, i.e., without detailed numerical cost-benefit comparisons, etc.

18. A BAT solution may consist of a combination of several individual techniques. Moreover, the probability that a technique is characterized as BAT increases when this has the potential to address more than one pollutant. A list of individual BAT candidates is given in 'Annex I: Description of individual BAT candidates', each one accompanied with a short explanatory description. This list contains measures that can be used to control emissions including engine measures, aftertreatment devices, alternative fuels and powertrains, and the most frequently used non-technical measures.

19. A number of candidate techniques, comparable in terms of their environmental effects and economic dimension, may fulfill the BAT criteria. If so, all of these are considered reasonable BAT options. This guidance document does not aim to provide "one best BAT". Because of technology evolution and other technical limitations, BAT may differ according to the age of the vehicle or machinery equipment concerned and its applicability may well depend on a country's specific economic, environmental, and/or technological circumstances.

20. Techniques implemented by manufacturers to meet latest emission standards, considering the period of preparing this guidance document (2014), are assumed BAT for new vehicle and machinery types. BAT for the existing stock are in general different than the ones implemented for new types. Finally, techniques with further emission reduction potential for future vehicle and machinery types (prospective or promising emerging technologies) are separately addressed.

21. Similarly to the stationary sources, Associated Emission Levels (AELs) are provided for mobile sources in this document. These are emission levels expected to be achieved by using BAT. In particular, BAT AELs can be derived by combining the emission reduction efficiency of each BAT candidate (given as percentage range in the corresponding tables below) with the emission level of the reference technology (reference emission level). Due to the diversification of vehicle/engine types and characteristics, size and age of vehicles/machinery equipment, driving and operating conditions, speed, etc., these BAT AELs usually cover a wide range of values and should only be considered as an order of magnitude estimate.

V. BAT for emission control from mobile sources

22. This section provides specific recommendations for emission reduction per mobile source category based on the assessment of BAT candidates. For each category, the proposed measures are distinguished into those for new vehicles/engines, in-use vehicles/engines (existing stock), and future vehicles/engines (prospective or promising emerging technologies). Some general common issues for the assessment and selection of BAT, related to all mobile source categories, are discussed below.

- *Applicability of a technique on new or existing vehicles/engines:* Some of the BAT candidates may concern only the existing stock (e.g. accelerated scrappage schemes), some can be used in both new and existing vehicles (e.g. DPF OEM and DPF retrofit for HDVs), and, finally, for some techniques there may be such technical difficulties (e.g. integrating EGR on existing engines), so that it is impractical to recommend them for retrofit applications (therefore, they mainly concern the new vehicles). By presenting in this guidance document BAT clearly distinguished into measures for new and existing vehicles/engines, any risk for misunderstandings is avoided.
- *New vehicles/machinery types and latest emission standards:* The terms ‘new’ and ‘latest’ should be considered relative to the period of preparing this guidance document (2014). In general, the techniques implemented by the manufacturers to meet the latest emission standards are assumed BAT for the vehicles and machinery types currently produced (considered as new ones). Information on emission standards is available in Annex VIII of the 2012 revised Gothenburg Protocol, while a summary of regulation information (legislation, emission limits, etc.) per mobile source category is also available in the associated technical report [20].
- *Environmental benefit and cost:* These are the two key criteria which are examined first. They are intended to be considered as indicative order of magnitude estimates relative to a reference technology and not exact values. In general, the expected emission reduction range can be considered of the same order of magnitude for both new and retrofit applications. The cost is usually considered for retrofit application (if the examined technique can be retrofitted); otherwise, it is considered appropriately, e.g. as manufacturer cost. Especially for the manufacturer cost, this usually depends on commercial agreements with the suppliers and also includes engineering costs which are different for each OEM. Therefore, exact values are difficult to provide and only indicative order-of-magnitude estimates are given.
- *Limitations in applicability and implementation issues:* These criteria are of particular importance in the assessment process and include technological barriers, infrastructural needs, environmental conditions, fuel specifications, maintenance requirements, etc. They are examined to identify potential bottlenecks in applicability of each technique.
- *Environmental side effects, synergies and tradeoffs:* These criteria may increase or decrease the probability that a technique is characterized as BAT. They include impact on fuel consumption, non-regulated pollutants, synergetic and secondary effects, etc.

A. <u>Mopeds and motorcycles</u>

23. Gasoline powered mopeds and motorcycles have traditionally been significant emitters of VOC and CO. In particular, mopeds in the past have been powered mainly by two stroke engines, which have been notorious emitters of unburned hydrocarbons and, because of this, particulate matter as a result of piston scavenging losses. The contribution of these

vehicles to urban air pollution has been historically increasing, especially in densely populated (urbanized) areas of the world that rely on mopeds and motorcycles as an essential means of transportation.

A1. BAT for new vehicles (typical exhaust emission control and fuel evaporation control)

24. The technologies used to meet latest emission limits, considered as BAT for new vehicle types, are mainly port-fuel injection, stoichiometric combustion (i.e. controlled by a lambda sensor), and catalytic exhaust aftertreatment. Catalyst technology ranges from simpler design oxidation catalysts (e.g. on mopeds and small motorcycles) to control CO and HC, up to three-way catalysts with closed loop air/fuel ratio (on the largest four-stroke engines). In these cases the emission control technology is of similar concept to the one utilized in gasoline passenger cars.

25. Often, combustion in mopeds and some motorcycles (mainly of smaller size) is adjusted to the slightly rich side to enhance performance and responsiveness. In these cases, secondary air is injected in the exhaust port before the exhaust reaches the catalyst. The overall mixture may be off stoichiometry, but the catalyst effectively reduces CO and HC, while NO_x are suppressed in cylinder by the rich combustion. Depending on the catalyst and the tuning, some further NO_x reduction in the exhaust line is possible.

26. *Two-stroke engines:* Although recently there is a trend to phase out two-stroke engines because of the VOC emission problems, vehicles with such engine type are still in production. In order to meet the new emission limits, significant investments in the emission control is requested. This includes electronically controlled fuel injection directly in the cylinder for precise metering of the quantity and timing of the fuel supplied, secondary air injection in the exhaust line and oxidation catalyst to control HC emissions, and secondarily CO, while NO_x need to be controlled primarily by combustion calibration measures. The new components and the controls of the package make the two-stroke lose some of its edge regarding simplicity, cost and power-to-mass ratio, compared to four-stroke engines.

27. *Fuel evaporation control:* Evaporative emissions control on motorcycles consists of carbon canisters connected to the fuel system. Low permeability tanks are also used, similar to passenger cars. Evaporation control is only applicable to larger vehicle types, but it is expected to be extended to all vehicle types in the future.

A2. BAT for the existing stock (in-use vehicles)

28. The existing stock of mopeds and motorcycles is a good candidate for emission reduction measures, especially targeting at the old two-stroke engines and vehicles without aftertreatment control. However, the small displacement engines used in the majority of population complicates emission control issues due to space limitations and simple design characteristics of small engine technology. Hence, for vehicles without aftertreatment control, retrofitting a catalytic converter in general cannot be recommended as BAT. The only option that can be considered as BAT for the older existing stock is to focus on removing these vehicles from the road; such measures, i.e. accelerated replacement schemes boosted by financial incentives, by far correspond to the most effective approach in reducing urban air pollution. For motorcycles of more recent technology (newer existing stock), which are probably equipped with a catalyst, the following techniques are proposed as BAT options.

29. *Emission control system maintenance:* Emission control system failures and malfunctions can be identified by inspection and maintenance schemes. A program requiring annual inspections of all two-wheel vehicles is recommended and should consist of measuring vehicle emissions and requiring repairs when specified levels are exceeded.

30. *Fuel and lubrication oil of good quality:* Catalyst deactivation may be caused by impurities in the fuel and lubrication oils. For two stroke vehicles, in cylinder addition of lube oil magnified this problem. Hence, enforcing the use of manufacturer recommended oils rather than cheap alternatives, as well as lube oil changes at recommended intervals, can be considered as BAT for existing engine types.

A3. Assessment of alternative fuels considered for gasoline replacement in two-wheelers

31. Use of alternatives fuels (e.g. LPG, CNG) without further (aftertreatment) emission control does not offer substantial improvements in terms of air quality (see more detailed discussion on gasoline cars). In addition, there are significant safety and space limitations for storage of such fuels on board the motorcycle. Hence, in general, alternative fuels cannot be considered as BAT for gasoline replacement in mopeds and motorcycles.

A4. Future vehicle types

32. *Gasoline vehicles:* Upcoming Euro 4/5 standards already set very demanding targets, requiring advanced emission control technology. Specifically, for motorcycles it is expected that three-way catalysts and stoichiometric combustion will be extensively used, while for mopeds larger catalysts and overall better engine strategies will be necessary. Especially for the Euro 5 stage, it is expected that significant technological breakthroughs will be required, such as improved quality and packaging of the whole system (stoichiometric combustion with TWC). Cost and space limitations may be a limiting factor in smaller vehicles, i.e. mopeds, since closed loop control of the TWC will be required, as well as positioning of the catalyst close to the engine outlet (or dual layer exhaust line) for fast light-off, twin lambda sensors for long term performance verification of the emission control devices, etc. The whole package is expected to significantly increase the end price of mopeds; this, combined with the trend to replace two-stroke with four-stroke engines, is expected to result in much more competitive larger vehicles in terms of value for money. Moreover, the stringent standards are expected to further accelerate the phasing out of two stroke engines.

