Best Available Techniques for Mobile Sources

in support of a

Guidance Document to the Gothenburg Protocol of the LRTAP Convention

Technical Report

Final

Authors:

Giannis Papadimitriou[1], Valentini Markaki[1], Evi Gouliarou[1], Jens Borken-Kleefeld[2], and Leonidas Ntziachristos[1]

[1] EMISIA S.A., Thessaloniki, Greece

[2] IIASA, Laxenburg, Austria

13 March 2015

Contracting institution

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

Framework Contract ENV.C.3/FRA/2013/0013

Contractor

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

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

emisia MISSION FOR ENVIRONMENT

Table of contents

Acknowledgments

The authors of this report would like to sincerely thank the experts (stakeholders from research, industry, and other fields) who provided technical information and/or comments, feedback, and suggestions on the report on a voluntary basis. Specifically: Dirk Bosteels (AECC), Paul Greening (ACEA), Andreas Mayer (TTM), Seppo Mikkonen (NESTE OIL), Graeme Wallace (EFOA), Inmaculada Gómez Jimenez (OBSA), Joseph McCarney and Johnny Briggs (IACCSEA), Robert Ilg (Fraunhofer IBP), Holger Lochmann (STIHL), Peter Scherm (EUROMOT), Tony Rice (ICOMIA), Alisher Mamadzhanov (UNECE), Gaston Theis (FOEN), Mario Keller, Jacques Lemaire (AEEDA), Arjan Plomp (ECN).

We would also like to thank Peter Meulepas and Andre Zuber (DG ENV) for the excellent collaboration and for dealing with all administrative issues of the project. Furthermore, all participants who attended the meetings, and especially Tiziano Pignatelli, Jean-Guy Bartaire, and Nadine Allemand from the EGTEI group.

List of abbreviations and acronyms

ABS	Ammonium bisulfate
ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance System
ATV	All Terrain Vehicle
AVL	Automated Vehicle Location
BAT	Best Available Technique
BC	Black Carbon
BEV	Battery Electric Vehicle
BTL	Biomass To Liquid
CAD	Computer Aided Dispatch
CCV	Closed Crankcase Ventilation
CEE	Central and Eastern Europe
CH_4	Methane
CH_2O	Formaldehyde
CI	Compression Ignition
CNG	Compressed Natural Gas
CO	Carbon monoxide
CWI	Compression Wave Injection
DEF	Diesel Exhaust Fluid
DI	Direct Injection
DME	Dimethyl ether
DMFC	Direct Methanol Fuel Cell
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particle Filter
DWT	Deadweight Tonnage
EC	European Commission
ECA	Emission Control Area
ECE	Economic Commission for Europe
ECU	Electronic Control Unit
EDP	Emission Durability Period
EEC	European Economic Commission
EECCA	Eastern Europe, Central Caucasus and Asia region
EEV	Enhanced Environmentally-friendly Vehicle
EGR	Exhaust Gas Recirculation
EtOH	Ethanol

EU	European Union
EZ	Environmental Zone
FCEV	Fuel Cell Electric Vehicle
FFV	Flexi Fuel Vehicle
FWE	Fuel Water Emulsion
GDI	Gasoline Direct Injection
GHG	Greenhouse gas
GP	Gothenburg Protocol
GPF	Gasoline Particle Filter
GVW	Gross Vehicle Weight
H_2	Hydrogen
HAP	Hazardous Air Pollutant
HC	Hydrocarbon
HDV	Heavy Duty Vehicle
HFO	Heavy Fuel Oil
HVO	Hydrotreating of Vegetable Oil
IARC	International Agency for Research on Cancer
IC	Internal Combustion
I/M	Inspection and Maintenance
IMO	International Maritime Organization
ISA	Intelligent Speed Adaptation
ITS	Intelligent Transport Systems
IWW	Inland Water Ways
LCV	Light Commercial Vehicle
LDV	Light Duty Vehicle
LEZ	Low Emission Zone
LNG	Liquefied Natural Gas
LNT	Lean-NO_x Trap
LPG	Liquefied Petroleum Gas
LRTAP	Long-range Transboundary Air Pollution
LSFO	Low Sulfur Fuel Oil
LTO	Landing / Take-Off
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
MIL	Malfunction Indicator Light
MtOH	Methanol
N_2	Nitrogen

NAM	North America
NaOH	Sodium hydroxide (caustic soda)
NECA	NO_x Emission Control Area
NH_3	Ammonia
NMVOC	Non-Methane Volatile Organic Compounds
NO_x	Nitrogen Oxides
NRMM	Non-road Mobile Machinery
OBD	On-Board Diagnostics
OC	Organic Carbon
OEM	Original Equipment Manufacturer
OVC	Off Vehicle Charging
PAH	Polyaromatic hydrocarbons
PC	Passenger Car
PEMS	Portable Emission Measurement System
PFI	Port Fuel Injection
PM	Particulate Matter
PMP	Particle Measurement Program
PN	Particle Number
POC	Particle Oxidation Catalyst
RDE	Rear Driving Emissions
ROI	Return Of Investment
RSD	Remote Sensing Device
SAI	Secondary Air Injection
SCR	Selective Catalytic Reduction
SECA	Sulfur Emission Control Area
SI	Spark-ignition
SO_x	Sulfur Oxides
TCP	Thermal Conversion Process
TLC	Traffic Light Control
TSAP	Thematic Strategy on Air Pollution
TWC	Three-way catalyst
UFP	Ultra Fine Particles
ULSD	Ultra Low Sulfur Diesel
UN	United Nations
UNECE	United Nations Economic Commission for Europe
US	United States
VOC	Volatile Organic Compounds

WEU	Western Europe
WHO	World Health Organization
WMTC	Worldwide harmonized Motorcycle emissions Certification/Test procedure

1 Introduction

1.1 Scope and objectives

The aim of this report is to identify and evaluate 'Best Available Techniques' (BAT) to control and reduce emissions from mobile sources. This report provides the technical background for an update of the guidance document on mobile sources supporting the implementation of the Gothenburg Protocol (GP) of the UNECE LRTAP Convention.

This report summarizes both technical and non-technical measures to reduce emissions from new and existing engines and vehicles, mobile machinery, railcars, locomotives, sea and inland waterways vessels, and aircrafts. Technical measures include powertrain, fuel, and aftertreatment technologies that can be used to control emissions. Non-technical measures include infrastructural, regulatory and policy interventions that can also contribute in reducing emissions.

Those techniques that are proven in practice to be effective in emission control and economical in relation to the benefit they bring, are all candidates for 'best available techniques' (BAT) for emission reduction. A more precise definition of how different techniques can be elected as BAT is provided in subsection 2.5.

1.2 Background

The UNECE Convention on Long-Range Transboundary Air Pollution (LRTAP Convention)[1] aims at limiting atmospheric emissions of pollutants that have harmful impacts on human health and the environment. Specific Protocols under the Convention specify targets and agreements in reducing emissions of specific pollutants from the various anthropogenic sources.

The 1999 Protocol to the LRTAP Convention to abate acidification, eutrophication and ground-level ozone (Gothenburg Protocol)[2] entered into force in 2005 and set national reduction commitments for Parties, while at the same time applying specific emission limit values and/or 'Best Available Techniques' (BAT) for sources listed in the GP. The detailed description of BAT in each case is to be outlined in guidance documents that are adopted by the Parties and which are to be used when meeting the obligations under the GP.

The GP was revised in 2012[3] extending its scope of pollutants as well as the range of sources covered. The revision also called for an update of the guidance documents under the GP which have been partly updated and adopted by the Parties for application both under the current and revised GP[4]. Specifically for mobile sources the GP requires Parties to apply limit values for certain fuels and new mobile sources (product standards) identified in Annex VIII and that they should apply BAT to existing and new mobile sources.

The existing guidance document for mobile sources was adopted in 1999 by the Parties to the LRTAP Convention. Since then, major advances in engine and exhaust control techniques have been made, specifically to control fine particulate matter emissions. The revised GP also significantly extended the range of covered mobile source categories and

---

[1] http://www.unece.org/env/lrtap/welcome.html

[2] http://www.unece.org/env/lrtap/multi_h1.html

[3] http://www.unece.org/fileadmin/DAM/env/lrtap/full%20text/Informal_document_no_17_No 23_Consolidated_text_checked_DB_10Dec2012_-_YT_-_10.12.2012.pdf

[4] http://www.unece.org/environmental-policy/treaties/air-pollution/guidance-documents-and-other-methodological-materials/gothenburg-protocol.html

also included particulate matter emissions (PM) in the focus of control. Therefore, the old guidance document related to BAT for mobile sources needs to be updated.

The current report provides the analysis of the technical and the non-technical measures that are currently identified as BAT candidates, in order to provide the background technical information required to produce a new guidance document.

1.3 Content and structure of the report

This report is structured as follows:

- Section 2 describes the mobile sources and pollutants considered, health and environmental impacts, and general information of present emission levels. It also provides the methodological outline that has been followed to analyze the different BAT candidates, including sources, evaluation scheme and assessment methodology.
- Section 3 presents the main BAT candidates for different aggregate categories of mobile sources. A range of technical details is presented for each of the techniques identified (e.g. pollutants addressed, environmental benefit, synergies and side-effects, cost, technical and other limitations, and more).
- Section 4 performs the synthesis of the results per mobile source category and pollutant considered, using the methodology presented in Section 2, so that the selection of BAT is facilitated. Justification of BAT assessment is also provided.
- Finally, section 5 summarizes the main conclusions of the study. Based on the technical descriptions of section 3 and the assessment of section 4, this summary section contains specific recommendations for emission reduction clearly distinguished into measures for new vehicles/engines produced by OEMs (current situation), in-use vehicles/engines (existing stock), and future vehicles/engines (prospective or promising emerging technologies).

1.4 Statement on copyrights

Written permission has been acquired from the original source for each third party images used in this document. The original source of images or other third party information is properly referenced throughout the document.

2 Methodology

2.1 Mobile sources considered

Mobile sources include a wide range of vehicle types, engine categories, machinery, vessels, with different technologies and usage (e.g. from large deep sea ships of thousands of horsepower to light handheld equipment with fractions of a horsepower). Therefore, identification of possible BAT candidates is not a priori possible without distinction of the different mobile sources considered. Table 2-1 shows the range of mobile sources considered in this report.

Table 2-1: Individual vehicle, vessel, and equipment type to be considered for evaluation of BAT

Mode	**Vehicle**	**Type**	**Main fuel concerned***
Road	Mopeds	2-stroke	Gasoline
		4-stroke	
	Motorcycles	2-stroke	
		4-stroke	
	Passenger cars	Small	Gasoline / Diesel
		Lower-Medium	
		Upper-Medium	
		Executive	
	Buses	Urban	Diesel
		Coaches	
	Light Commercial Vehicles	N1 - I	Gasoline/Diesel
		N1 - II	Diesel
		N1 - III	
	Heavy Duty Trucks	Rigid <=14 t	
		Rigid >14 t	
		Articulated <34 t	
		Articulated >34 t	
Aviation	Aircraft	Jumbo and wide-body jet	Jet fuel
		Narrow-body jet	
		Regional jet	
		Turboprop	
		Supersonic jet	
Railway	Train	Locomotive	Diesel
		Urban train	
		Railcar	
Waterborne	Short sea shipping vessel	<5000 GT	HFO/MGO
		5000-30000 GT	
		>30000 GT	
	Deep sea shipping vessel	>1000 GT	HFO
	Inland waterway ship	0-250 t	MGO
		250-3000 t	
		>3000 t	
	Recreational crafts		Gasoline/Diesel
Non-road	Industrial, construction, agricultural and forestry machines	<75 kW	Diesel
		>75 kW	
	Agricultural and forestry tractors	<75 kW	
		>75 kW	
	Household and gardening	Handheld	Gasoline
		Non handheld <225 cm^3	
		Non handheld >=225 cm^3	
Electric public transport systems	Tram, metro, and trolleybuses		

* The main fuel concerned should be seen as a reflection of the combustion concept considered. For example, passenger cars may also operate on liquefied petroleum gas (LPG), however its combustion (and hence the BAT candidate techniques) do not fundamentally differ to gasoline combustion.

The above classification originates mainly from the TRACCS[5] project with extensions for off-road equipment according to EMEP/EEA AEIG[6]. In performing the analysis of the various BAT options, we have considered the applicability of the techniques for each of these vehicle/engine/vessel types and fuels.

It should be noted that in view of the continuous tightening of emission limits, vehicles, vessels and other non-road machinery are expected to be increasingly equipped with more advanced powertrain and aftertreatment systems. At the same time, there is an increase in the diversification in powertrain (conventional, hybrid, battery electric, range extender, etc.) and fuel types. The above classification tries to balance on one hand the need to provide the necessary vehicle and technology detail to assess the suitability of different BAT options and, on the other, the need to work on a manageable level of analysis.

2.1.1 Mobile sources not included in the Gothenburg Protocol

Annex VIII of the GP does not include all transport modes identified in Table 2-1. In particular, the following are not covered: aircraft emissions, sea going ships (short sea or deep sea), and (electric) trams, metros, and trolley buses.

However, emissions from airplanes, in particular during the landing and take-off (LTO) phases are included in the national inventories in the framework of LRTAP; hence, there is a need to include them in the transport modes to be considered. Similarly, domestic shipping is also included in the national inventories. Deep sea shipping (international maritime) is not included in national inventories; however, (i) such vessels use the same engine types as domestic vessels (though somewhat larger), and (ii) there are considerations how to include international shipping emissions to inventories. Hence, there is the need that these are covered in this report. Electric trams, metros, and trolley buses do not have tailpipe emissions, but they produce heavy metal emissions due to the wear of their components and, in particular, sparking that occurs in the power lines.

Based on the above, this report covers all mobile sources identified in Table 2-1, including those not covered in the GP. However, it is clarified that aviation and electric public transport systems (tram, metro, and trolley buses) are only addressed in section 3 (technical description of BAT candidates) and no further detailed assessment (with the evaluation scheme and methodology described below) is provided for them. This is because, for aviation, the two techniques which are described can be implemented by the manufacturers only; hence, no assessment can be made to compare various options and propose measures that can be implemented by public authorities. For electric trams, metros, and trolley buses, which produce heavy metal emissions, the existing literature and assessment studies are very limited; hence, only a list of indicative measures is provided without further assessment.

In addition to the above mobile sources, there are two emission sources missing from Annex VIII of the GP for all modes. These are:

- non-exhaust PM emissions from component wear and abrasion,
- NMVOC emissions from fuel evaporation.

Relevant studies (in particular for the road sector) show increasing relative contribution of these two sources due to less stringent emission controls compared to exhaust emission sources. Therefore, BAT recommendations for these two separate pollution generation mechanisms are also identified.

[5] http://traccs.emisia.com

[6] http://www.eea.europa.eu//publications/emep-eea-guidebook-2013

2.1.2 Source categories for BAT assessment

The individual vehicle/vessel types in Table 2-1 provide an extended list for which the suitability of each technique should be assessed. This would make the analysis overwhelming with multiple repetition of information. In order to make the analysis useful, we have aggregated the individual types to higher level categories that are of similar relevance for assessment of each technique. When a technique is considered to have a differentiated impact depending on the type considered, then the individual types from Table 2-1 for which a differentiation is expected are identified and clearly presented in the analysis. The following aggregated mobile source categories have been selected to assess each of the available techniques:

- Gasoline road vehicles (mopeds, motorcycles, passenger cars, light commercial vehicles)
- Diesel light duty road vehicles (passenger cars, light commercial vehicles)
- Diesel heavy duty road vehicles (heavy duty trucks, buses)
- Gasoline engines in non-road mobile applications (hand-held and non hand-held equipment, i.e., household and gardening)
- Diesel engines in non-road mobile applications (industrial, construction, agricultural, and forestry machinery, trains)
- Gasoline engines in boats and recreational crafts
- Diesel engines in vessels, propulsion as well as auxiliary engines
- Aircrafts[7]
- Trams, metros, and trolley buses[8]

In some cases that this is considered relevant, some of these categories are further aggregated in Section 3.

2.2 Pollutants considered

The following pollutants are covered by the Protocol:

- SO_2
- NO_x
- NH_3
- VOC
- $PM_{2.5}$

Mobile sources are a key category to PM and NO_x. Sulfur components may also be important for fuels with high sulfur content such as heavy fuel oil (HFO) used in sea going vessels. In all other applications, including road, rail, aviation and IWW, low sulfur fuels are used and the contribution of the sectors in total anthropogenic sulfur emissions is decreased. Even in cases where this category heavily contributes to sulfur emissions, the obvious technique to control the problem is to reduce the sulfur in the fuel. Hence, most emphasis is given to BAT options for controlling PM and NO_x emissions (cf. also Figure 2-1 to Figure 2-4 below).

[7] Only addressed in section 3 (technical description of BAT), no further assessment in section 4.

[8] -//-

VOC can be important from gasoline vehicles and engines, while NH_3 emissions may also increase for some of the emission aftertreatment concepts considered. Hence, the emphasis which is given in each pollutant varies depending on the application and the mobile source category considered.

Other pollutants may also be significant and may also be affected by the use of each BAT technique. Again, specific discussion is provided when a potential BAT has a significant impact on a species not included in the GP. The most relevant pollutants for mobile sources include CO, direct NO_2, PM_{10}, PN (particle number), BC (black carbon), smoke, individual heavy metal emissions, as well as some other organic species such as aldehydes, ketones, polyaromatic hydrocarbons, etc. Also, impacts on greenhouse gases (GHG – CO_2, N_2O, CH_4) are considered. A discussion on the effect of techniques on these pollutants is included in the following sections when this is deemed necessary.

In addressing the control of pollutants, the following two effects need to be taken into account in the evaluation of the various techniques:

1. Synergies: Certain techniques may result to synergetic effects for some of the pollutants. For example, an oxidation catalyst used to reduce hydrocarbon emissions has been shown to also have a positive effect in terms of PM reduction. Such synergistic effects are clearly identified and generally boost the probability that a technique is considered as BAT.
2. Secondary effects: Several of the techniques used in the past to control a particulate pollutant were proven to have detrimental effects to some other pollutants. The best known example is the implementation of oxidation catalysts in urban buses (e.g. in London) that led to a decrease in PM but a significant increase in NO_2 emissions. Such phenomena are also considered in the study and are clearly earmarked.

2.2.1 Health and environmental impacts

If we could burn gasoline or diesel perfectly in pure oxygen it would produce only carbon dioxide (CO_2), water vapor, and energy[9]. However, in reality there are always some emissions of unburned and partially burned fuel, giving carbon monoxide (CO), hydrocarbon (HC) and – especially for diesel engines – particulate matter (PM), plus nitrogen oxides (NO_x) formed from nitrogen present in the air. Health and environmental experts have concluded that emitted pollutants adversely affect human health and contribute to acid rain, ground-level ozone and reduced visibility. Specifically[10]:

- *Human health:* exhaust emissions can lead to serious health conditions like asthma, allergies, and respiratory problems; they can worsen heart and lung disease, especially in vulnerable populations such as children and the elderly, and there is increasing evidence that they may cause cancer in humans.
- *Environment:* the engines used in mobile applications (especially the diesel ones) emit particulate matter (soot), nitrogen oxides which contribute to the production of ground-level ozone (smog) and acid rain, hydrocarbons, air toxics, and black carbon; these emissions can damage plants, animals, crops, and water resources.
- *Global climate:* climate change affects air quality, weather patterns, sea level, ecosystems, and agriculture; reducing greenhouse gas (GHG) emissions from mobile sources can help address climate change and improve energy security.

---

[9] http://www.aecc.eu/en/Air_Quality_and_Health_Effects.html

[10] http://www.epa.gov/cleandiesel/basicinfo.htm

A short summary of health and environmental risks per main vehicle pollutant follows.

- *Particulate matter (PM)* is mainly soot particles with volatile hydrocarbons and some sulfate and metallic residues from the fuel and engine lubricant. Particles are found in the air in a range of sizes. Diesel engines are responsible for the majority of ultra-fine particulates (less than one micron in diameter or PM_1). There is evidence that fine and ultra-fine particles are linked to increased rates of premature death for causes such as cardiovascular and lung disease. Also, WHO IARC[11] has classified untreated diesel exhaust as carcinogenic to humans. In addition, diesel PM is primarily made of black carbon (BC) which is a short-lived climate forcer with a high global warming potential.
- *Nitrogen oxides (NO_x)* react with hydrocarbons in sunlight to form harmful ozone and photochemical smog. Ozone in turn causes breathing difficulties and damages plants and materials, and is also a climate gas. NO_x is furthermore a contributor to acid rain and eutrophication, both affecting ecosystems and their biodiversity. NO_2 alone is implicated with direct respiratory illnesses and other health problems.
- *Hydrocarbons (HC)* and particularly *Volatile Organic Compounds (VOC)* contribute to photochemical smog in the atmosphere. Some HCs, such as benzene, are known carcinogens.
- *Carbon dioxide (CO_2)* is the final product of all combustion processes and the major contributor to the 'greenhouse' effect.

2.3 General information of present emission levels

Mobile sources contribute varying amounts to the total pollutant emissions, depending on pollutant, the region and its economic structure. The following charts present an overview about current emissions in four major UNECE regions: North America (NAM), Western Europe (WEU), Central and Eastern Europe (CEE), and the Eastern Europe, Central Caucasus and Asia Region (EECCA)[12].

[11] http://www.iarc.fr/index.php

[12] The following countries are associated with

WEU (17 countries): Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom;

CEE (18 countries): Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, FYROM, Malta, Poland, Romania, Serbia and Montenegro, Slovak Republic, Slovenia;

EECCA+TURK (12 countries): Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Russia, Tajikistan, Turkey, Ukraine, Uzbekistan;

NAM (2 countries): Canada, United States of America.

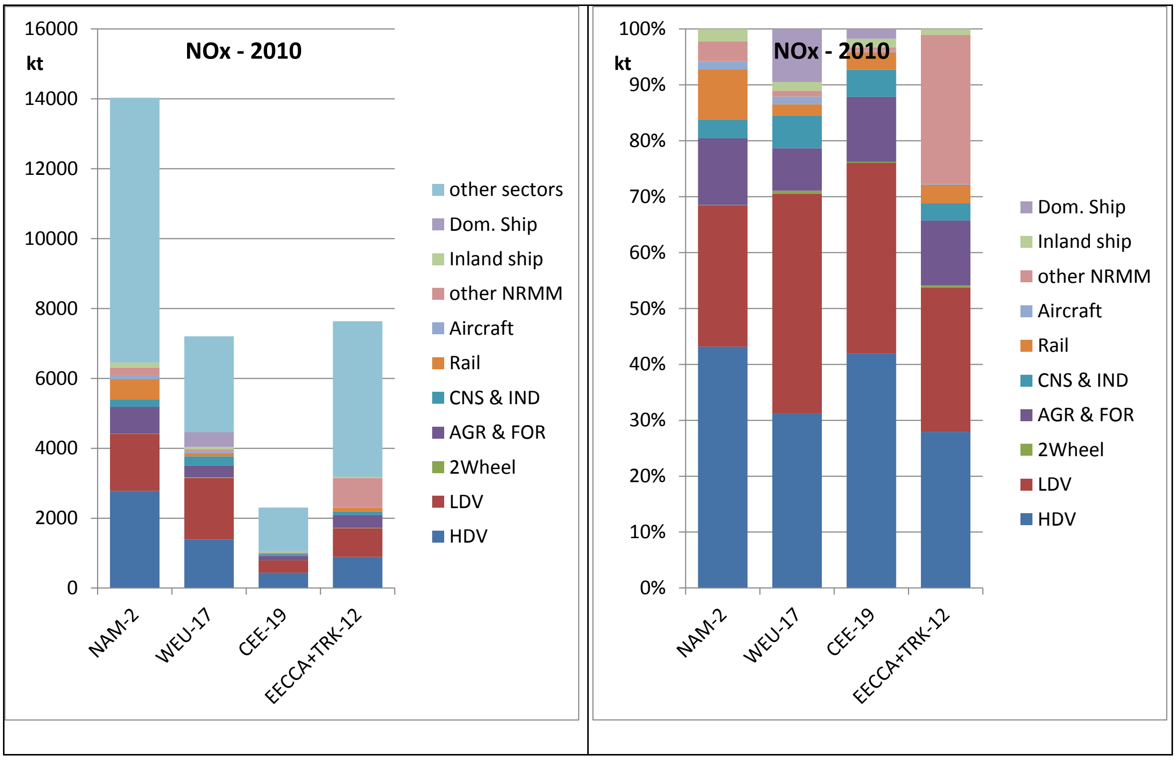


Figure 2-1: NO_x emissions from mobile sources in different UNECE regions in year 2010: Absolute emissions with all sources (left), relative distribution of mobile sources only (right). Data source: WEU and CEE: GAINS TSAP; NAM and EECCA: GAINS ETP.

Mobile sources contribute about 40% to 60% of all NO_x emissions in the different UNECE regions in the year 2010 (Figure 2-1, IIASA GAINS 2014). The biggest single sources are (diesel powered) cars and trucks, followed by agricultural tractors. Diesel powered rail traction can be a significant source in some countries, as well as ships. Transmission stations in long pipeline networks may also be a significant source.