33. *Electric vehicles:* Electric two-wheelers have the potential to provide significant air quality benefits and such vehicles have started to become popular in several markets recently. Challenges in terms of weight and space constraints need to be addressed. In any case, a wider penetration of electric mopeds/motorcycles is to be expected in the future when the technology and the cost competitiveness of batteries improves and this could lead to reduced vehicle weight for the same driving range requirement.

B. Spark-ignition (gasoline) on-road light duty vehicles

34. In a spark-ignition (SI) engine, fuel with high vapor pressure is mixed with air and the combustible mixture is ignited by a spark plug to produce power [18]. SI (gasoline) engines have traditionally been the most popular propulsion system for passenger cars, but they are also used (to a smaller extent) in light commercial vehicles. Gasoline powered vehicles significantly contribute to the total VOC emissions, while their contribution to NO_x and PM is lower than their diesel counterparts.

B1. BAT for new vehicles (typical exhaust emission control and fuel evaporation control)

35. Latest emission standards are met by emission control measures that include both engine and aftertreatment technologies and are considered as BAT for new vehicle types. There are two main combustion concepts of gasoline engines with distinct characteristics. The most widespread one is the so-called port-fuel injection (PFI), while the second concept is the

gasoline direct injection (GDI) engine. Because of their distinct (and different) performances, these two concepts are considered separately.

36. *PFI engines:* For emission control, PFI engines are calibrated stoichiometrically and combined with a closed-loop TWC. Typically, the exhaust system also includes an upstream oxygen sensor that monitors the oxygen content of the exhaust and continuously adjusts the fueling to match the operation conditions. A downstream oxygen sensor is used to monitor the oxygen storage capacity of the catalyst and, by this, its real world performance. Over the years this typical configuration has been proven very efficient and may lead to the lowest emission levels of all conventional vehicle technologies today in all regulated pollutants.

37. *GDI engines:* GDI is a more recent technology of SI engines introduced to improve fuel efficiency and power output by directly injecting fuel into the cylinder. Today, most of the GDI engines operate stoichiometrically over their complete operation range, but engines that combine both modes (lean and stoichiometric combustion) in different load regions are also available. Stoichiometric GDI NO_x emissions do not substantially differ from conventional PFI vehicles. However, partial lean burn GDI engines are prone to high NO_x emissions because of oxygen availability in the exhaust. A lean NO_x trap (LNT) can be used in these lean applications to reduce NO_x. Because of engine control limitations and sulfur intolerance, not many commercial applications of such a concept (lean operation with LNT) are available today. GDI vehicles may also lead to increased PM (and PN) emissions. These can be controlled by modified injection strategy and an improved fuel system. Gasoline particle filter (GPF) is also an effective technology to reduce particulate emission with high filtration performance under all engine operation points and ambient temperature variation, if engine measures alone prove not enough.

38. *Fuel evaporation control:* Non-methane volatile organic compounds (NMVOC) originating from the vehicle's fuel system (evaporative emissions) occur as a result of fuel volatility combined with the variation in ambient temperature and the temperature changes in the fuel system of the vehicle. The activated carbon canister is an essential component of the evaporative emission control system and it is used to trap vapors in the vent line of the fuel tank. Low permeability tanks are also used to control evaporative emissions. They reduce the permeability of plastics and polymers to gasoline in either the liquid or vapor phase.

B2. BAT for the existing stock (in-use vehicles)

39. The majority of gasoline LDVs on the road today is already equipped with TWC in Western European and North American countries. A well maintained TWC equipped gasoline vehicle is generally considered a low emitter, although some exceptions may exist due to adverse operating conditions like extreme temperatures. Therefore, the focus of a BAT approach for such vehicles would be to maintain their good overall performance. In regions where a significant fraction of non-catalytic vehicles is still in operation, then efforts focusing on removing such vehicles from the road are likely to be considered as BAT, since such measures by far correspond to the most effective approach in reducing air pollution. Experience shows that accelerated replacement schemes boosted by financial incentives are very effective in removing these old vehicles from the road [14] [21] [22]. The following two techniques are proposed as BAT options for TWC equipped (in-use) vehicles.

40. *Emission control system maintenance:* The emission reduction effectiveness of the catalyst may be severely degraded over time due to a variety of reasons. Emission control system failures and malfunctions can be identified by inspection and maintenance schemes. Techniques involving remote sensing of emissions coupled to number plate recognition can be very effective in identifying high emitters. Traditional periodical simplified tests need to

be enhanced to be more effective (e.g. including measurement of NO_x levels). Finally, OBD related failure identification techniques can be an additional option for more recent vehicle technologies. Once a malfunction has been identified, maintenance may include component replacement (e.g. catalyst), re-calibration, or cleaning (e.g. injectors). Replacement of old catalysts identified by inspection is expected to have a significant impact not only to the three main pollutants (CO, VOC, and NO_x), but also a very positive side effect on NH_3 emissions, since aged catalysts reduce NO_x preferably to NH_3 rather than N_2.

41. *Fuel evaporation control:* Despite some technical difficulties, retrofitting activated carbon canisters and low permeability tanks can be considered as BAT to reduce evaporative emissions. Moreover, since no inspection techniques exist for the efficiency of the canister and no manufacturer maintenance schedule includes canister replacement, including such tests in regular inspection programs may be a very effective policy. Replacing the canister can be considered a BAT for older vehicle types.

B3. Assessment of alternative fuels considered for gasoline replacement in LDVs

42. Alternative fuels offered for spark ignition vehicles, such as natural gas, liquefied petroleum gas and bio alcohols, are often promoted as 'clean' alternatives to conventional fuels. When compared to gasoline, most alternative fuels offer limited or no net emission improvements [19]. In several cases, alternative fuel use may lead to a reduction of a specific pollutant, but it might also result to an increase of other toxic, but non-regulated, pollutants. In addition, retrofits of existing vehicles to run on alternative fuels entail the risks of increased emission levels due to often limited technical sophistication of the retrofit technology and the lack of efficient mechanisms to verify the quality of the retrofit and the resulting emission level in the real world. Hence, in general, alternative fuels cannot be considered as BAT with regard to regulated pollutants for gasoline replacement in road vehicles. This in principle means that emission reductions achieved by any of these fuels can be also achieved by an improved gasoline combustion and aftertreatment system as well. On-going scientific research and regulatory efforts in the production and promotion of alternative fuels mainly stem from energy security considerations (e.g. natural gas) and the need to reduce GHG from transport. In any case, fuel changes for spark ignition vehicles need to consider changes in the emission profiles of both regulated and non-regulated pollutants as well as possibilities to verify the in-use emission performance of modified vehicles.

B4. Future vehicle types

43. *Gasoline vehicles:* TWC will continue to be the main component for emission control in the future. Advanced TWCs are designed and produced with better catalyst layering and formulation while engine calibration is further enhanced. The most significant changes are expected for GDI vehicles with regard to the upcoming more stringent Euro 6c PN limit, which is expected to require the use of GPF (possibly combined with TWC) for several vehicle types. Engine measures may also be used to achieve PM and PN GDI Euro 6c limits, i.e., high-pressure spray-guided multi-injection with advanced piezoelectric injectors. For NO_x control, either stoichiometric combustion with TWC or lean burn with LNT can be used. Further to the more stringent control of exhaust emissions, future gasoline vehicles will also be more stringently regulated in terms of their evaporation emissions, as indicated by the revision of the relevant European legislation which is currently underway [11]. This revision aims to improve the control of evaporative emissions in real world driving conditions.

44. *Hybrid and electric vehicles:* Gasoline hybrids primarily aim at reducing energy consumption and greenhouse gas emissions, but studies have shown that some of them can also achieve impressive reductions in air pollutants. Battery and fuel cell electric vehicles are

also advanced technology vehicle types with the potential to achieve significant GHG and air pollutant emission reductions in the future. Currently, all these concepts have penetrated the market in various (small) degrees [13], depending on the concept, due to various limitations (technical, economical, infrastructural). Especially for electrics, a significant real world penetration can only take place when the technical and cost competitiveness of batteries improves and when the limiting factors for the proliferation of hydrogen power systems (safe, economical, and clean production and distribution of hydrogen) are addressed.

C. Compression ignition (diesel) on-road light duty vehicles

45. In a compression ignition engine, fuel is self-ignited after pressure and temperature inside the combustion chamber rise by compression [18]. CI engines used in road applications are fueled up mainly with diesel fuel and, in general, produce high NO_x and PM emissions. The latter include a large fraction of black carbon (BC) and are associated with elevated particle number (PN) emissions.