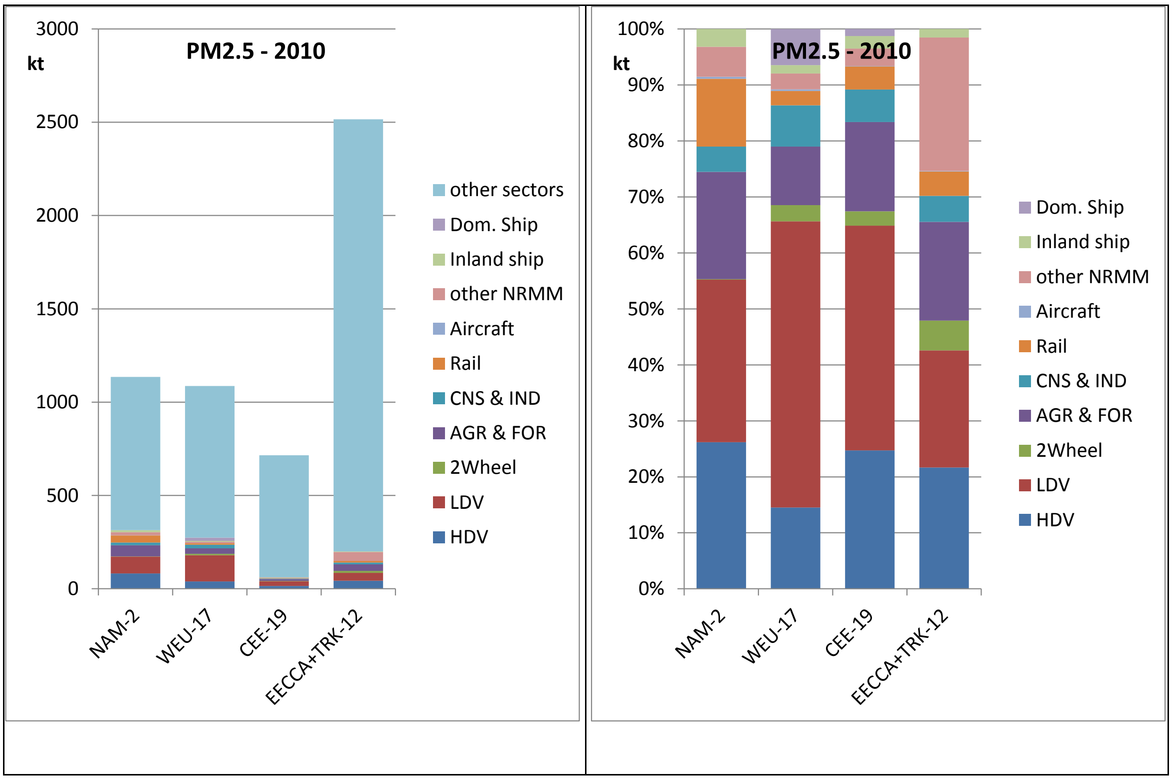


Figure 2-2: $PM_{2.5}$ emissions from mobile sources in different UNECE regions in year 2010: Absolute emissions with all sources (left), relative distribution of mobile sources only (right). Data source: WEU and CEE: GAINS TSAP; NAM and EECCA: GAINS ETP.

Mobile sources contribute about 10% to 30% of all $PM_{2.5}$ emissions in the different UNECE regions in the year 2010 (Figure 2-2, IIASA GAINS 2014). The biggest single sources are (diesel powered) cars and trucks, followed by agricultural tractors and construction machinery. Rail, ships and pipeline transmission stations can also be significant sources in individual countries.

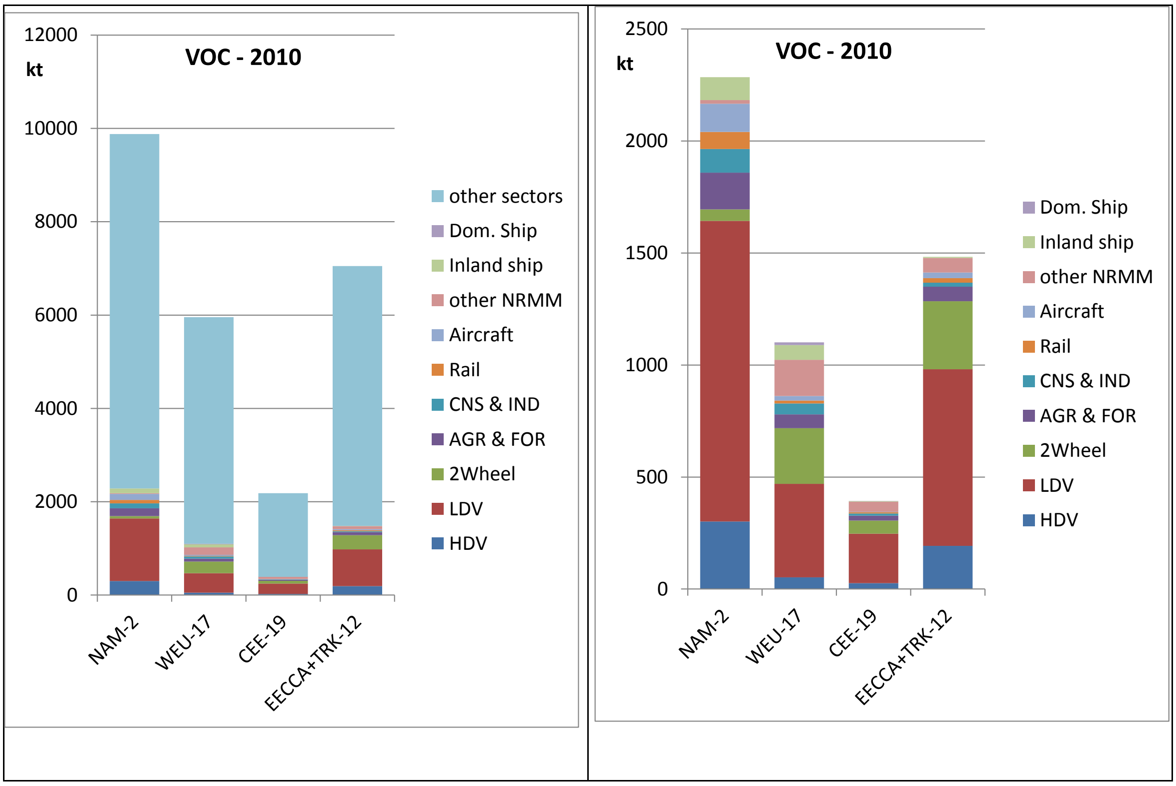


Figure 2-3: VOC emissions from mobile sources in different UNECE regions in year 2010: Absolute emissions with all sources (left), absolute emissions of mobile sources only (right). Data source: WEU and CEE: GAINS TSAP; NAM and EECCA: GAINS ETP.

Mobile sources contribute about 20% of all VOC emissions in the different UNECE regions in the year 2010 (Figure 2-3, IIASA GAINS 2014). The biggest single sources are (gasoline powered) cars, mopeds and motorcycles, followed by smaller machinery, and agriculture machines, and in some countries aircrafts and pleasure crafts.

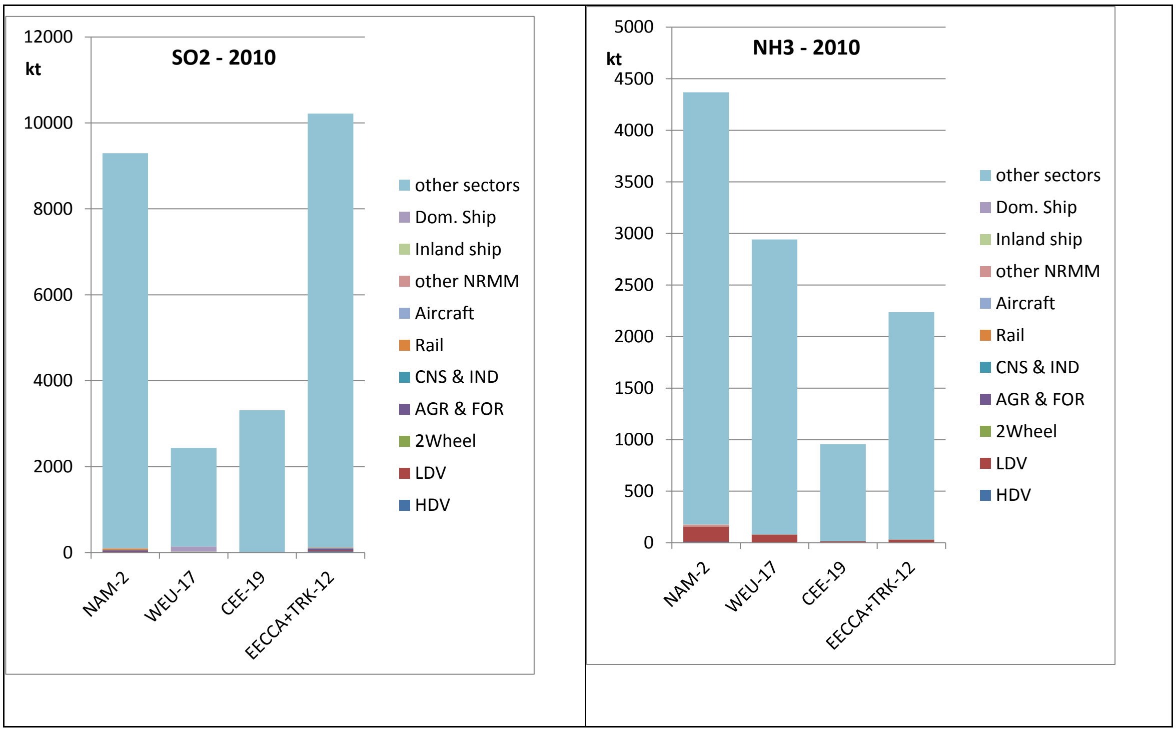


Figure 2-4: Emissions from mobile sources in different UNECE regions in year 2010: SO_2 (left) and NH_3 (right). Data source: WEU and CEE: GAINS TSAP; NAM and EECCA: GAINS ETP.

Land based mobile sources contribute less than 1% to total SO_2 emissions and 1% to 4% of total NH_3 emissions in the different UNECE regions in the year 2010 (Figure 2-4, IIASA GAINS 2014). Emissions of SO_2 essentially depend on the sulfur contents of the fuels used. Generally marine fuels have still very high sulfur levels, but also diesel fuel in individual countries may not be desulfurized. NH_3 emissions originate mostly from catalyst equipped (gasoline) cars and some other non-road mobile machinery.

Given this situation, most attention is on control of NO_x and PM emissions from mobile sources, and road vehicles in particular. In addition, controls of VOC emissions are treated with some detail in this document.

2.4 Data collection and organization

An extensive collection of information on available control techniques has been performed. This includes literature analysis, interviews with stakeholders from research and industry, as well as data collection by questionnaire. Here, we summarize comprehensive and up-to-date information on the technical and environmental performance, boundary conditions and infrastructural requirements, technical and economic feasibility and potential restrictions. The performance is considered separately for each pollutant controlled by the GP, as well as for potential side-effects on GHG and other pollutants and, in cases deemed important, on fuel efficiency.

Estimates of additional costs related to emission control measures are an important part of the assessment. Here, we take the perspective of a regulator/policy maker and consider potential costs and benefits over the full lifetime of the equipment (an indicative period of 10 years is usually assumed), at social discount rate of 3% p.a., and using costs to the consumer/end user. Typical cost values were collected from publicly available sources.

These were streamlined to the extent possible to come up with comparable values. The approach followed is explained in subsection 2.5.3.

2.5 Operational definition of BAT for mobile sources

The overarching question that the guidance document has to respond to is: "*What are the best proven solutions that can be applied to reduce emissions from mobile sources?*" However, neither the CLRTAP nor the GP provide an exact definition on what BAT for mobile sources stands for. For consistency, the tentative definition used for mobile sources here is based on the respective guidance document on control techniques for emissions from stationary sources[13]. In this (stationary sources) document, BAT is defined as "*the most effective and advanced stage … to prevent and … to reduce emissions and the impact on the environment as a whole*". This definition is general enough to be applicable to mobile sources as well.

The term 'available' refers in the guidance document for stationary sources to technical and economic conditions; the technique in question needs to be "*developed to a scale that allows implementation in the relevant … sector, under economically and technically viable conditions…*" Whether a technique is economically viable for the operator or customer is hard to judge a priori (the guidance document for stationary sources mainly lists costs for control measures without judging on viability). The term 'best' means most effective in achieving a high general level of protection of the environment as a whole.

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

2.5.1 Criteria used to identify BAT

The following criteria are used in identifying the environmental and economic suitability of a potential BAT option:

(i) emission and effect of regulated pollutants,

(ii) emission and effect of non-regulated pollutants,

(iii) energy efficiency,

(iv) consumption of fossil or renewable resources,

(v) consumption of rare or precious elements,

(vi) emission of noise,

(vii) use of hazardous material, wastes and recyclability.

Related work in the framework of the Scientific Assessment of Strategic Transport Technologies provides justification for the transport-related criteria (Aparicio et al., 2012; Ntziachristos, 2012).

Some techniques may present trade-offs, i.e. having less emissions for some pollutant, but higher for some other, or performing worse on other criteria. Such trade-offs are clearly

[13] http://www.unece.org/fileadmin/DAM/env/documents/2012/air/Guidance_document_on_control_techniques_for_emissions_of_sulphur__NOx....pdf

signaled and options for reducing negative impacts are discussed, e.g. by combining with other techniques.

2.5.2 Reference technology

We consider BAT candidates for both, existing and new vehicles. Together with the different technical level in the UNECE regions, this means that different technologies have to be considered as current standard (or reference) technologies against which BAT candidates are assessed. Any alternative (viable) technology that performs better, i.e. has lower pollutant emissions, without performing worse on any other criteria, can be considered better compared to the reference technology.

For each vehicle or vessel type we define a reference technology which is used as a baseline for the assessment and comparison of different techniques. The reference technology does not coincide with the latest emission control technology, but with good common practice (a technology still met often in many countries, with known environmental impacts that should be addressed). We then make the implicit assumption that the relative impact of a BAT remains within the same order of magnitude for more advanced or less advanced technologies. When this assumption is obviously violated, this is clearly identified in the evaluation.

2.5.3 Evaluation scheme

The assessment of a technique as BAT is based on a two-step approach. First, the cost-effectiveness of the various techniques is assessed using the boxes of Figure 2-5. In this way, a technique is evaluated in terms of its expected cost and environmental benefit for a specific pollutant, and then it is allocated to one of the nine classes shown below. The various techniques are compared to each other on a relative scale and their placement within the boxes of the evaluation grid is indicative.