C1. BAT for new vehicles (typical exhaust emission control)

46. In terms of engine measures, a typical diesel engine for a new vehicle utilizes high-pressure multi-pulse common rail injection, multi-valve cylinder heads, and exhaust gas recirculation (EGR). The approach for aftertreatment NO_x control diversifies for different models and ranges from i) control of NO_x with engine measures only (no $deNO_x$ aftertreatment), ii) utilization of a lean NO_x trap (LNT), and iii) SCR with urea injection in the exhaust line. DPF is used to control PM and PN levels within regulatory limits.

47. It should be mentioned, that up to the first generation of Euro 6 vehicles introduced in 2014, in-use NO_x emissions are reported at much higher level than the corresponding emission limits. In-use conditions cover a much wider operation range than what the certification driving cycle does. Emission control in such off-cycle conditions relaxes to the benefit of fuel economy. In order to decrease NO_x emissions over a wider operation range, engine and aftertreatment systems need to be recalibrated. In particular, EGR map will have to be widened in terms of engine speed and load and/or urea injection will have to be increased in SCR systems. Finally, better thermal management may be required so that aftertreatment devices reach optimum conditions faster after first switch on of the engine. Relevant tests have shown that the combination of engine measures, EGR and SCR can lead to in-use NO_x levels which do respect Euro 6 limits over a wide operation range.

C2. BAT for the existing stock (in-use vehicles)

48. The existing stock of diesel LDVs is a good candidate for emission reduction measures because, in particular for NO_x, these vehicles have been shown to substantially exceed their corresponding type-approval limits in real world operation [2] [10]. This is the result of the tuning of the emission control systems to deliver emission reductions only within the operation boundaries of the type approval driving pattern.

49. However, the options to control emissions from such vehicles, in particular the older stock, are limited. Emission control systems retrofits (e.g. SCR) encounter technical difficulties and limited space availability, which make their wide scale application difficult to achieve in practice (e.g. as a retrofit program in a city level). For vehicles of more recent technology (newer existing stock), several of the available emission control technologies do have the potential to lead to significant emission reductions, even over real world operation, when properly calibrated/retuned to improve their functioning. Regarding the possibility to use alternative fuels as a diesel replacement, only renewable diesel can lead to realistic (but rather moderate) emission reductions. Although other fuels (e.g. natural gas) could

theoretically offer some reduction, they cannot be recommended for widespread use on existing vehicles due to excessive modifications required and various limitations (technical, economical, etc.), or low emission reduction effectiveness (biodiesel).

50. As a consequence of the above discussion, the range of emission reduction measures for such vehicle types is restricted mainly to the following non-technical ones.

51. *Access restrictions and/or complete removal from roads:* Restricting access of diesel light duty vehicles to city centers and enforcement of environmental zones can offer significant environmental benefits. In regions with a significant fraction of diesel cars, efforts focusing on removing such vehicles from the road should be considered as BAT and by far correspond to the most effective approach in reducing urban air pollution. Experience shows that accelerated replacement schemes boosted by financial incentives are very effective in removing particular vehicle types from the road and replacing them with cleaner vehicle technologies. In the case of diesel LDVs, such a measure could assist in replacing diesel vehicles with gasoline, natural gas, or other cleaner vehicle types.

52. *Inspection and maintenance:* Current periodic tests usually not include NO_x tests and are not reliable enough for detecting broken DPF. Hence, they need to be developed further in this respect. OBD enabled identification techniques seem reliable. However, currently they will at best be relevant for PM controls; as long as NO_x emissions in real-world driving are high by design, OBD will not signal malfunction.

C3. Future vehicle types

53. *Typical diesel emission control:* A combination of EGR, DOC, SCR (or LNT for smaller vehicles), and DPF is expected to constitute the default emission control system for future diesel light duty vehicles. Real drive emissions (RDE) testing for diesel NO_x is expected to require a new calibration and control strategy of the whole system; monitor of the performance of the various components by means of OBD will guarantee the efficient long term performance. Although no provisions on ammonia slip control for Euro 6 cars have been made in the regulations yet (as is the case with HDVs), it can be stated that an ammonia slip catalyst (downstream of the SCR catalyst) is necessary to avoid ammonia slip when SCR is used. This may require further uptake in regulations.

54. *Alternative fuels and powertrains:* CNG can be used as a diesel replacement in the future, not only because of the emission reductions it can achieve, but also because it is seen as diversifying the energy mix and, hence, reducing dependence on oil. Second generation biofuels are currently under investigation, but there is not much information yet on emission benefits that these fuels can offer apart from their greenhouse gas savings. Concerning diesel hybrids, the experience is limited [19].

D. <u>Compression ignition (diesel) on-road heavy duty vehicles</u>

55. Similar to LDVs, compression ignition engines in heavy duty vehicles are fueled up to now mainly with diesel fuel and, in general, produce high NO_x and PM emissions. Furthermore, crankcase emissions of older engines also contribute to VOC and PM emissions.

D1. BAT for new vehicles (typical exhaust emission control)

56. Latest emission standards are met by emission control measures that include both engine and aftertreatment technologies and are considered as BAT for new vehicle types. Key engine measures include exhaust gas recirculation (EGR), high pressure injection with precise fuelling control, and optimized air exchange processes. Aftertreatment consists of a combination of diesel oxidation catalyst (DOC) for CO/HC control, selective catalytic

reduction (SCR) for NO_x control, diesel particle filter (DPF) for PM control and an ammonia slip catalyst (ASC) to eliminate excess NH_3 emissions produced by the SCR operation. Both Euro VI in EU and US2010 in US standards require such advanced emission control measures to regulate emissions within the emission limit levels for HDVs.

D2. BAT for the existing stock (in-use vehicles)

57. Existing HDVs constitute a good candidate for emission reduction measures. Several of these vehicles are state-owned or belong to captive fleets (e.g. urban buses, refuse trucks); hence, implementation of measures such as retrofits and fuel changes can be materialized.

58. The reference technology considered for in-use vehicles is a turbocharged compression ignition engine with high pressure fuel injection and without aftertreatment, which roughly corresponds to Euro III or pre US2007 emission levels. Order of magnitude NO_x and PM emission levels for such a technology are in the range of 4-16 g NO_x/km and 0.1-0.5 g PM/km, respectively, depending on the size and age of vehicle, driving conditions, speed, etc. In practice, even some Euro IV (or newer) vehicles (e.g. rigid/articulated trucks with more than 20t GVW and buses) may emit more than 4 g NO_x/km, especially in urban conditions, and, hence, the BAT proposed may be applicable to such vehicles as well [7].

59. Technical measures that can be considered as BAT candidates are given in Table 2 for NO_x and Table 3 for PM. Emission reductions are expressed over the reference technology. These should be seen individually for each technique and not cumulatively if several measures are implemented at the same time. Combination of the emission level of the reference technology and the emission reduction achieved by each technique can give the order of magnitude Associated Emission Level (AEL) that each BAT candidate can lead to.

60. The additional costs estimated per technology may include installation, operation and maintenance, etc. Monetary benefits are also estimated and mainly originate from reduced fuel expenses. Costs are expressed as final consumer prices without accounting for taxes or incentives. In cases were consumer prices were not available, the values quoted represent cost to the manufacturers and are clearly distinguished.

61. Costs and benefits quoted are given as an order of magnitude estimate per vehicle, assuming widespread application of the technique and an indicative period of 10 years. For example, conversion to natural gas has high initial 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, it is sufficient for the purpose of this relative cost-benefit comparison. Considering a period of 8 or 12 years for example (instead of 10 years) 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.

62. The techniques listed in Table 2 and Table 3 are qualitatively compared on the basis of their expected emission reductions and costs in Figure 1 and Figure 2, respectively. The placement of techniques in the boxes of the evaluation grid is indicative and relative; hence, should not be scaled. Techniques within the same box have similar potential to be identified as BAT and location within the same box is irrelevant. Different levels of Euro standards have been placed on the environmental benefit axis for reference. This placement is indicative and it should not directly be concluded that emission standards 'are equal to' (or can be achieved with) specific BAT techniques in all cases, because this depends on the specific application considered.