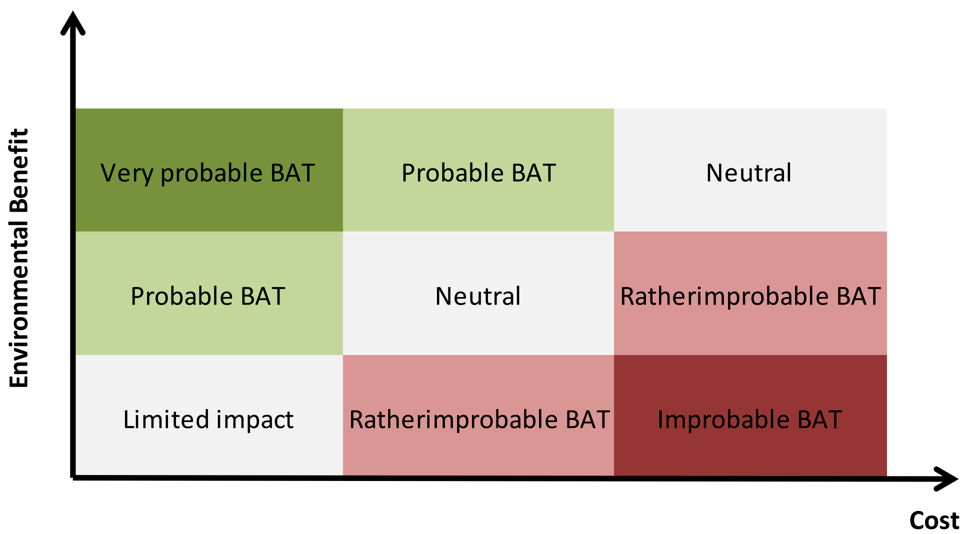


Figure 2-5: Nine classes for the relative cost-benefit comparison of potential BAT techniques for a specific pollutant and mobile source category (1st step of evaluation scheme)

The exact cost and environmental benefit of each technique will vary with application. Therefore the position of individual techniques on this graph is not to be scaled; rather this should correspond to the relative assessment of the individual techniques. In general, measures that fall in the green cells appear more probable to be recognized as BAT than measures in the red cells (the important for each technique is the box, not the placement within the box). The following clarifications have to be provided with respect to environmental effects and costs:

- Environmental Effect

  The environmental effect of the implementation of each particular technique refers to the total environmental benefit expected (emission reduction potential) if all individual vehicles of reference technology are affected by the technique proposed. Obviously, the benefit decreases proportionally as the extent of implementation of each technique decreases. The expected effect should be seen for individual measures and is not to be used cumulatively if more than one measure are implemented at the same time.

- Cost

  Costs depend on production volumes, technical specifications and desired performance, discount rates, etc. and all this in turn usually changes with time. Therefore, costs given are intended as indicative of the magnitude, not exact end-user costs. They usually comprise purchase and registration costs, ownership and maintenance costs, end-of-life costs, etc. Costs are expressed on a per vehicle basis, to create a meaningful order-of-magnitude value that can be used for comparison of the various technical and non-technical measures identified. Depending on the extent of the implementation (whether all vehicles or some vehicles only are affected by the measure) this cost unit will fluctuate upwards or downwards. Again, to simplify our approach, and in consistency with the approach followed in the “environmental effect” analysis, each measure is considered to affect the whole fleet of vehicles.

Once promising BAT candidates are identified through the cost-effectiveness assessment, compliance or exclusion with respect to the additional criteria is checked, as illustrated in the flow chart diagram of Figure 2-6. This approach examines whether there are any limiting factors (and possible solutions to those) that limit the wide implementation of the techniques identified as probable BAT.

The techniques that have been allocated to the dark green area (i.e. the ‘best’ at first sight) are examined first and, depending on the outcome of the process, less attractive options are gradually examined (hierarchically going from dark green to light green, to grey, to light red and, finally, dark red).

There are two critical questions that have to be answered with this approach in a successive order:

- First (Q1), one has to answer whether despite the low relative extra costs and the high environmental benefit of the selected technique, does the particular measure fail a minimum threshold for any of the other criteria? For example, use of SCR in agricultural tractors is an option that can be economically manageable and has proven benefits in terms of NO_x emissions. However, low sulfur fuel is required and urea additive will need to be made available in the rural areas of the region considered. This is currently not the case in the whole UNECE region.
- The second question (Q2) examines whether reasonable interventions can be foreseen. In the above example, this could e.g. be a ban of high sulfur diesel and expansion of the additive network. Indeed, the decrease of sulfur in the fuel may be considered as BAT for SO_x emissions in other sectors; hence SCR may become a reasonable policy intervention for the future.

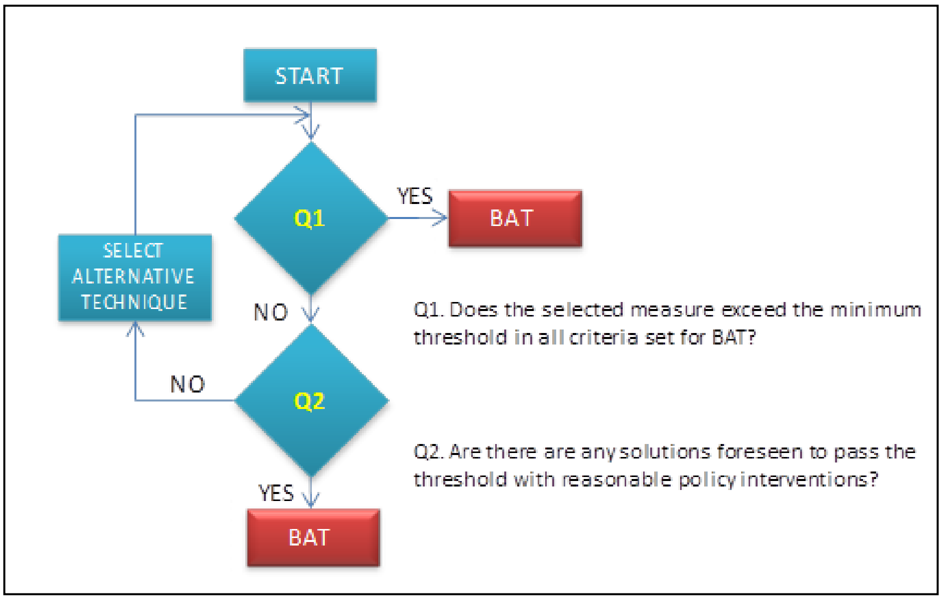


Figure 2-6: Flow chart diagram of BAT selection process (2nd step of evaluation scheme)

With this approach, a multi parametrical problem is addressed in two levels. First, two key criteria (environmental benefit and costs) are examined on a relative scale to order options in terms of BAT probability. Then, the remaining criteria are examined in a more qualitative manner by identifying potential bottlenecks and major obstacles. Such an approach is suggested as a starting point for the discussions and for consideration of the different stakeholders.

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

In general, the above approach for assessment of various emission control techniques intends to provide an evaluation scheme that considers both the relative position of each technique in the boxes of Figure 2-5 and the limiting factors in the flow chart of Figure 2-6.

2.6 Range of techniques considered

The techniques considered as BAT candidates first and foremost consider engine and exhaust aftertreatment measures which have long been established as key technologies in reducing emissions of pollutants.

Second, fuel improvements are considered. Apart from the main fuels used in each vehicle type (Table 2-1), fuel switching (i.e. use of alternative fuels and biofuels) is also considered as possible BAT candidate. The fuels and energy carriers that are mainly considered are: conventional fuels (gasoline/diesel/HFO/MGO/jet fuel), LPG and CNG/LNG, 1st and 2nd generation biodiesel, renewable diesel, emulsified diesel, bioethanol, (bio)methanol, biokerosene, DME, H_2, and electricity.

Although current vehicles are already compatible with E10 (10% vol. ethanol blended in gasoline) and B7 (7% vol. biodiesel blended in diesel), higher biofuel blends may be additional options for certain vehicle types. Also, different control techniques might be considered depending on the type of fuel used (e.g. higher activated carbon quality and low permeation materials may be required for controlling evaporative emissions when ethanol blends are used).

Non-technical measures may also offer significant benefits, as they can be applied to a wide range of the existing fleet. For example, implementation of environmental zones and Intelligent Transport Systems (ITS), introduction of fiscal incentives, enhanced inspection and maintenance schemes, scrappage schemes, etc.

3 Technical description of BAT candidates

In this section, each BAT candidate is described in detail. The emission control techniques considered here are for both new and existing vehicles and machines, and include technical and non-technical measures. The following issues are clarified below, concerning the applicability of BAT on new or existing vehicles:

- Some of the BAT candidates described in this section may concern only the existing stock (e.g. accelerated scrappage schemes), some may 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 (therefore, they mainly concern the new vehicles). In any case and in order to avoid unnecessary duplications, each technique is described only once; if there is a worth mentioning distinction between new/retrofit application, then this is presented here and further clarified in the next sections 4 and 5.
- In order to retain consistency and assist in the assessments of section 4, the environmental benefit (% reduction range of pollutants addressed) of each technique is given relative to a reference technology (described in this section and further elaborated in section 4). This given range is intended as indicative of the magnitude of the emission reduction that can be achieved and, in general, can be considered the same for both new and retrofit applications.
- A similar approach is also followed for costs; that is, the given cost range is intended as indicative of the magnitude of the cost to implement the technique considered. If this technique can be retrofitted, then the cost is usually given for a retrofit application; otherwise, it is given appropriately, e.g. manufacturer cost, cost as a replacement part, etc. 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 we only give an indicative order-of-magnitude estimate as guidance for further assessment.

In general, the description follows to the extent possible the outline as described below, in order to retain consistency in comparing different techniques.

1. General description
    - name of technique
    - pollutants addressed
    - engine/vehicle/vessel types considered
    - short description of technique
2. Environmental benefit and costs
    - specific claims (% reduction range of pollutants addressed)
    - costs for implementation and operation, i.e. to the final customer
3. Environmental side-effects
    - impact on fuel consumption (positive/negative impact and typical % effect)
    - non-regulated pollutants and trade-offs (e.g. on NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)
4. Limitations and implementation issues

- limitations in applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)
- ease of implementation (technology or expertise required, infrastructural needs, etc.)
- maintenance and operation (additional maintenance and/or monitoring requirements, etc.)
- durability/lifetime of emission control equipment
- impacts on safety (users, citizens, etc.)

5. Examples, references and other points
   - any other comments or remarks not addressed above
   - successful examples of implementation (with literature reference)
   - references for further details

The justification of selecting the key measures presented in this section is to seek for solutions in order to address the main environmental problems related to mobile sources. These can be summarized as follows:

- Gasoline road vehicles
  - VOC from mopeds/motorcycles
  - NO_x and PM from gasoline direct injection (GDI) vehicles
- Diesel road and non-road vehicles
  - NO_x and PM tailpipe emissions
  - VOC crankcase emissions
- Small gasoline engines non-road
  - PM and VOC emissions
- Diesel vessels
  - NO_x, PM, sulfur
- Aircraft
  - NO_x (no clear evidence for PM)
- Component wear and abrasion
  - PM

The range of techniques considered is summarized as follows.

a) Measures organized per mobile source and key pollutant addressed:
   - Engine measures
   - Exhaust aftertreatment
b) Horizontal measures:
   - Non-exhaust PM control (component wear and abrasion)
   - Control of VOC from fuel evaporation
   - Fuels, fuel switching, alternative powertrains (multiple impacts on pollutants)
c) Non-technical measures

Due to their importance for air quality, measures discussed here focus on $PM_{2.5}$ and NO_x controls, but VOC and sulfur are also addressed separately where this is appropriate. As mobile sources are not a key category for ammonia, effects on NH_3 and the other pollutants identified in section 2.2 are not separately presented but, where necessary, are discussed within the "environmental side effects" assessment of each individual technique.

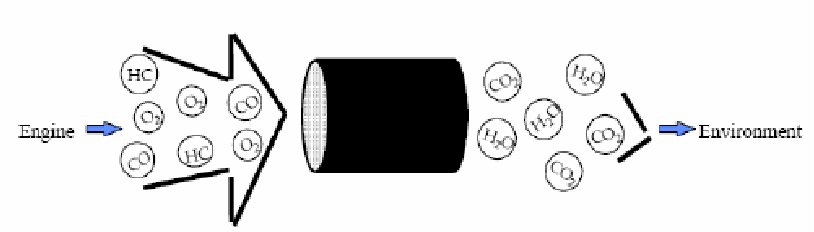
Engine measures and exhaust aftertreatment provided per mobile source category and key pollutant will be compared with techniques from the horizontal categories in order to make the final assessment in section 4. For example, Exhaust Gas Recirculation (engine measure), Selective Catalytic Reduction and Lean-NO_x Trap (aftertreatment) are described for NO_x control in diesel vehicles category. These options will be compared with techniques such as hybridization (alternative powertrain) and natural gas (fuel switching) for the assessment in section 4.

3.1 Gasoline road vehicles

3.1.1 Volatile organic compounds (VOC)

3.1.1.1 Two-way oxidation catalyst

Table 3-1: Summary information for two-way oxidation catalyst

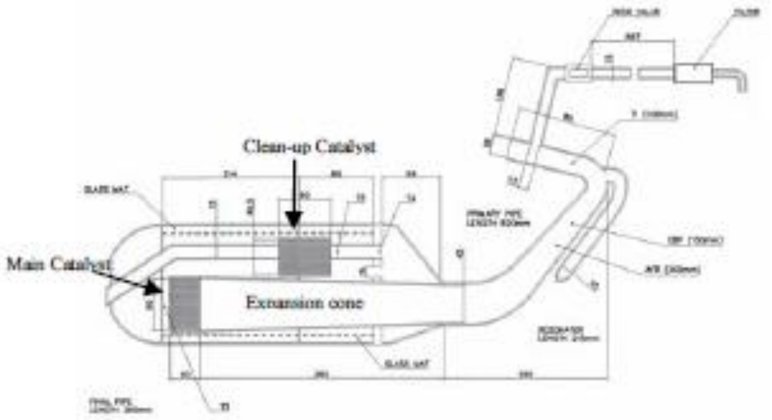
General Description	
Name of technique	**Two-way oxidation catalyst**
Pollutants addressed	Mainly: VOC, CO, NMVOC, Synergies: CH_2O (formaldehyde), HAPs (EPA classified Hazardous Air Pollutants)
Engine/vehicle/vessel types considered	• All gasoline vehicles: passenger cars, light commercial vehicles, mopeds and motorcycles. • Mainly used in the past, now superseded by three-way catalysts.
Short description of technique	• Oxidation catalysts are the original type of auto catalysts and were used from the mid-1970's for gasoline cars until superseded by three-way catalysts. They look much the same as three-way catalysts and their construction and composition is similar but slightly less complex. • Oxidation catalysts convert unburned hydrocarbons (HC) and carbon monoxide (CO) to carbon dioxide (CO_2) and water (H_2O) by burning (oxidizing) them over a platinum and/or palladium (see figure below[14]), but have little positive effect on nitrogen oxides (NO_x). They are now rarely used on gasoline cars in Europe because of the advantages of three-way catalysts, but they are still used in some parts of the world where emissions legislation is less stringent. They may also be used on some CNG buses. 
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	Reference technology: Spark-ignition gasoline engine without aftertreatment control • VOC (60-95%), CO (70-95%), NMVOC (40-90%)
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	€150–€300 (indicative cost as a replacement part for passenger cars, even lower for smaller vehicles).
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	No significant impact on fuel consumption.
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O	Reduction in CH_2O (60-95%), HAPs (60-95%).

[14] Source of figure: http://www.meca.org/galleries/files/Motorcycle_whitepaper_final_081908.pdf

emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• Two-way oxidation catalysts have little positive effect on nitrogen oxides (NO_x) and have been superseded for this reason by three-way catalysts. • To work most effectively, a catalytic converter needs to reach an optimum temperature; it may not reach this in a short journey (devices to pre-warm the catalyst may be necessary). • Precious metals required for production (platinum, palladium).
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	• When catalytic converters were first introduced, most vehicles used carburetors that provided a relatively rich air-fuel ratio. O_2 levels in exhaust stream were generally insufficient for catalytic reaction to occur efficiently, so most installations included secondary air injection into the exhaust stream to increase available oxygen and allow the catalyst to function. • Many newer vehicles do not have air injection systems. Instead, they provide a constantly varying air-fuel mixture that quickly and continually cycles between lean and rich exhaust.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	• Vehicle must be regularly serviced (according to manufacturer specifications) to ensure that the catalyst works correctly. • Fuel additives must be carefully used, since they may not be suitable for use with the catalytic converter.
Durability/lifetime of emission control equipment	• The emission reduction effectiveness of a catalytic converter may be severely degraded or even completely destroyed over time. • Excessive vibration or shock, excessive heat, lack of proper vehicle maintenance or improper operation each can cause catalyst failures. • The catalytic converter can also be damaged if the engine is not properly tuned and excess fuel enters the component. • In addition, converters can be structurally damaged in vehicle accidents or by hitting an obstruction on the road.
Impacts on safety (users, citizens, …)	Trained personnel should make any modifications.
References and Other Points	
Comments or remarks not addressed above	No other comments or remarks.
Successful examples of implementation	Manufacturers of mid-1970's equipped gasoline vehicles with catalytic converters to comply with stricter regulation of exhaust emissions; two-way catalytic converters were rendered obsolete by TWCs that also reduce NO_x.
References for further details	- http://www.meca.org/galleries/files/MECA_aftermarket_converter_white_paper_1209_FINAL.pdf - http://www.aecc.eu/en/Technology/Catalysts.html - http://catalyticconverters.com/ - http://catiatutorialsv5.blogspot.gr/2012/02/exhaust-system.html

3.1.1.2 *Secondary air injection (SAI) (for mopeds and motorcycles)*

Table 3-2: Summary information for secondary air injection (SAI)

General Description	
Name of technique	**Secondary air injection (SAI)**
Pollutants addressed	Mainly: VOC, CO, Synergies: white smoke
Engine/vehicle/vessel types considered	• Mainly for mopeds and motorcycles • Improves the effectiveness of two-way oxidation catalyst
Short description of technique	• Air/fuel calibration of both two-stroke and four-stroke engines directly affects the release of undesirable pollutants to the environment. Supplemental air delivery systems may be incorporated in the exhaust stream to increase the oxygen content in the exhaust (e.g. in the form of a simple reed valve). • The typical two-stroke scavenging losses provide one source of oxygen, but this is usually not enough; in advanced two-stroke engine designs, oxygen availability is improved by adjusting the air-to-fuel ratio to provide a relatively lean intake charge. • Additionally, a simple passive secondary air injection system (SAI), such as a reed valve, can be installed upstream of the catalyst to provide excess air to the catalyst (see figure below[15] – two catalysts in combination with SAI).  • The rich air/fuel calibration of four-stroke engines may limit the availability of oxygen for post-combustion oxidation of HC and CO and, therefore, four-stroke engines must use a secondary air injection system upstream of the catalyst (e.g. reed valves).
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	• Two-stroke: the addition of SAI is estimated to increase average reduction efficiencies to approximately 80% for VOC (from 50% without SAI) and to 75% for CO (from 50% without SAI). • Four-stroke: two-way oxidation catalyst in combination with SAI achieves estimated reduction efficiencies of 80% for VOC and 90% for CO.
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	€80–€150 (indicative cost as a replacement part).
Environmental Side Effects	
Impact on fuel consumption	No significant impact on fuel consumption.

[15] Source of figure: http://www.meca.org/galleries/files/Motorcycle_whitepaper_final_081908.pdf

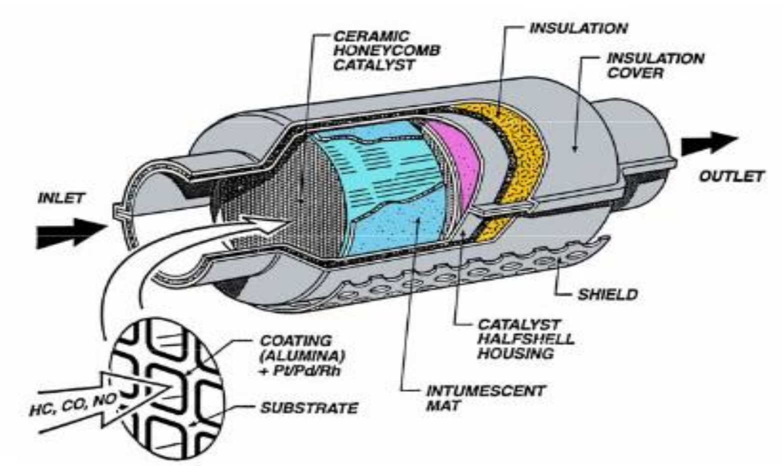
(positive/negative impact and typical % effect)	
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	No significant impact on non-regulated pollutants.
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	No specific limitations in applicability.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	Easy to install.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	No specific maintenance requirements.
Durability/lifetime of emission control equipment	Trouble free operation.
Impacts on safety (users, citizens, …)	Trained personnel for installation.
References and Other Points	
Comments or remarks not addressed above	SAI improves catalyst light-off performance during cold start.
Successful examples of implementation	Mostly recommended in countries where two wheelers usage (especially two-stroke) has been expanding rapidly over the past several years (e.g. urbanized areas of Asia).
References for further details	- http://www.meca.org/galleries/files/Motorcycle_whitepaper_final_081908.pdf - http://dspace.mit.edu/bitstream/handle/1721.1/57990/648965340.pdf?...1

3.1.1.3 Three-way catalyst (TWC) with oxygen sensor control

Table 3-3: Summary information for three-way catalyst (TWC) with oxygen sensor control

<table>
<tr><th colspan="2">General Description</th></tr>
<tr><td>Name of technique</td><td>Three-way catalyst (TWC) with oxygen sensor control</td></tr>
<tr><td>Pollutants addressed</td><td>Mainly: NO_x, VOC, CO, Synergies: CH_2O (formaldehyde), HAPs (EPA classified Hazardous Air Pollutants)</td></tr>
<tr><td>Engine/vehicle/vessel types considered</td><td>All gasoline vehicles: passenger cars, light commercial vehicles, mopeds and motorcycles.</td></tr>
<tr><td>Short description of technique</td><td>

- Three-Way Catalyst (TWC) has been the primary emission control technology on light-duty gasoline vehicles (and gasoline engines in general) since the early 1980s. Although the primary components and function of a TWC have remained relatively constant, each of these components (catalytic coating, substrate, mounting materials) has gone through a continuous evolution and redesign process in order to improve the overall performance while maintaining a competitive cost effectiveness of the complete assembly.
- The reduction and oxidation catalysts are typically contained in a common housing, however in some instances they may be housed separately. A three-way catalytic converter has three simultaneous tasks (these three reactions occur most efficiently when the catalytic converter receives exhaust from an engine running slightly above the stoichiometric point):
  - reduction of nitrogen oxides to nitrogen and oxygen,
  - oxidation of carbon monoxide to carbon dioxide,
  - oxidation of unburned hydrocarbons (HC) to carbon dioxide and water.
- The catalyst uses a ceramic (as in figure below[16]) or metallic substrate with an active coating incorporating alumina, ceria and other oxides and combinations of the precious metals – platinum (Pt), palladium (Pd), and rhodium (Rh). The substrate typically provides a large number of parallel flow channels to allow for sufficient contacting area between the exhaust gas and the active catalytic materials without creating excess pressure losses.



- Operates in a closed-loop system including a lambda or oxygen sensor to regulate air:fuel ratio. It oxidizes CO and HC to CO_2 and H_2O while reducing NO_x to nitrogen. Fast light-off catalysts allow the catalytic converter to work sooner by decreasing exhaust temperature required for operation.

</td></tr>
</table>

[16] Source of figure: http://www.meca.org/galleries/files/MECA_aftermarket_converter_white_paper_1209_FINAL.pdf

Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	Reference technology: Spark-ignition gasoline engine without aftertreatment control • NO_x (90-95%), VOC (60-95%), CO (90-95%)
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	€600–€1,200 (indicative cost as a replacement part for passenger cars and light commercial vehicles).
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	No significant impact on fuel consumption.
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	• Reduction in CH_2O (80-95%), HAPs (80-95%). • Unwanted reactions can occur, e.g. formation of hydrogen sulfide (H_2S) and ammonia (NH_3).
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• To work most effectively, a catalytic converter needs to reach an optimum temperature (devices to pre-warm the catalyst may be necessary, e.g. electrically heated catalyst systems). • TWCs are effective when the engine is operated within a narrow band of air-fuel ratios near stoichiometry, such that the exhaust gas oscillates between rich (excess fuel) and lean (excess oxygen) conditions. However, conversion efficiency falls very rapidly when the engine is operated outside of that band. Under lean engine operation, there is excess O_2 and the reduction of NO_x is not favored. Under rich conditions, the excess fuel consumes all of the available O_2 prior to the catalyst, thus only stored oxygen is available for the oxidation function. • Precious metals required for production (platinum, palladium, rhodium).
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	• Closed-loop control systems are necessary because of the conflicting requirements for effective NO_x reduction and HC oxidation. The control system must prevent NO_x reduction catalyst from becoming fully oxidized, yet replenish O_2 storage material to maintain its function as an oxidation catalyst. • Oxygen sensors are used to monitor the exhaust oxygen content before and after the catalytic converter and this information is used by the electronic control unit (ECU) to adjust the fuel injection.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	• Vehicle must be regularly serviced (according to manufacturer specifications) to ensure that the catalyst works correctly. • Fuel additives must be carefully used, since they may not be suitable for use with the catalytic converter.
Durability/lifetime of emission control equipment	• The emission reduction effectiveness of a catalytic converter may be severely degraded over time; excessive vibration or shock, excessive heat, lack of proper vehicle maintenance, or improper vehicle operation each can cause catalyst failures. • The catalytic converter can also be damaged if the engine is not properly tuned and excess fuel enters the component; in addition, converters can

	be structurally damaged in vehicle accidents or by hitting an obstruction. • More thermally durable catalysts with increased stability at high temperature allow the catalytic converter to be mounted closer to the engine and increase the life of the catalyst.
Impacts on safety (users, citizens, …)	Trained personnel should make any modifications.
References and Other Points	
Comments or remarks not addressed above	Improvements: • Electrically heated catalyst systems. They use a small catalyst ahead of the main catalyst. The substrate, onto which the catalyst is deposited, is made from metal so that, when an electric current is passed, it will heat up quickly. This brings the catalyst to its full operating temperature in a few seconds. • Optimized systems. The use of additional catalytic converters close to the exhaust manifold (close-coupled catalysts) reduces the time to light-off in the cold start and, therefore, the total emissions. Light-off times have been reduced from as long as one to two minutes to a few seconds. Improved substrate technology, combined with highly thermally stable catalysts and oxygen storage components, allows the close-coupled catalyst approach to meet latest standards. Improved oxygen storage components stabilize the surface area of the washcoat, maximize the air:fuel 'window' for three-way operation and indicate the 'health' of the catalyst for OBD systems.
Successful examples of implementation	- Development of Advanced and Low PGM TWC System for LEV2 PZ EV and LEV3 SULEV30. Matsuzono, Y., kuroki, K., Nishi, T., Suzuki, N. et al. SAE Technical Paper, 2012-01-1242, 2012. - Utilization of advanced Pt/Rh TWC technologies for advanced gasoline applications with different cold start strategies. Schmidt, J., et al. SAE 2001-01-0927. - Practical experience with the EHC system in the BMW Alpina B12. Hanel, F-J., et al. SAE 970263.
References for further details	- http://www.aecc.eu/en/Technology/Catalysts.html - http://www.aecc.eu/content/pdf/Emissions Control Technologies to meet current and future European vehicle emissions legislation.pdf - http://www.meca.org/technology/technology-details?id=5&name=Catalytic%20Converters - http://www.meca.org/galleries/files/MECA_aftermarket_converter_white_paper_1209_FINAL.pdf - http://www.meca.org/galleries/files/LEV_III_Tier_3_white_paper_final.pdf - http://www.corning.com/WorkArea/showcontent.aspx?id=60285 - http://catalyticconverters.com/ - http://catiatutorialsv5.blogspot.gr/2012/02/exhaust-system.html