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

Reference technology: Turbocharged CI engine with high pressure fuel injection **Reference emission level:** 4-16 g/km		
Technique	Expected emission reduction	Cost per vehicle (Euro)
Exhaust Gas Recirculation (EGR)	25-45%	400-700 (indicative manufacturer cost)
Selective Catalytic Reduction (SCR)	70-95%	Retrofit cost: 5k-10k Per annum: +500 for urea +200 for maintenance –800 possible fuel savings
Conversion to natural gas (NG)	20-50%	Conversion cost: 12k-15k Per annum: –500-1,000 fuel cost benefits (depending on NG/diesel price ratio)
Dimethyl ether (DME)	40-60%	Comparable to conventional diesel (cost depends on production method and fuels taxation)
Emulsified diesel	10-20%	1,200-1,600 per annum (due to production costs of the end fuel and higher fuel consumption)
Renewable diesel	5-10%	Comparable to conventional diesel (more expensive to produce but can benefit from lower taxation)
Hybridization	40-50%	Initial (marginal)[b] cost: 50k-100k Per annum: –5k-10k lower fuel costs

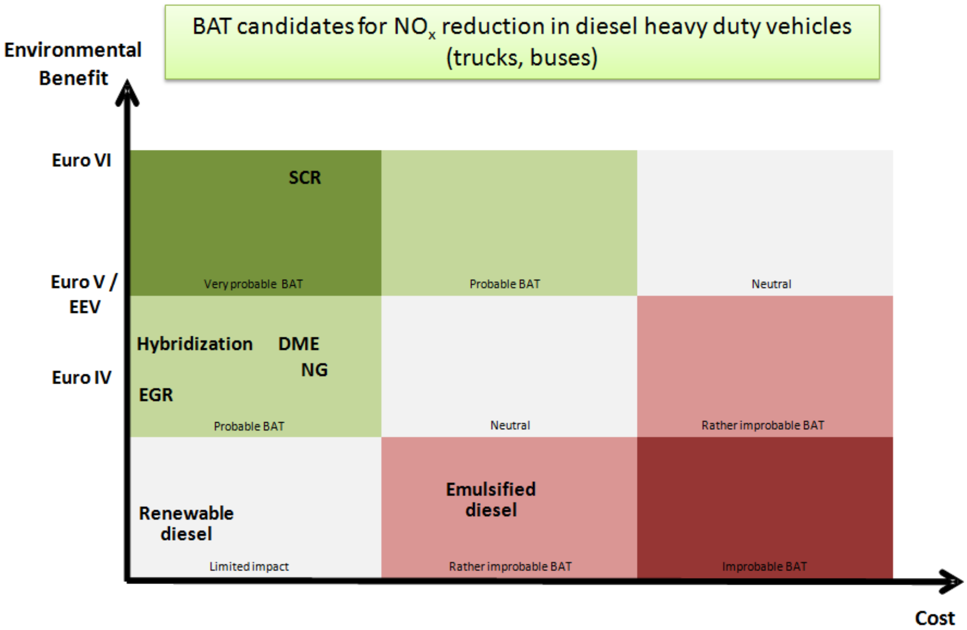

Figure 1: Relative cost-benefit comparison of BAT candidates for NO_x reduction in diesel heavy duty vehicles (trucks, buses)

[b] Additional (marginal) cost required to buy a new hybrid vehicle compared to buying a conventional diesel one in replacement of an older vehicle.

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

Reference technology: Turbocharged CI engine with high pressure fuel injection **Reference emission level:** 0.1-0.5 g/km		
Technique	Expected emission reduction	Cost per vehicle (Euro)
Closed Crankcase Ventilation	5-15%	Retrofit cost: 250-3,000
Diesel Particle Filter (DPF)	80-95%	Retrofit cost: 3k-5k Per annum: +200-700 additional fuel and maintenance costs
Diesel Oxidation Catalyst (DOC)	20-40%	Retrofit cost: 1,500-1,700
Conversion to natural gas (NG)	85-95%	Conversion cost: 12k-15k Per annum: –500-1,000 fuel cost benefits (depending on NG/diesel price ratio)
Dimethyl ether (DME)	85-95%	Comparable to conventional diesel (cost depends on production method and fuels taxation)
Emulsified diesel	50-60%	1,200-1,600 per annum (due to production costs of the end fuel and higher fuel consumption)
Renewable diesel	15-25%	Comparable to conventional diesel (more expensive to produce but can benefit from lower taxation)
Low biodiesel blends (up to B20)	10-15%	Comparable to conventional diesel (more expensive to produce but have been incentivized)
Hybridization	40-50%	Initial (marginal) cost: 50k-100k Per annum: –5k-10k lower fuel costs

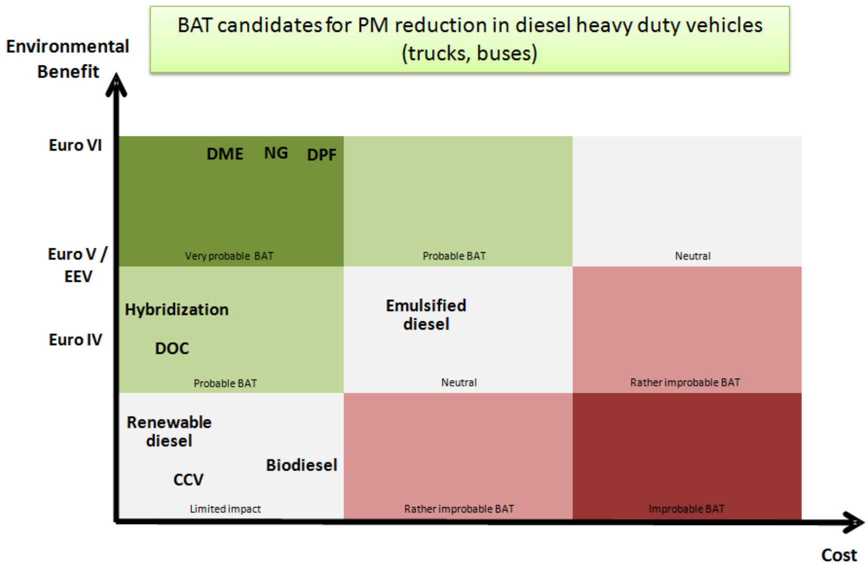

Figure 2: Relative cost-benefit comparison of BAT candidates for PM reduction in diesel heavy duty vehicles (trucks, buses)

63. Based on the above cost-benefit comparisons, and the technical, economical, or other limitations of the various BAT candidates, the following discussion summarizes specific BAT recommendations for the existing stock.

64. *SCR and DPF retrofits:* Retrofitting exhaust aftertreatment devices is a cost-effective technique that can achieve high environmental benefits. Especially SCR (for NO_x) and DPF (for PM) appear to be best available techniques for emission reduction from existing heavy duty vehicles. SCR and DPF can be implemented together for combined positive effect on both NO_x and PM with potential cost advantages (compared to separate implementations). Several examples around the world have demonstrated successful retrofits of NO_x and PM control systems in both long haul trucks and urban buses.

65. *Other retrofits:* DOC can be implemented in combination with DPF and SCR. As a stand-alone retrofit, it can be considered as BAT, especially in large-scale applications, being more tolerant to fuel sulfur than DPF, and when other technical factors (e.g. regeneration possibilities) exclude the applicability of DPFs. Closed crankcase ventilation (CCV) retrofits can be considered as BAT to control crankcase emissions of older vehicles. If left to openly vent to the atmosphere, the crankcase from an old diesel engine can contribute up to 25% of total VOC (and PM) emissions, hence, CCV retrofit can contribute to total emission reduction. CCV can be combined with a DOC or DPF. EGR on the other hand has limited potential due to technical difficulties integrating this on existing engines.

66. *Fuel switching:* Conversions to natural gas (most frequently in compressed form) are possible (e.g. in urban buses), but difficult to implement due to technical complications (in particular with regard to the storage tanks) and high initial costs. Among other fuel possibilities, only renewable diesel can deliver measured, yet moderate, reductions, primarily to PM. Alternatives such as DME and emulsified diesel are not recommended due to various technical, economical, or other limitations. DME in particular seems to have a promising future, once economical issues with its production are solved. First generation biodiesel has low emission reduction effectiveness in blending levels currently allowed by regulations. Second generation biofuels may have the potential for cleaner combustion but these remain to be proven for specific market fuels.

67. *Hybridization:* Replacement of an old heavy duty vehicle with a new hybrid one can achieve some emission reductions with additional (significant) fuel consumption benefits. Hybridization can be considered as BAT, especially for buses in urban applications. In addition to their contribution to overall city-level emission reductions, urban buses have the advantage of reducing exposure of passengers as they queue in bus stops and/or as buses take off from the bus stop. The key limitations for hybrid buses include the high initial capital cost, although fuel efficiency improvements may lead to cost benefits in the long run. Also, questions still exist on the long term performance of the hybrid system batteries. Hybrid trucks are not at mass production yet.

D3. Future vehicle types

68. *Typical diesel emission control:* A combination of EGR, DOC, SCR, and DPF is expected to constitute the default emission control system for diesel HDVs in the future. Further optimizations of the system and monitor of the performance of the various components by means of OBD will guarantee the efficient long term performance of the various subsystems.

69. *Alternative fuels and powertrains:* DME may have the potential for diesel replacement in the future (effectively addressing PM and simplifying NO_x control), but the

issues of production and distribution must be first addressed. Different other versions of renewable fuels can also constitute possible future BAT candidates for long-haul trucks. Concerning the use of alternative powertrains, certainly a wider diversification is to be expected, especially in hybrid urban buses, possibly combined with an alternative fuel (e.g. natural gas) for additional emission reductions. Full electric buses may also be a possibility as fast or wireless charging systems start to be become available. There are also some small fleets of prototype hydrogen fuel cell buses already operating in different parts of the world [4], but the proliferation of hydrogen technologies can only be achieved if the production and distribution of hydrogen become economically competitive. Long-distance trucks are unlikely to significantly benefit from hybrid powertrain concepts, but developments for delivery trucks are ongoing.

E. PM from component wear and abrasion from road vehicles

70. PM from component wear and abrasion may contribute significantly to total PM emissions [8]. Related measures to improve air quality should tackle both primary emissions (new dust material produced) and resuspension of dust (already accumulated on the road), as vehicles pass by [3]. For example, street sweeping has produced mixed results in reducing resuspension; it does however not at all address primary emissions. However, the Gothenburg Protocol that this document responds to only addresses primary emissions. Hence, specific measures to reduce resuspension (such as road sweeping) are not included in the recommendations.

71. *Measures for abatement:* There are two directions to follow in order to minimize the negative effects of wear dust [1]. These are i) minimize the sources (adjustment of pavements and gritting material, use of coarser, wear resistant rock aggregates, alternative pavements, adjustment of tyres, avoid using studded tyres), and ii) minimize dispersion to air (wet roads, dust binding materials) [12]. In addition, traffic measures, such as reducing traffic activity, decreasing the share of trucks and calming traffic would also assist in both minimizing the sources of wear dust and its dispersion to air. Gentle braking (and accelerations) also produce less wear.

72. *Brake measures:* Brake wear is due to forced deceleration of road vehicles during which brake linings are subject to large frictional heat generation. Brake (as well as tyre) wear contain heavy metals that are known for their toxicity. A measure for emission reduction is to change brake composition (e.g. ceramic brakes have fewer emissions). A brake particulate collection system was also recently developed that recuperates particulates generated by brake shoes. Regenerative braking also becomes increasingly widespread in late vehicle models. With this system, mild to moderate braking is achieved by the resistance of a coupled generator to the wheels. This recuperates part of the kinetic energy to charge the battery of the vehicle and hence improves fuel economy. The system has, as a positive side effect, the reduction of brake pad wear.

F. Gasoline engines in non-road applications

73. Non-road gasoline engines comprise a highly diverse category, including handheld and non-handheld equipment (household, gardening, agricultural and forestry machinery), over a range of sizes and power outputs [5] [14]. The main pollutants of concern emitted by engines of this category are VOC and CO [9]. VOC are the result of incomplete combustion and scavenging losses, mostly due to the widespread utilization of two-stroke engines in this category. There are also concerns with regard to PM emissions from such engine types (excess hydrocarbons). These are mostly a concern for those immediately exposed to their exhaust, such as the operator.

F1. BAT for new engines (typical emission control)

74. Emission control in such engine categories is less advanced than in gasoline engines used in on-road applications because of limiting factors including space, maximum operation temperature, noise and limited total lifetime. Often these engines are required to operate in various position angles. Because of their high power-to-weight ratio and the lack of a lube oil carter, two-stroke engines are ideal in this category.

75. Emission control mostly focuses on reducing scavenging losses from two-stroke engines. Techniques used in this respect include improved combustion and mixture exchange control for two-stroke engines (direct injection, compression wave injection, stratified scavenging, etc.). Those are the most widespread techniques used in the smaller engines applied in handheld machinery, such as chain saws. A different strategy involves replacement of two-stroke by four-stroke engines, in particular for larger ground-supported machinery, such as lawn mowers or compactors.

76. Emission control by catalytic aftertreatment is less frequent in small gasoline engines of this category (than in larger gasoline engines) and is limited by a number of factors. The operation of the engines with fuel rich mixtures to control exhaust gas temperature limits the efficiency of oxidation aftertreatment. Furthermore, oxidation catalysts can increase the exhaust gas temperature above comfortable or permissible levels. Therefore, catalytic control is used on special machinery only.

F2. BAT for the existing stock (in-use engines)

77. The special character and emission control practices of non-road gasoline engines calls for individual techniques in order to attempt to address emissions from the existing stock. Hence, the following measures correspond to BAT for this particular engine category.

78. *Replacement:* Machinery in this category can have very short lifetime (5-6 years) and is of relatively low cost. Therefore, replacement of the complete item with a younger generation one can be considered BAT in this case, considering that the new equipment will comply with latest emission limits.

79. *Lubrication oil of good quality:* Use of good quality (approved by the manufacturer) and low additized (e.g. Ca-free and S-free) lubrication oil is important, in particular for two-stroke engines, and increases the efficiency and long term performance of any catalytic aftertreatment possibly used. Sophisticated lubrication is essential to allow lubrication of the engine in multiposition tools (hedge trimmers, chainsaws, cut off machines); therefore, good quality lube oil becomes increasingly important, regardless of the existence or not of a catalyst. Enforcing the use of manufacturer recommended oils rather than cheap alternatives can be considered BAT for existing engine types.

80. *Aromatic free (alkylate) gasoline:* Start up and normal (hot) operation emissions can be reduced by using gasoline which is free of aromatics, benzene, and olefins. Such fuel is called ‘alkylate gasoline’ due to its high content in branched paraffins (alkylates). Moreover, the rather simplistic fuel system of small engines results to relatively elevated fuel evaporation; the use of aromatic free and benzene free gasoline therefore reduces the PAH, benzene, and other toxic (including mutagenic) content of pollutants liberated with evaporation.

F3. Future engines

81. New engine types which are designed to fulfill the next step of emission control (Stage III) standards may benefit from the following more advanced technological solutions.

82. *Combustion improvements:* Four-stroke will continue to proliferate and is expected to appear for smaller engines as well. Hybrid engines, where lubrication is similar to two-stroke (via the combustible mixture), while combustion occurs in four strokes to eliminate scavenging losses, have also started to appear. Stratified scavenging where fuel-less air drives the exhaust out of the two-stroke cylinder is also a concept for two-stroke engines.

83. *Evaporation control:* Evaporation losses are significant contributors to total VOC emissions from engines of this category. This is mainly due to the rather simplistic fuel system of small engines that allows increased fuel evaporation. Therefore, usage of low permeability tanks and fuel lines is a BAT to reduce evaporative emissions. While the technology to control emissions is available and US regulations calls for evaporation control, such requirements have not been adopted by European regulations yet.

G. Diesel non-road mobile machinery (NRMM) and rail

84. Diesel NRMM is a mobile source category with environmental problems similar to on-road heavy duty vehicles, i.e., high NO_x and PM emissions, VOC (and PM) from crankcase emissions of older engines. The problem with the emissions of NRMM is of particular importance in environmentally sensitive environments, e.g. tunnels, mines, etc.

G1. BAT for new engines (typical exhaust emission control)

85. Latest emission standards are met by control measures which constitute BAT for new engines. A typical configuration of a Stage IV / Tier 4 emission control system comprises a direct injection diesel engine with turbocharging and intercooler. Exhaust gas recirculation (EGR) may be present in some applications, but selective catalytic reduction (SCR) is usually sufficient to achieve the NO_x emission reductions required. An ammonia slip catalyst (ASC) may also be used to oxidize any excess NH_3 and avoid slipping above the regulatory limit of 25 ppm. For PM control, diesel oxidation catalysts (DOC) or particle oxidation catalysts (POC) are usually used. Wall-flow diesel particle filters (DPF) are generally not necessary to achieve Stage IV / Tier 4 limits.

G2. BAT for the existing stock (in-use engines/machinery)

86. NRMM have a long lifetime and, because of this, several technical measures can be considered as BAT candidates for the existing stock. The reference technology considered for in-use engines is a conventional compression ignition diesel engine without aftertreatment, which roughly corresponds to Stage IIIA / Tier 3 emission levels. Order of magnitude NO_x and PM emission levels for such a technology are in the range of 5-15 g NO_x/kWh and 0.2-1.0 g PM/kWh, respectively, depending on the size and age of machinery, driving and operating conditions, speed, etc.

87. Technical measures that can be considered as BAT candidates are given in Table 4 for NO_x and Table 5 for PM. Similarly to the on-road heavy duty vehicles, emission reductions are expressed over the reference technology and should be seen individually for each technique. Additional costs and benefits quoted are given as an order of magnitude estimate per unit (of machinery, equipment, etc). The techniques of Table 4 and Table 5 are qualitatively compared on the basis of their expected emission reductions and costs in Figure 3 and Figure 4, respectively.