3.1.2 Nitrogen oxides (NO_x) from direct injection vehicles

3.1.2.1 Stoichiometric combustion for gasoline direct injection (GDI) vehicles

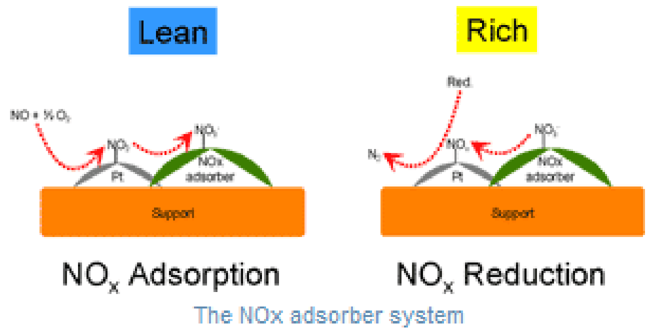
Table 3-4: Summary information for stoichiometric combustion for GDI vehicles

General Description	
Name of technique	**Stoichiometric combustion for GDI vehicles**
Pollutants addressed	NO_x
Engine/vehicle/vessel types considered	Gasoline direct injection vehicles (passenger cars, light commercial vehicles)
Short description of technique	• One of the main changes in recent years on SI engines is the development of gasoline direct injection (GDI) engines. Early fuel injected engines used a port injection approach where fuel was injected into a port to allow it to evaporate and mix uniformly with the air. This provides little control over the air and fuel mixture entering the cylinder. • GDI engines inject the fuel directly into the combustion chamber allowing varying injection strategies depending on engine load. At high load, fuel is injected into the engine early during the induction stroke giving a stoichiometric or rich air/fuel ratio. A GDI engine can also operate in an ultra lean combustion mode during cruising situations when little acceleration is required. • The reason that partial lean burn GDI engines have not reached broad application in the market is the difficulty in meeting NO_x emissions regulation during long periods of lean operation. GDI engines can also be designed for stoichiometric operation and make use of three-way catalysts for lowering exhaust emissions.
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	Reference technology: Gasoline direct injection lean-burn engine • NO_x (70-85%)
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	Cost for manufacturer: €85-€290 (individual components of a GDI system with “bottom up” approach at incremental costs for injectors, fuel pumps, etc., 2008 data from http://www.epa.gov/otaq/climate/420r08008.pdf).
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	Fuel consumption increase by ~5% (compared to lean).
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	Positive impact on non-regulated pollutants imposed by use of TWC.
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological	Imposed by use of TWC.

barriers, behavioral changes, etc.)	
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	• Well-established technology. • Can basically be implemented only by the manufacturer.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	Vehicle must be regularly serviced (according to manufacturer specifications) to ensure proper operation.
Durability/lifetime of emission control equipment	Imposed by use of TWC.
Impacts on safety (users, citizens, …)	No safety impacts.
References and Other Points	
Comments or remarks not addressed above	To improve mixing and reduce rich PM formation, some stoichiometric and all lean GDI engines operate in a multi-injection mode. This mode of operation injects the fuel over several pulses that can span both the intake and compression stroke.
Successful examples of implementation	Several manufacturers have released GDI engines in recent years.
References for further details	- http://www.meca.org/technology/technology-details?id=11&name=Enhanced%20Combustion%20Technologies - http://www.epa.gov/otaq/climate/420r08008.pdf

3.1.2.2 *Lean NO_x Trap (LNT) for gasoline direct injection (GDI) vehicles*

Table 3-5: Summary information for Lean-NO_x Trap for GDI vehicles

General Description	
Name of technique	**Lean NO_x Trap (LNT) for GDI vehicles** (also known as NO_x adsorber)
Pollutants addressed	NO_x
Engine/vehicle/vessel types considered	Gasoline direct injection vehicles (passenger cars, light commercial vehicles)
Short description of technique	• Conventional three-way catalyst used on gasoline engines needs a 'richer' environment with less oxygen in the exhaust than is available in lean-burn GDI engines. So, other approaches are required, like LNT that can be used in these lean applications. • LNTs function by trapping the NO_x in the form of a metal nitrate during lean operation of the engine. Under lean air to fuel operation, NO_x reacts to form NO_2 over a platinum catalyst. • Following a certain amount of lean operation, the trapping function will become saturated and must be regenerated. This is commonly done by operating the engine in a fuel rich mode for a brief period of time (one or two seconds is enough) and giving up NO_x in the form of N_2 or NH_3 (see figure below[17]). 
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	Reference technology: Gasoline direct injection lean-burn engine • NO_x (70-85%)
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	€800–€1,000 (indicative cost as a replacement part).
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	Fuel economy penalty (~2%) because of required brief periods of rich operation to regenerate (also a corresponding increase in CO_2 emissions).
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	Ammonia (NH_3) is generated in the LNT during the rich regeneration phase.

[17] Source of figure: http://www.aecc.eu/en/Technology/Adsorbers.html

Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	Low-sulfur fuel is required, because NO_x adsorbers also adsorb sulfur oxides resulting from the fuel sulfur content.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	No specific implementation requirements.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	• Periodically, the system has to automatically run a short "desulfation" cycle to remove any adsorbed sulfur compounds (which are more difficult to desorb). • This "DeSO$_x$" regeneration procedure requires high temperatures (typically around 700^{o}C) and requires about 15 to 20 minutes to be completed.
Durability/lifetime of emission control equipment	The durability of LNT is linked directly to sulfur removal by regeneration.
Impacts on safety (users, citizens, …)	Trained personnel required for installation.
References and Other Points	
Comments or remarks not addressed above	LNT (NO_x adsorber) should not be confused with Lean NO_x Catalyst (LNC), which refers to the selective catalytic reduction of NO_x by hydrocarbons (an entirely different emission control technology).
Successful examples of implementation	- https://www1.eere.energy.gov/vehiclesandfuels/pdfs/merit_review_2010/veh_sys_sim/vss017_wagner_2010_o.pdf - http://energy.gov/sites/prod/files/2014/03/f10/ace022_daw_2012_o.pdf
References for further details	- http://www.aecc.eu/en/Technology/Adsorbers.html - http://www.aecc.eu/content/pdf/Emissions Control Technologies to meet current and future European vehicle emissions legislation.pdf - http://www.meca.org/technology/technology-details?id=5&name=Catalytic%20Converters - http://www.meca.org/galleries/files/MECA_diesel_retrofit_white_paper_1009.pdf - http://www.corning.com/WorkArea/showcontent.aspx?id=60285

3.1.3 Particulate matter (PM) from direct injection vehicles

3.1.3.1 Engine measures for gasoline direct injection (GDI) vehicles

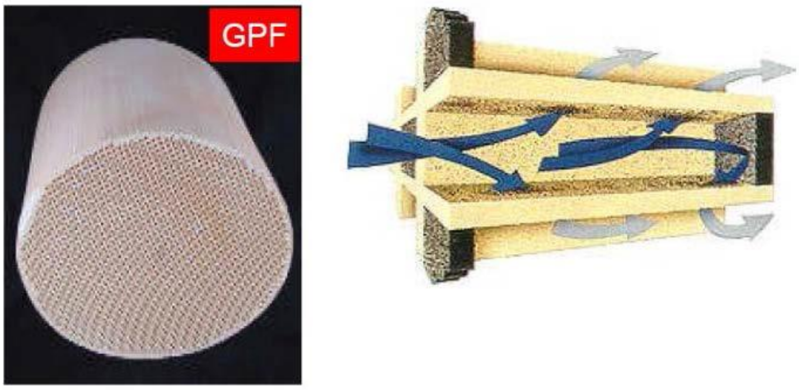
Table 3-6: Summary information for engine measures for GDI vehicles

General Description	
Name of technique	**Engine measures for GDI vehicles (high pressure "spray-guided" multi-injection)**
Pollutants addressed	PM, PN, BC
Engine/vehicle/vessel types considered	Gasoline direct injection vehicles (passenger cars, light commercial vehicles)
Short description of technique	• GDI (gasoline direct injection) improves engine fuel economy and power by directly injecting fuel into the cylinder rather than upstream of the intake valve. This allows the engine to operate in a diesel-like lean combustion mode at light engine loads or in a stoichiometric combustion mode similar to PFI (port fuel injection) engines in other situations. • Lean combustion mode of operation reduces the amount of time the fuel has to mix with the air, which can increase PM and UFP (ultra fine particles) formation due to the incomplete combustion caused by heterogeneous mixing. • In the stoichiometric mode, PN and PM emissions strongly depend on the injection strategy and hardware configuration used in the engine. _ Many GDI engines use "wall-guided" fuel injection. In this configuration, the fuel injector is placed off center from the cylinder and injected fuel impinges on the cylinder wall and piston head. Fuel in contact with the cylinder wall during combustion is more likely to form soot or other semi-volatile compounds. _ The alternative to wall-guided injection is "spray-guided" injection. In this configuration, the injector is centered over the cylinder (where the spark plug would be on a wall-guided or PFI engine). The fuel injector confines the fuel spray such that it does not contact the cylinder walls, improving mixing and reducing soot formation. • While the wall-guided injector configuration is not optimal, it is commonly used because it is cheaper to implement than spray-guided designs. More stringent emissions standards (e.g. Euro 6c GDI PN limits) are likely to compel engine manufactures to move to spray-guided designs with advanced piezoelectric injectors to meet lower PN and PM emission limits.
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	Engines with spray-guided injection produce particle emissions smaller in mass and less in number (even two orders of magnitude) than wall-guided injection.
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	• Spray-guided injection is more expensive to implement than wall-guided injector configuration (which, although not optimal, is commonly used). • Fuel savings 2-5%.
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	Fuel consumption may improve 2-5% (corresponding reduction in CO_2 emissions).
Non-regulated pollutants and trade-	No significant impact on non-regulated pollutants.

offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	Low-sulfur fuel is required.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	• More difficult to implement than wall-guided injection. • Only implemented by OEM.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	No specific maintenance requirements.
Durability/lifetime of emission control equipment	No significant performance degradation over time.
Impacts on safety (users, citizens, …)	Trained personnel for any modifications or maintenance.
References and Other Points	
Comments or remarks not addressed above	To improve mixing and reduce rich PM formation, some stoichiometric and all lean GDI engines operate in a multi-injection mode. This mode of operation injects the fuel over several pulses that can span both the intake and compression stroke.
Successful examples of implementation	- Piock, W., Hoffmann, G., Berndorfer, A., Salemi, P., Fusshoeller, B., Strategies towards meeting future particulate matter emission requirements in homogeneous gasoline direct injection engines. SAE technical paper 2011-01-1212.
References for further details	- http://www.meca.org/resources/MECA_UFP_White_Paper_0713_Final.pdf - https://delphiauto.com/pdf/techpapers/2011-01-1212.pdf - Ogris, M., Hollerer, P., Kapus, P., Fraidl, G., Reduction of particulate number emission of GDI engines by application. 6th International Forum for Exhaust Gas and Particulate Emissions, 2010. - Price P, Stone R, Collier T, Davies M., Particulate matter and hydrocarbon emissions measurements: comparing first and second generation DISI with PFI in single cylinder optical engines. SAE technical paper 2006-01-1263; 2006.