Table 4: Summary of emission reduction potential and additional costs of techniques for NO_x control in diesel NRMM (including rail)

Reference technology: Conventional CI diesel engine **Reference emission level:** 5-15 g/kWh		
Technique	Expected emission reduction	Cost per unit (Euro)
Exhaust Gas Recirculation (EGR)	25-45%	500-800 (indicative manufacturer cost)
Selective Catalytic Reduction (SCR)	70-95%	Retrofit cost: 6k-11k Per annum: +500 for urea +200 for maintenance –800 possible fuel savings
Conversion to natural gas (NG)	20-50%	Conversion cost: 13k-16k Per annum: –500-1,000 fuel cost benefits (depending on NG/diesel price ratio)
Dimethyl ether (DME)	40-60%	Comparable to conventional diesel (cost depends on production method and fuels taxation)
Emulsified diesel	10-20%	1,200-1,600 per annum (due to production costs of the end fuel and higher fuel consumption)
Renewable diesel	5-10%	Comparable to conventional diesel (more expensive to produce but can benefit from lower taxation)
Hybridization	40-50%	Initial (marginal) cost: 50k-100k Per annum: –5k-10k lower fuel costs

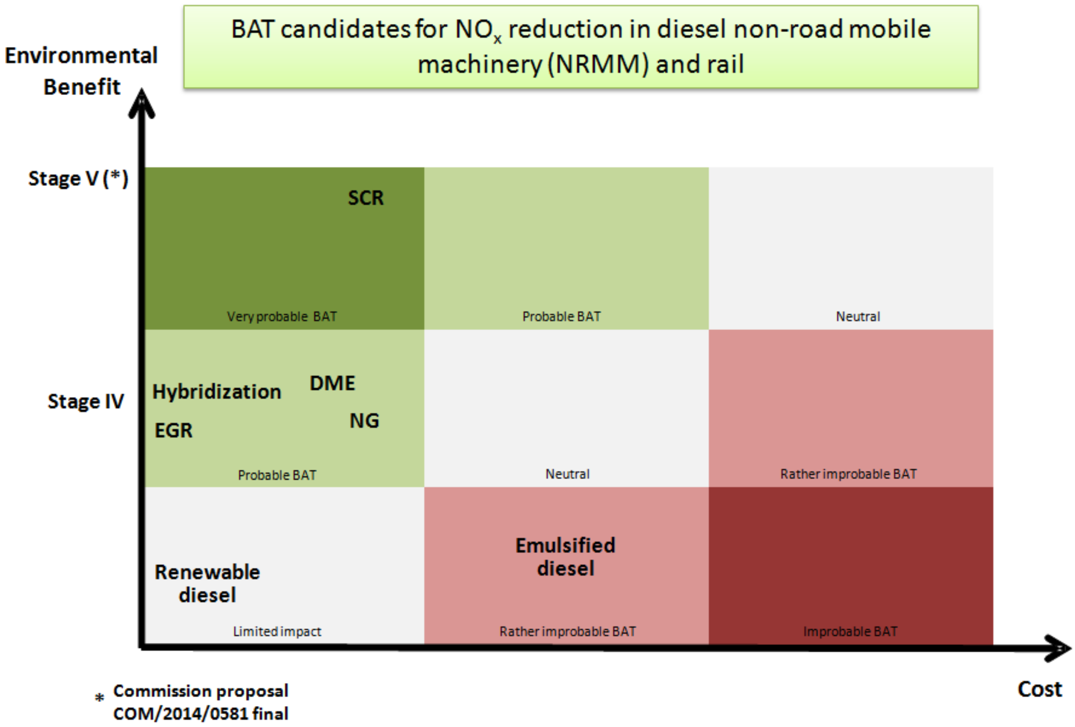

Figure 3: Relative cost-benefit comparison of BAT candidates for NO_x reduction in diesel NRMM (including rail)

Table 5: Summary of emission reduction potential and additional costs of techniques for PM control in diesel NRMM (including rail)

Reference technology: Conventional CI diesel engine **Reference emission level:** 0.2-1.0 g/kWh		
Technique	Expected emission reduction	Cost per unit (Euro)
Closed Crankcase Ventilation	5-15%	Retrofit cost: 250-3,000
Diesel Particle Filter (DPF)	80-95%	Retrofit cost: 4k-7k Per annum: +200-700 additional fuel and maintenance costs
Diesel Oxidation Catalyst (DOC)	20-40%	Retrofit cost: 1,500-2,500
Conversion to natural gas (NG)	85-95%	Conversion cost: 13k-16k Per annum: –500-1,000 fuel cost benefits (depending on NG/diesel price ratio)
Dimethyl ether (DME)	85-95%	Comparable to conventional diesel (cost depends on production method and fuels taxation)
Emulsified diesel	50-60%	1,200-1,600 per annum (due to production costs of the end fuel and higher fuel consumption)
Renewable diesel	15-25%	Comparable to conventional diesel (more expensive to produce but can benefit from lower taxation)
Low biodiesel blends (up to B20)	10-15%	Comparable to conventional diesel (more expensive to produce but have been incentivized)
Hybridization	40-50%	Initial (marginal) cost: 50k-100k Per annum: –5k-10k lower fuel costs

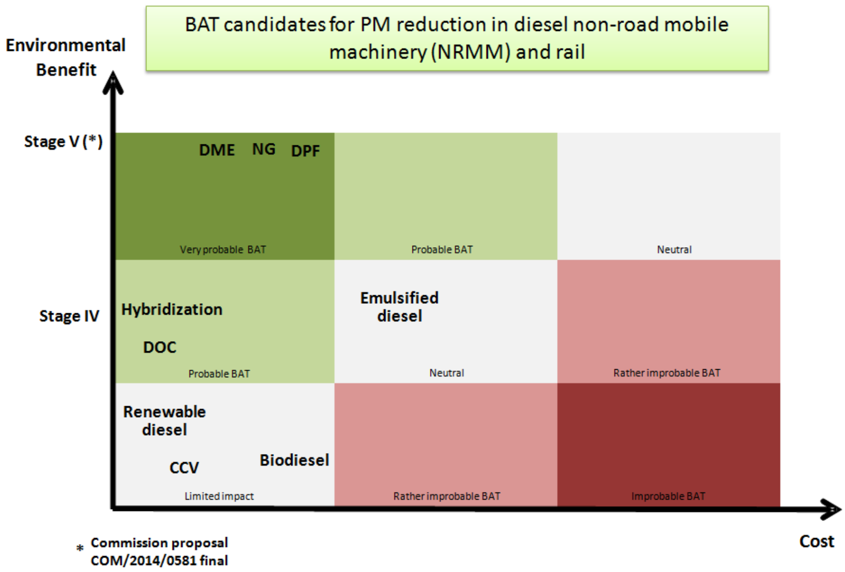

Figure 4: Relative cost-benefit comparison of BAT candidates for PM reduction in diesel NRMM (including rail)

88. Based on the above cost-benefit comparisons, and the technical, economical, or other limitations of the various BAT candidates, the following discussion summarizes specific BAT recommendations for the existing stock.

89. *SCR and DPF retrofits:* Aftertreatment retrofits for diesel NRMM is a widely used practice with usually very good results in terms of reducing emission levels. SCR (for NO_x control) and DPF (for PM control), or a combination of the two, is a widespread practice and can significantly reduce emissions, which is important to achieve for equipment used in environmentally sensitive environments (tunnels, mines, etc).

90. *Other retrofits:* DOC can be implemented in combination with DPF and SCR. As a stand-alone retrofit, it can be considered as BAT, especially in large-scale applications, being more tolerant to fuel sulfur than DPF, and when other technical factors (e.g. regeneration possibilities) exclude the applicability of DPFs. Closed crankcase ventilation (CCV) retrofits can be considered as BAT to control crankcase emissions of non-road diesel engines and it can be combined with a DOC or DPF. EGR on the other hand has limited potential due to technical difficulties integrating this on existing engines.

91. *Fuel switching:* Among the alternative fuels that can be used, only renewable diesel is suggested for existing engines. However, reductions that can be achieved are only moderate. Other fuels, such as natural gas, DME, and emulsified diesel, although they can offer some emission reductions and/or GHG benefits, cannot be recommended for widespread implementation due to various technical, economical, or other limitations. First generation biodiesel has low emission reduction effectiveness in blending levels currently allowed by regulations.

92. *Hybridization:* Replacement of old NRMM equipment with new hybrid one can achieve some emission reductions with additional fuel consumption benefits. However, the technology is not yet at mass production and the experience is very limited. In any case, it has the potential to be further established in the future for some engine categories (e.g. port handling equipment). Current applications have mixed results on both pollutant emissions and fuel consumption, very much depending on the match between hybrid operating strategy and duty cycle. Main limitations are purchase price premium, payback and return of investment, real fuel economy, and competing technologies.

93. In addition to the above techniques for emission control of the existing stock, repowering (i.e. replacing only the existing engine with a new one) can also be an effective strategy in certain cases. Because of the long useful lifetime of some NRMM equipment, repowering can provide the opportunity to install a new engine (or a new engine equipped with exhaust emission controls) that meets much lower emission standards than the original engine, often in conjunction with fuel economy benefits and lower maintenance costs. Repowering is particularly common to old diesel locomotives (engine replacement by generator sets) and can be extended to other machinery types, in particular when the engine comprises a relatively low fraction of the total cost of the machinery (e.g. cranes).

G3. Future engines/machinery

94. *Emission control for diesel concepts:* The major update expected in upcoming Stage V [6] is the introduction of wall-flow DPFs to control PM and particle numbers. In principle, this is expected to bring emission control on par with the latest on-road Euro VI emission stage. In-use recording of emissions using PEMS, included in the regulation, will guarantee the efficiency of the emission control during normal operation. Other enhancements in the

emission control may include more widespread implementation of EGR, SCR optimization, and possible combination of SCR and DPF in the same component.

95. *Alternative fuels and powertrains:* It is certainly more difficult for these concepts to penetrate in the NRMM market (than in on-road vehicles), since diesel combustion is by far preferable to such engine types owed to its high efficiency, durability and torque characteristics. In any case, the concepts that may have a potential in the future are natural gas, DME, and hybrid engines in specific applications (e.g. port handling equipment). Currently, the experience on all of them is very limited.