3.1.3.2 Gasoline Particle Filter (GPF)

Table 3-7: Summary information for gasoline particle filter (GPF)

General Description	
Name of technique	**Gasoline Particle Filter (GPF)**
Pollutants addressed	PM, PN, BC
Engine/vehicle/vessel types considered	Gasoline direct injection vehicles (passenger cars, light commercial vehicles)
Short description of technique	• Euro 6 legislation introduces a particle number limit for gasoline direct injection (GDI) vehicles (which show significantly higher PM and PN emissions compared to fuel port injection engines) and may require the use of GPFs to ensure particulate emissions control under real-world operation. • GPF is an effective technology to reduce particulate emission with high filtration performance under all engine operation points and ambient temperature variation. • The filter technology is drawn from the large experience base with diesel particle filters (DPFs) based on wall-flow filter technology (see figure below – GPF construction)[18]. 
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	Reference technology: Gasoline direct injection engine • PM (75-95%)
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	• Indicative cost as a replacement part: €800–€1,600. • Some more detailed info can be found in http://www.theicct.org/sites/default/files/publications/GFPworkingpaper2011.pdf
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	Increase in fuel consumption ~1-3% due to increased back pressure and GPF regeneration, especially in high engine speeds and full load (with a corresponding increase in CO_2 emissions).
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	No significant impact on non-regulated pollutants (any effects should rather be on the positive side).

[18] Source of figure: http://www.meca.org/resources/MECA_UFP_White_Paper_0713_Final.pdf

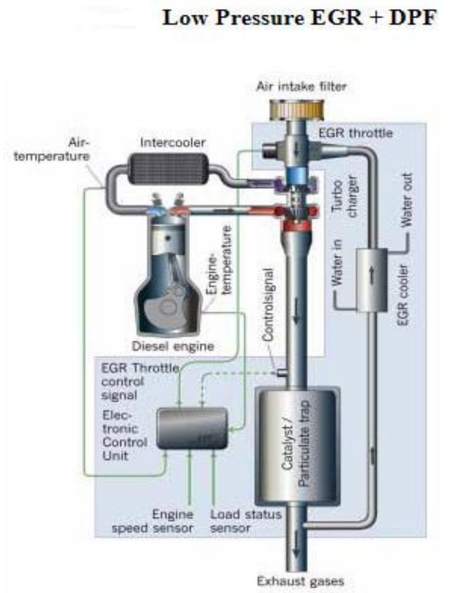
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	Similar to diesel applications, the accumulation and uncontrolled oxidation of soot is expected to lead to high GPF temperatures and therefore high thermal stress.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	Trained personnel required for the implementation, approved components need to be used.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	• Regeneration and cleaning system needed as in DPFs (filters require periodic maintenance to clean out non-combustible materials and accumulated soot). To prevent blocking of filter, it is necessary to 'regenerate' it by periodically burning-off the collected particulate. • However, the problem is not as intense as in DPFs, because the soot mass emitted by the engine is lower and the gasoline engine exhaust temperatures are relatively higher than those of their diesel counterparts.
Durability/lifetime of emission control equipment	No significant performance degradation if properly maintained.
Impacts on safety (users, citizens, …)	Devices need to be maintained by trained personnel to limit exposure to pollutants.
References and Other Points	
Comments or remarks not addressed above	Current research focus on combination of TWC and GPF (commercial systems already appearing). Potential on-engine system configurations include: _ "Add on" systems (uncoated or low washcoat containing GPF in downstream position) or _ Integrated systems (substitution of conventional coated flow-through substrates by close coupled or underbody GPF with integrated TWC functionality).
Successful examples of implementation	- Mamakos, A., Steininger, N., Martini, G., Dilara, P., Drossinos, Y., 2013. Cost effectiveness of particulate filter installation on Direct Injection Gasoline vehicles. Atmospheric Environment 77, 16-23. - Richter, J., Klingmann, R., Spiess, S., Wong, K., 2012. Application of catalyzed gasoline particulate filters to GDI vehicles. SAE International Journal of Engines 5, 1361-1370. - Chan, T., Meloche, E., Kubsh, J., Rosenblatt, D. et al., Evaluation of a Gasoline Particulate Filter to Reduce Particle Emissions from a Gasoline Direct Injection Vehicle. SAE Int. J. Fuels Lubr. 5(3):1277-1290, 2012, doi:10.4271/2012-01-1727.
References for further details	- http://www.aecc.eu/en/Applications/Light_duty.html - http://www.meca.org/galleries/files/LEV_III_Tier_3_white_paper_final.pdf - http://www.meca.org/resources/MECA_UFP_White_Paper_0713_Final.pdf - http://www.corning.com/WorkArea/showcontent.aspx?id=60285 - http://www1.eere.energy.gov/vehiclesandfuels/pdfs/deer_2012/wednesday/presentations/deer12_bischof.pdf - http://www.cambridgeparticlemeeting.org/sites/default/files/Presentations/2013/PKattouah%28NGK%29_2013_Wall%20flow%20filter%20for%20particulate%20emission%20reduction%20of%20petrol%20engines.pdf

3.2 Diesel vehicles road/non-road (excl. vessels)

3.2.1 Nitrogen oxides (NO_x)

3.2.1.1 Exhaust Gas Recirculation (EGR)

Table 3-8: Summary information for exhaust gas recirculation (EGR)

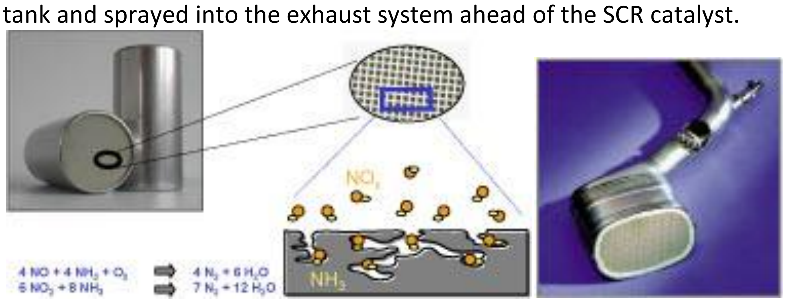
General Description	
Name of technique	**Exhaust Gas Recirculation (EGR)**
Pollutants addressed	NO_x
Engine/vehicle/vessel types considered	Diesel engines and vehicles: cars, light commercial vehicles, heavy-duty trucks, buses, non-road vehicles (construction and agriculture machinery), trains.
Short description of technique	• As the name implies, EGR redirects (re-circulates) a portion of engine exhaust back into the engine (charger inlet or intake manifold) to cool and reduce peak combustion temperatures and pressures. In most systems, an intercooler lowers the temperature of the re-circulated gases, which then have higher heat capacity and contain less O_2 than air; hence, combustion temperature in the engine is lowered, thus inhibiting NO_x formation. • EGR is commonly used by engine manufacturers as a method to comply with new engine emission control standards. DPFs can be used with a low-pressure EGR system to ensure that large amounts of particulate matter are not re-circulated to the engine (see figure below[19]). 
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	Reference technology: _ Road and non-road: Turbocharged compression-ignition engine with high-pressure fuel injection _ Railcars and locomotives: Conventional compression ignition diesel engine • NO_x (25-45%)
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	Indicative cost for manufacturer: _ €150–€250 (light duty vehicles). _ €400–€700 (heavy duty vehicles). _ the cost can be even higher e.g. for a large piece of non-road equipment.

[19] Source of figure: http://www.meca.org/diesel-retrofit/what-is-retrofit

Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	EGR slightly reduces engine power.
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	Risks by PM recirculation if not combined with a diesel particle filter (DPF).
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	Use of EGR as a retrofit technology is limited.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	Retrofit EGR systems require major engine integration.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	• EGR requires electronic control strategy to ensure operation. • Functionality and effectiveness of EGR is enhanced by the use of diesel particle filters (DPFs), which ensure that large amounts of particulate matter are not re-circulated to the engine.
Durability/lifetime of emission control equipment	Exhaust cooling may result in engine wear due to excess water vapor.
Impacts on safety (users, citizens, …)	Trained personnel required for installation.
References and Other Points	
Comments or remarks not addressed above	EGR is expected to be taken off the engines as SCR efficiency approaches 99%.
Successful examples of implementation	- http://www.epa.gov/cleandiesel/verification/verif-list.htm - http://www.epa.gov/cleandiesel/verification/emerg-list.htm - http://www.arb.ca.gov/diesel/verdev/vt/cvt.htm
References for further details	- http://www.epa.gov/cleandiesel/technologies/retrofits.htm - http://www.meca.org/diesel-retrofit/what-is-retrofit - http://www.meca.org/galleries/files/MECA_diesel_retrofit_white_paper_1009.pdf - http://www1.iaphworldports.org/toolbox%201/cleantech.htm - http://www.corning.com/WorkArea/showcontent.aspx?id=60285

3.2.1.2 *Selective Catalytic Reduction (SCR)*

Table 3-9: Summary information for selective catalytic reduction (SCR)

General Description	
Name of technique	**Selective Catalytic Reduction (SCR)**
Pollutants addressed	Mainly: NO_x, Synergies: VOC, CO, PM
Engine/vehicle/vessel types considered	Diesel engines and vehicles: cars, light commercial vehicles, heavy-duty trucks, buses, non-road vehicles (construction and agriculture machinery), trains.
Short description of technique	• SCR is fitted to most new diesel engines; it is also available as retrofit device for NO_x emissions reduction. • Ammonia is used as a selective reductant (also known as diesel exhaust fluid - DEF), in the presence of excess oxygen, to convert NO and NO_2 to elemental nitrogen and water (two natural components of the air we breathe) over a special catalyst system (see figure below[20]). Different precursors of ammonia can be used; one of the most common options is a solution of urea in water (e.g. AdBlue®) carefully metered from a separate tank and sprayed into the exhaust system ahead of the SCR catalyst.  • AdBlue® is a stable, non-flammable, colorless fluid containing 32.5% urea which is not classified as hazardous to health and does not require any special handling precautions. It is made to internationally-recognized standards. Urea is used as an artificial fertilizer and is found in products such as cosmetics. • The consumption of AdBlue® depends on the amount of NO_x that needs to be converted. For example, a Euro III engine, emitting 5g/kWh NO_x, has been brought to Euro V (2g/kWh NO_x) with a retrofit SCR system using ~2% urea compared to the fuel consumption. Typical AdBlue® consumption is 3-4% of fuel consumption for a Euro IV engine, and 5-7% for a Euro V engine, depending on driving, load and road conditions. Systems on-board the vehicle, alert the driver when it is time to top up with AdBlue®.
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	Reference technology: _ Road and non-road: Turbocharged compression-ignition engine with high-pressure fuel injection _ Railcars and locomotives: Conventional compression ignition diesel engine • NO_x (70-95%), VOC (50-90%), CO (50-90%), PM (20-40%)
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	_ For light duty vehicles: • Indicative manufacturer cost: €350–€500. • Possible fuel savings (OEM): €30–€130 per year (e.g. assuming 2,000 l of fuel per year, 3% fuel economy because of SCR use, and 1.38 €/l diesel price, fuel savings is 83 €). • Cost for urea: €30–€70 per year (e.g. assuming AdBlue® consumption 4% of fuel consumption, and 0.6 €/l AdBlue® price, the cost is 48 €). • Additional maintenance cost: 50 € per year.

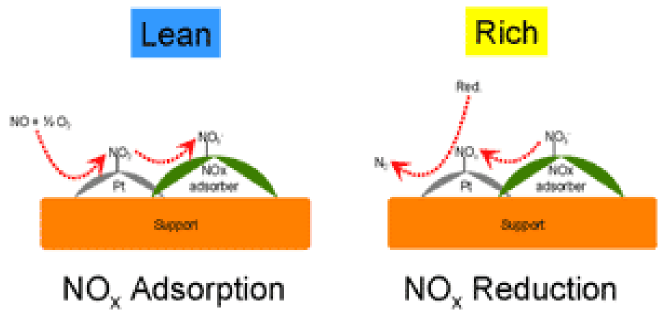
[20] Source of figure: http://www.aecc.eu/en/Technology/Catalysts.html

	_ For heavy duty and non-road vehicles: • Retrofit installation: €5,000–€10,000 (one-off) (the cost can be even higher e.g. for a large piece of non-road equipment). • Possible fuel savings (mainly for OEM applications, not guaranteed for retrofitting): €500–€1,100 per year (e.g. assuming 20,000 l of fuel per year, 3% fuel economy because of SCR use, and 1.38 €/l diesel price, fuel savings is 828 €). • Cost for urea: €400–€600 per year (e.g. assuming AdBlue® consumption 4% of fuel consumption, and 0.6 €/l AdBlue® price, the cost is 480 €). • Additional maintenance cost: 200 € per year.
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	3-5% possible improvement in fuel efficiency (and, therefore, CO_2 benefits) (mainly for OEM applications, not guaranteed for retrofitting).
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	• Risk for ammonia (NH_3) slip. Can be controlled e.g. through calibration optimization or introduction of a clean-up catalyst downstream of the SCR catalyst. • SCR systems reduce the characteristic odor produced by a diesel engine and diesel smoke.
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• Application of SCR may not be appropriate for all vehicles; care must be taken to design an SCR system for the specific vehicle or equipment application involved. Retrofit for LDVs has limited potential due to technical difficulties and limited space available to install SCR. • Urea additive (as a precursor of ammonia) has to be made widely available. • The catalytic reaction requires certain temperature criteria for NO_x reduction to occur; data logging must be performed to determine if the exhaust gas temperatures meet the specific SCR system requirements. • Lower NO_x conversion efficiencies maybe observed in low-load city driving (due to low exhaust gas temperatures and limited urea dosing); better performance at higher engine loads (e.g. highway conditions, higher speeds). • SCR performance is enhanced by the use of low sulfur fuel.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	• SCR units are large, heavy, complex and bulky systems. • Urea infrastructure is necessary in order to facilitate the use of SCR systems.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	• SCR systems require periodic refilling with urea and the system needs to be resistant to ice and freezing conditions. • Systems on-board the vehicle, alert the driver when it is time to top up with urea.
Durability/lifetime of emission control equipment	SCR technology is reliable and allows the engine to stay focused on producing efficient power and torque over a long life.
Impacts on safety (users, citizens, …)	• Trained personnel required for installation. • Urea is a nonhazardous material that does not become toxic at any temperature.