H. Diesel vessels (inland waterways)

96. Diesel vessels and engines are amongst the longest lived transport equipment with lifetimes that may exceed 30 years of age. Moreover, only a very small fraction of them are scrapped and replaced every year. Therefore, control measures addressing new vessels are expected to have a very slow real-world impact. On the contrary, measures targeting to existing ships and fuels are expected to have a larger impact. Below, the main measures for NO_x and PM control in diesel vessels are discussed. SO_x emissions can be controlled with the provision of low sulfur fuels.

97. *NO_x control with on-board aftertreatment devices:* SCR systems, conceptually similar to those used on road diesel vehicles, can be retrofitted on existing ships or can be used on new vessels to effectively control NO_x emissions. Efficiency issues in low-loads (<25%) and during slow steaming need some further attention.

98. *PM control with on-board aftertreatment devices:* Scrubbers are mostly known for the SO_x emission reduction they can achieve, but they can also have a positive impact on PM. They can be considered as BAT especially for new vessels (possibly combined with SCR for additional NO_x reduction); retrofit is possible, but there are technical limitations for implementation (space, weight, and ship stability constraints). DPF cannot be considered as a mainstream technology for ships. It is not ready for commercial operation and the expected effect on PM is not guaranteed to be as high as in automotive/NRMM. However, it may have a better future potential especially in inland waterways where low sulfur fuel is used.

99. *Alternative fuels:* An option to control both NO_x and PM could be a switch to LNG. This would additionally eliminate most of (climate relevant) black carbon emissions and allow operators to reduce dependence on fossil fuel oil. However, this requires major modifications and, hence, is considered economical mainly for newly built vessels. Fuel availability is currently considered the largest obstacle against its more widespread use. Attention should also be given to methane emissions from natural gas use in ships [20].

I. Sea going ships

100. Sea going ships (domestic or international maritime) use the same diesel engine types as inland waterways vessels (though somewhat larger); hence, similar on-board aftertreatment devices can be used for NO_x and PM control, as well as switching to LNG. Additional issues related to sea going ships and emission control techniques specifically targeted to those are discussed below.

101. *Emission control areas:* ECAs are specifically designed coastal areas, where air quality problems are acute and more stringent emission requirements are mandated for ships operating in these waters. So far this has been implemented as sulfur emission control area (SECA) requiring much lower sulfur content in the fuels, and as nitrogen emission control area (NECA) requiring much lower NO_x emissions from newly built (or major re-engined)

ocean-going vessels. In Europe, the Baltic Sea and the North Sea are specified as SO_x emission control areas, while in the Americas, SO_x and NO_x limits are applicable for the North American, United States and Caribbean Sea coastal waters. The emission control measures which are required in ECAs can be considered as BAT. These include particular fuels with maximum allowed sulfur levels and/or on-board emission control technologies, e.g. SCR and scrubbers. The latter have been successfully implemented to enable HFO operating vessels to enter ECAs. Extension of such emission control areas can lead to additional significant air pollution benefits for the affected areas.

102. *Fuel sulfur restrictions:* Final targets for equivalent fuel sulfur content include 0.5% m/m max limit outside of ECA zones and 0.1% m/m inside ECA zones to be gradually phased in for all fuels. These reductions can be achieved either with the use of low sulfur diesel fuel, or repowering of the engine with an alternative fuel (e.g. natural gas) or alternatively with the use of scrubber on board the vehicle. Economical, accessibility and technical limitations exist in either case. Any of these technical options may be a good candidate to meet reduced SO_x levels and final decisions depend on the ship type and its operations patterns.

103. *Port-level initiatives:* Several ports around the world have initiated programs in which power to the ships while at berth is provided by on-shore units, instead of running the ship engines. This approach may bring significant local air quality benefits for all pollutants. Universally agreed power delivery specifications is a limiting factor in extending such programs to more ports. Nation-wide emission reductions that can be achieved with such measures depend on the energy mix and the technologies used for power generation. Other port incentives include velocity control, reduction of maneuvering, etc.

J. Aircrafts

104. Low NO_x combustion and aircraft design improvements are two emission control techniques that can be implemented on each single aircraft by the manufacturer. Low NO_x combustion is achieved with lean premixed combustion and clean combustor design, including design of fuel injector, thermal liner, dynamics and operability, while peak temperature and time spent at this temperature is limited. Aircraft design improvements concern reduction of basic aircraft weight, improvement of aerodynamics and of overall specific performance of the engine, and design of aircrafts that fly at lower altitudes with reduced speed. In the latter case, attention should be given to possible negative impacts on fuel consumption and operating cost.

K. Electric trams, metros, and trolley buses

105. Electric trams, metros, and trolley buses do not generate tailpipe or evaporation emissions. However, they are a source of heavy metal emissions owed to the wear of their components and, in particular, friction on the rails and on the power line. Sparking that occurs in the power lines is an additional mechanism of heavy metal emissions. Emissions produced when vehicle poles glide and spark on the power lines are largely unknown and their contribution to an urban inventory is not accounted for. This does not mean they do not exist. Several studies in US and Europe have demonstrated increased concentrations of carbon and several metals in metro stations [15] [16]. Moreover, it should not be forgotten that electric power generation is also associated with significant pollution generation problems at the power station sites, depending on the energy mix of each country.

106. Using these public transportation systems is by itself an effective measure to reduce air pollution and improve air quality in cities, by shifting traffic from private cars (and diesel buses) on to cleaner and higher capacity electric means of transport. An indicative list of

additional measures related to the usage of these transportation systems in order to increase environmental protection and energy efficiency and improve air quality is given below.

- *Fleet and network measures:* modernization of existing stock and fleet management optimization, increase of commercial speed through segregated tracks and traffic management measures, inspection and maintenance of rails, fixed installations, etc.
- *General measures:* make the usage attractive (e.g. by park and ride policies, low fare policies, expansion of network, new routes), increase intermodality and reduce trip duration, use advanced traffic management systems.
- *Technology measures:* reduce friction by better design and materials, eliminate sparking by either mechanical or, most probably, electrical measures.

L. Non-technical measures

107. Non-technical measures are complementary to the technical ones in order to assist in further emission reductions. Directly comparing non-technical to technical measures could give misleading results. Therefore, non-technical measures can rather be considered as 'good practices' and have been referenced wherever deemed necessary in the previous discussion. A short description of the most commonly used non-technical measures is summarized at the end of 'Annex I: Description of individual BAT candidates'. In addition to the measures described there, various implementations may differ in practice and may be combined with specific funds and incentives schemes, tax exemption or tax reductions, etc.

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Annex I: Description of individual BAT candidates

VOC control in gasoline on-road vehicles

Two-way oxidation catalyst: Oxidation catalyst was the original type of auto catalyst mainly used in the past in gasoline vehicles. It is now rarely used in Europe because of the advantages of the three-way catalyst, but it may still be met in some parts of the world where emissions legislation is less stringent.

Secondary air injection: SAI is a technique used in mopeds and motorcycles to improve the efficiency of the oxidation catalyst. A supplementary air delivery system (e.g. reed valve) is incorporated in the exhaust stream to increase the oxygen content and provide excess air to the catalyst for better oxidation of HC and CO.

Multi-pollutant control in gasoline on-road vehicles

Three-way catalyst with oxygen sensor: TWC is the main component for emission control in gasoline vehicles (PFI and GDI), oxidizing CO and HC to CO_2 and water and reducing NO_x to nitrogen (N_2) in stoichiometric combustion mode. Its use became mandatory across Europe in 1992 for passenger cars and it is still used, only improved in its technical implementation, in all gasoline vehicles produced around the world today.

NO_x control in gasoline direct injection (GDI) on-road vehicles

Stoichiometric combustion: Most of the GDI engines today operate stoichiometrically (similar to port fuel injection engines) with a TWC for emission control. Stoichiometric GDI NO_x emissions do not differ substantially from conventional PFI vehicles.

Lean NO_x Trap: Lean burn GDI engines have difficulties in maintaining low NO_x emission levels during long periods of lean operation. LNT can be used in this case to reduce NO_x (instead of conventional TWC used in stoichiometric combustion mode). Because of engine control limitations and sulfur intolerance, not many commercial applications of such a concept (lean operation with LNT) are available today.

PM control in gasoline direct injection (GDI) on-road vehicles

Engine measures: Directly injecting the fuel in the cylinder decreases the time that the fuel has to mix with air and can induce wall impingement of fuel droplets. Both mechanisms may lead to increase of PM (and ultrafine particle) formation. PM (and PN) emissions can be controlled by modified injection strategy and an improved fuel system (i.e. high pressure “spray-guided” multi-injection).

Gasoline Particle Filter: GPF is also an effective technology to reduce particulate emission with high filtration performance under all engine operation points and ambient temperature variation, if engine measures alone prove not enough. The upcoming Euro 6c PN limit may mandate the use of GPF in some or in all GDI vehicles.

NO_x control in diesel vehicles/engines/vessels

Exhaust Gas Recirculation: It redirects portion of engine exhaust back into the engine to cool and reduce peak combustion temperatures and pressures, inhibiting NO_x formation. It may reduce engine power and requires electronic control strategy to ensure efficient operation.

Selective Catalytic Reduction: SCR uses ammonia as selective reducing agent, in the presence of excess oxygen, to convert NO and NO_2 to N_2 and water over a special catalyst system.

Different precursors of NH_3 can be used, e.g. urea in water carefully metered from a separate tank and sprayed into the exhaust system ahead of the SCR catalyst.

Lean-NO_x Trap: LNT functions by trapping NO_x in the form of a metal nitrate during lean operation of the engine. To avoid saturation of the trapping function, regeneration is commonly done by operating the engine in a fuel rich mode for a brief period of time (one or two seconds), giving up NO_x in the form of N_2 or NH_3. Used in light duty vehicles only.

<u>PM control in diesel vehicles/engines/vessels</u>

Diesel Oxidation Catalyst: DOC converts CO and HC to CO_2 and water; it also decreases the mass of particulate emissions by oxidizing some of the hydrocarbons that are adsorbed onto the carbon particles. It may increase the NO_2 fraction of total NO_x emissions.

Diesel Particle Filter: DPF removes PM by filtering diesel 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. Regeneration and cleaning system are needed to clean out non-combustible materials.

Scrubbers (for ships): Scrubbers are mostly known for the SO_x emission reduction they can achieve, but can also have a positive impact on PM. A scrubber can operate in open-loop, closed-loop, or hybrid mode. Design and installation on ship becomes a greater challenge than land applications and, when retrofitted, there are space, weight and ship stability constraints.

<u>VOC control (crankcase emissions) from diesel heavy duty vehicles / NRMM</u>

Closed Crankcase Ventilation: Crankcase emissions concern older vehicles and are released directly from the engine into the atmosphere through a vent or ‘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.

<u>VOC (and PM) control in gasoline non-road engines</u>

Oxidation catalyst: Catalytic control is limited by a number of factors and is used in special machinery only. Catalysts usually increase exhaust and surface temperatures (safety concerns). Rich combustion is used to decrease the temperature by excess fuel evaporation. This solution unavoidably deteriorates fuel economy and increases VOC and CO emissions.

Engine measures for 2-stroke engines: Incomplete combustion and scavenging losses of 2-stroke engines are addressed by the manufacturers with improved combustion and measures such as stratified scavenging, compression wave injection, and direct injection. Another measure is to enforce the replacement of 2-stroke engines with 4-stroke ones.

<u>PM control from component wear and abrasion (horizontal measure for on-road vehicles)</u>

Tyre, brake, and road surface measures: Adjustment of tyres, avoiding using studded tyres, ceramic brakes, brake particulate collection system, gentle braking, regenerative braking, adjustment of pavements and gritting material, use of coarser, wear resistant rock aggregates, alternative pavements, wet roads, dust binding materials.

<u>VOC control from fuel evaporation (horizontal measure for gasoline vehicles/engines)</u>

Activated carbon canister: It is used to trap vapors in the vent line of the fuel tank. It consists of a plastic housing containing a high specific surface area carbon adsorbent material which traps vapors. Canisters come in many sizes and are proportional to the volume of vapor generated in the fuel tank (basically the tank size). Carbon is available in different particle sizes and working capacities.

Low permeability tank: It reduces the permeability of plastics and polymers to gasoline in either the liquid or vapor phase. Advanced tanks consist of coextruded, multilayer construction with fluoropolymers to reduce permeation.

<u>Alternative fuels and powertrains</u>

Gasoline related fuels

Liquefied Petroleum Gas: LPG can be used either as a single fuel or in bi-fuelled vehicles in order to increase vehicle range and security. It is stored in pressurized tanks on board the vehicle in liquid form and it may be combusted in a normal gasoline type of engine that has to be adjusted to the specifications of the fuel.

Ethanol: Ethanol is mostly used blended in gasoline or, more seldom, as a neat fuel. Conventional vehicles can be upgraded for use with lower percentage blends by changing the parts that are under risk of corrosion. Appropriate calibration of the lambda sensor is required to retain stoichiometry.

Methanol: Methanol can be used as a neat fuel or in blends with gasoline and it is ignited in cylinder by a spark, in an identical process to gasoline combustion. Hence, a similar profile of regulated pollutants as gasoline combustion is to be expected. Use of methanol is of limited interest due to its more toxic and poisonous nature than ethanol. It may be more interesting as a fuel in fuel cell vehicles (direct methanol fuel cells).

Gasoline components: Aromatic free (alkylate) gasoline can be used in small non-road gasoline engines to reduce start up and normal (hot) operation emissions. Moreover, use of aromatic free and benzene free gasoline reduces PAH, benzene, and other toxic (including mutagenic) content of pollutants liberated with evaporation.

Diesel related fuels

Dimethyl ether: DME is a natural gas derivative that can be produced from natural gas, biomass or coal. It offers much higher volumetric energy content than natural gas and similar combustion properties. Economical issues, related to its production and distribution, have not satisfactorily been addressed yet.

Biodiesel: It is a mix of fatty-acid methylesters produced by the transesterification of vegetable oils. It is usually used as blend with conventional diesel (current regulations in Europe limit blends to B7, higher blends allowed in captive fleets).

Renewable diesel: It can be produced a) by hydrotreating of vegetable oil (HVO), or b) thermal conversion process (TCP), or c) biomass to liquid (BTL). Neat renewable diesel has several advantages over fuels produced with the transesterification process.

Emulsified diesel: A blended mixture of diesel fuel, water, and other additives that lowers combustion temperatures. The used additives prevent water from contacting the engine. Availability of fuel, performance problems, and decrease in power and fuel economy (which leads to significant increase of fuel cost in the long run) are the main limitations.

Low-sulfur fuel (for ships): The most straightforward method of reducing SO_x emissions is to simply reduce fuel sulfur content. Low-sulfur fuel, provided in all inland transport sectors, satisfactorily addresses this.

Gasoline-diesel related fuel

Natural gas: NG (in compressed or liquid form) consists mainly of methane. LNG differs from CNG only to the way that the fuels are stored on board the vehicle; the combustion of the two forms is identical, hence, results to identical emission profiles.

Powertrains

Hybrid vehicles: In these vehicles power is provided by two alternative powertrain systems, an internal combustion engine combined with an electric motor. The principal objective is to save fuel, but a partial electric drive can also help reducing emissions.

Electric vehicles: Battery electric or fuel cell electric vehicles are advanced technology vehicles for reduction of GHGs and air pollutant emissions. Such vehicles comprise an all-electric powertrain, where power to the wheels is provided solely by conversion of electric to mechanical power. The difference of the two concepts is in the way that energy is stored on the vehicle.

Hydrogen combustion: Apart from being used in fuel cells, an alternative pathway for utilization of hydrogen is that of its combustion in an internal combustion engine. This usually results to similar operation and performance characteristics to those of gasoline. In terms of conventional pollutant emissions, hydrogen combustion is free of CO and any traces of HC emissions are due to lube oil consumption.

Non-technical measures

Environmental zones: The primary aim of an environmental zone (or low emission zone) is to improve air quality by accelerating natural fleet turnover. Usually, it is a designated area where specific access restrictions are applied in order to reduce vehicle emissions and improve air quality. Regulations within the zone can include access restrictions to vehicles that do not comply with set emission standards and/or access restrictions based on the vehicle registration plate to days, pick hours or areas. Non-compliant vehicles entering the zone are usually charged with penalty fines.

Intelligent transport systems: These systems can be divided in the following categories, i) systems in the vehicle (driver behavior systems, advanced driver assistance systems, driver condition monitoring system), ii) navigation and information (systems used before, during, and after the trip), and iii) management and traffic control systems.

Enhanced inspection and maintenance schemes: Inspection and maintenance (I/M) is a way to check and improve the level of emissions, fuel consumption and safety of vehicles, and repair those that do not meet specific emission standards. These tasks are accomplished with visual checks, emission measurements, and use of various technical means/devices. Basic I/M performance standard usually includes idle testing, test of exhaust emissions, checking that critical emission control components are present and operational. Enhanced I/M performance standard includes exhaust test and purge testing of the evaporative control system, visual inspection of the catalyst and fuel inlet restrictor. On-board diagnostics (OBD) is a computer-based system that continually monitors the electronic sensors, emission control system, and catalytic converter, to ensure they are working as designed. Remote sensing devices (RSD) can also be used to measure emissions in the exhaust stream.

Accelerated scrappage schemes: Older and high-emitting vehicles meeting less stringent emission standards and with degraded pollution control equipment often emit a disproportionately high share of total emissions. Accelerated scrappage schemes are early retirement programs for older vehicles usually established by giving grants to vehicles owners. These schemes are quite likely to achieve environmental benefits, since newer vehicles meet more stringent emission standards, and fuel savings. Replacing an entire vehicle may be the best option for a vehicle that is near the end of its useful life or was manufactured before stringent emissions standards were put in place.

Modal shift to 'clean' public transport: Incentives and policies to promote modal shift to cleaner public transportation systems is an effective measure to reduce air pollution and improve air quality in cities (e.g. shifting traffic from private cars and diesel buses to higher capacity electric means of transport such as trams, metros, and trolley buses, or buses that use cleaner fuels, powertrains, etc).