References and Other Points	
Comments or remarks not addressed above	SCR can be combined with Diesel Particle Filter (DPF) for additional emission reductions.
Successful examples of implementation	- http://www.dieselretrofit.eu/map.aspx - http://www.epa.gov/cleandiesel/verification/verif-list.htm - http://www.epa.gov/cleandiesel/verification/emerg-list.htm
References for further details	- http://www.dieselretrofit.eu/technologies_SCR.html - http://www.epa.gov/cleandiesel/technologies/retrofits.htm - http://www.meca.org/diesel-retrofit/what-is-retrofit - http://www.meca.org/galleries/files/MECA_diesel_retrofit_white_paper_1009.pdf - http://www.aecc.eu/en/Technology/Catalysts.html - http://www.aecc.eu/content/pdf/Emissions Control Technologies to meet current and future European vehicle emissions legislation.pdf - http://www.factsaboutscr.com/default.aspx - http://www1.iaphworldports.org/toolbox%201/cleantech.htm - http://www.dieselforum.org/about-clean-diesel/what-is-scr- - http://www.corning.com/WorkArea/showcontent.aspx?id=60285

3.2.1.3 Lean NO_x Trap (LNT)

Table 3-10: Summary information for Lean-NO_x Trap (LNT)

General Description	
Name of technique	**Lean NO_x Trap (LNT)** (also known as NO_x adsorber)
Pollutants addressed	NO_x
Engine/vehicle/vessel types considered	• Diesel passenger cars and light commercial vehicles. • Especially of interest in applications with limited space or in which urea usage for SCR is difficult. • For heavy duty and non-road vehicles LNT does not seem to be a preferable option, SCR dominates in these vehicles.
Short description of technique	• LNTs function by trapping the NO_x in the form of a metal nitrate during lean operation of the engine. The most common compound used to capture NO_x is barium hydroxide or barium carbonate. Under lean air to fuel operation, NO_x reacts to form NO_2 over a platinum catalyst followed by reaction with the barium compound to form $BaNO_3$. • Following a certain amount of lean operation, the trapping function will become saturated and must be regenerated. This is commonly done by operating the engine in a fuel rich mode for a brief period of time (one or two seconds is enough) to facilitate the conversion of the barium compound back to a hydrated or carbonated form and giving up NO_x in the form of N_2 or NH_3 (see figure below[21]). • The rich running mode can be accomplished in a number of ways (usually includes combination of intake air throttling, EGR, late ignition timing and post-combustion fuel injection).  The NOx adsorber system
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	Reference technology: Turbocharged compression-ignition engine with high-pressure fuel injection • NO_x (70-85%)
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	€300–€500 (indicative manufacturer cost).
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	Fuel economy penalty (~2%) because of required brief periods of rich operation to regenerate (also a corresponding increase in CO_2 emissions).

[21] Source of figure: http://www.aecc.eu/en/Technology/Adsorbers.html

Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	Ammonia (NH_3) is generated in the LNT during the rich regeneration phase.
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• Retrofit has limited potential due to technical difficulties and limited space available to install LNT. • Ultra-low-sulfur diesel (ULSD) fuel required (<10ppm), because NO_x adsorbers also adsorb sulfur oxides resulting from the fuel sulfur content.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	No specific implementation requirements.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	• Periodically, the system has to automatically run a short “desulfation” cycle to remove any adsorbed sulfur compounds (which are more difficult to desorb). • This “$DeSO_x$” regeneration procedure requires high temperatures (typically around 700^{o}C) and requires about 15 to 20 minutes to be completed.
Durability/lifetime of emission control equipment	The durability of LNT is linked directly to sulfur removal by regeneration.
Impacts on safety (users, citizens, …)	Trained personnel required for installation.
References and Other Points	
Comments or remarks not addressed above	• LNT can be combined with DPF and SCR. • LNT (NO_x adsorber) should not be confused with Lean NO_x Catalyst (LNC), which refers to the selective catalytic reduction of NO_x by hydrocarbons (an entirely different emission control technology).
Successful examples of implementation	- http://www.epa.gov/cleandiesel/verification/emerg-list.htm
References for further details	- http://www.dieselnet.com/tech/cat_nox-trap.php - http://www.aecc.eu/en/Technology/Adsorbers.html - http://www.aecc.eu/content/pdf/Emissions Control Technologies to meet current and future European vehicle emissions legislation.pdf - http://www.meca.org/technology/technology-details?id=5&name=Catalytic%20Converters - http://www.meca.org/galleries/files/MECA_diesel_retrofit_white_paper_1009.pdf - http://www.corning.com/WorkArea/showcontent.aspx?id=60285

3.2.2 Particulate matter (PM)

3.2.2.1 Diesel Oxidation Catalyst (DOC)

Table 3-11: Summary information for diesel oxidation catalyst (DOC)

<table>
<tr><th colspan="2">General Description</th></tr>
<tr><td>Name of technique</td><td>Diesel Oxidation Catalyst (DOC)</td></tr>
<tr><td>Pollutants addressed</td><td>PM, VOC, CO</td></tr>
<tr><td>Engine/vehicle/vessel types considered</td><td>Diesel engines and vehicles: cars, light commercial vehicles, heavy-duty trucks, buses, non-road vehicles (construction and agriculture machinery), trains.</td></tr>
<tr><td>Short description of technique</td><td>• DOCs are exhaust aftertreatment devices that reduce emissions from diesel engines. Typically packaged with the engine muffler, they are widely used as a retrofit technology because they require little or no maintenance (hundreds of thousands of on-road and off-road vehicles retrofitted worldwide).
• DOCs convert CO and HC to CO_2 and H_2O (see figure below[22]), but have little positive effect on NO_x; they also decrease the mass of diesel particulate emissions (but not their number) by oxidizing some of the hydrocarbons that are adsorbed onto the carbon particles. The level of particulate mass reduction is influenced in part by the percentage of Soluble Organic Fraction (SOF) in the particulate.

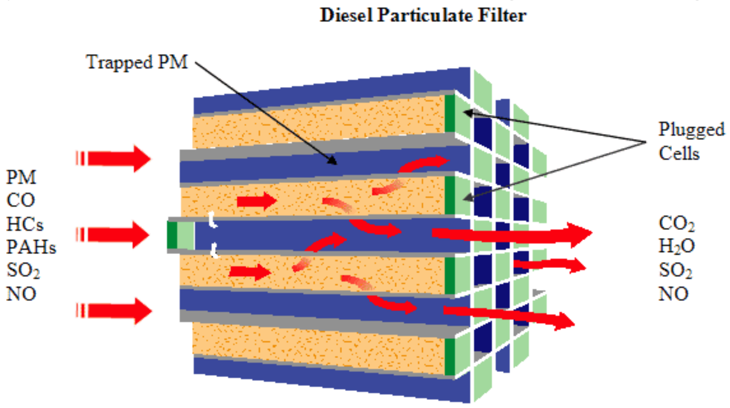

• DOCs consist of a flow-through honeycomb structure that is coated with a precious metal catalyst and surrounded by stainless steel housing. As hot diesel exhaust flows through the honeycomb (or substrate), the precious metal coating causes a catalytic reaction that breaks down the pollutants.</td></tr>
<tr><th colspan="2">Environmental Benefit and Costs</th></tr>
<tr><td>Specific claims (% reduction range of pollutants addressed)</td><td>Reference technology:
_ Road and non-road: Turbocharged compression-ignition engine with high-pressure fuel injection
_ Railcars and locomotives: Conventional compression ignition diesel engine
• PM (20-40%), VOC (40-70%), CO (40-60%)</td></tr>
<tr><td>Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)</td><td>_ For light duty vehicles (indicative manufacturer cost): €50–€100.
_ For heavy duty and non-road vehicles (retrofit installation): €1,500–€1,700.
_ The cost can be even higher e.g. for a large piece of non-road equipment.</td></tr>
<tr><th colspan="2">Environmental Side Effects</th></tr>
<tr><td>Impact on fuel consumption (positive/negative impact and typical % effect)</td><td>No significant impact on fuel consumption.</td></tr>
</table>

[22] Source of figure: http://www.meca.org/diesel-retrofit/what-is-retrofit

Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	Concerns that DOCs may increase the nitrogen dioxide (NO_2) fraction of total NO_x emissions.
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• Ultra-low-sulfur diesel (ULSD) fuel required (<50ppm). • No temperature limitations.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	Easy to install, DOCs are designed to be installed in-line into the existing exhaust system between the muffler and turbocharger.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	Little or no maintenance required.
Durability/lifetime of emission control equipment	Trouble free operation for hundreds of thousands of miles.
Impacts on safety (users, citizens, …)	Devices need to be maintained by trained personnel to limit exposure to pollutants.
References and Other Points	
Comments or remarks not addressed above	• DOCs can be coupled with closed crankcase ventilation, SCR or lean NO_x catalysts for additional reductions; they can also be integrated with DPFs. • DOCs have also been shown effective with biodiesel and emulsified diesel fuels, ethanol/diesel blends and other alternative diesel fuels.
Successful examples of implementation	- http://www.epa.gov/cleandiesel/verification/verif-list.htm - http://www.epa.gov/cleandiesel/verification/emerg-list.htm - http://www.arb.ca.gov/diesel/verdev/vt/cvt.htm
References for further details	- http://www.dieselretrofit.eu/technologies_oxidation_catalysts.html - http://www.epa.gov/cleandiesel/technologies/retrofits.htm - http://www.meca.org/diesel-retrofit/what-is-retrofit - http://www.meca.org/galleries/files/MECA_diesel_retrofit_white_paper_1009.pdf - http://www.aecc.eu/en/Technology/Catalysts.html - http://www.aecc.eu/content/pdf/Emissions Control Technologies to meet current and future European vehicle emissions legislation.pdf - http://www1.iaphworldports.org/toolbox%201/cleantech.htm - http://www.corning.com/WorkArea/showcontent.aspx?id=60285 - http://ipf.msu.edu/news/features/diesel-oxidation-catalysts.html

3.2.2.2 *Diesel Particle Filter (DPF)*

Table 3-12: Summary information for diesel particle filter (DPF)

General Description	
Name of technique	**Diesel Particle Filter (DPF)**
Pollutants addressed	Mainly: PM, PN, BC, Synergies: VOC, CO
Engine/vehicle/vessel types considered	Diesel engines and vehicles: cars, light commercial vehicles, heavy-duty trucks, buses, non-road vehicles (construction and agriculture machinery), trains.
Short description of technique	• As the name implies, DPFs remove particulate matter in diesel exhaust by filtering exhaust from the engine. Since a filter can fill up over time, a means of burning off or removing accumulated PM must be provided. A convenient means of disposing of accumulated particulate matter is to burn or oxidize it on the filter when exhaust temperatures are adequate. By burning off trapped material, the filter is cleaned or “regenerated”. • Filter Material: ceramic and silicon carbide materials, fiber wound cartridges, knitted silica fiber coils, ceramic foam, wire mesh, sintered metal structures, and temperature resistant paper in the case of disposable filters. • In the figure below[23], particulate-laden exhaust enters the filter from the left. Because the cells of the filter are capped at the downstream end, exhaust cannot exit the cell directly. Instead, exhaust gas passes through the porous walls of the filter cells. In the process, PM is deposited on the upstream side of the cell wall. Cleaned exhaust gas exits to the right.  • Major regeneration techniques: _ Catalyst-based regeneration using a catalyst applied to the surfaces of the filter _ Catalyst-based regeneration using an upstream oxidation catalyst _ Fuel-borne catalysts _ Air-intake throttling _ Post top-dead-center (TDC) fuel injection _ On-board fuel burners or electrical heaters _ Off-board electrical heaters
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	Reference technology: _ Road and non-road: Turbocharged compression-ignition engine with high-pressure fuel injection _ Railcars and locomotives: Conventional compression ignition diesel engine • Wall-flow DPF: PM (80-95%), VOC (85-95%), CO (50-90%) • Partial DPF: PM (30-60%), VOC (40-75%), CO (10-60%)

[23] Source of figure: http://www.meca.org/diesel-retrofit/what-is-retrofit

Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	_ For light duty vehicles (indicative manufacturer cost): • Wall-flow DPF: €250–€450. Plus €100-€400 additional fuel/maintenance costs per year. _ For heavy duty and non-road vehicles (one-off retrofit installation): • Wall-flow DPF: €3,000–€5,000 (the cost can be even higher e.g. for a large piece of non-road equipment). Plus €200-€700 additional fuel/maintenance costs per year.
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	Usually, installation of a filter system on a vehicle may cause a fuel economy penalty ~1-2% (with a corresponding increase in CO_2 emissions).
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	• Concerns that catalyzed DPFs may increase the NO_2 fraction of total NO_x emissions. Some DPFs generate NO_2 as a means to help filter regeneration at lower temperatures. The NO_2 produced by a DPF depends on the catalyst formulation. • Soot particulates burn-off forms water and CO_2 in small quantity (less than 0.05% of the CO_2 emitted by the engine).
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• DPF should be properly designed for the particular application to be used. Ideally suited for new vehicles. Retrofit for LDVs has limited potential. • Exhaust gas temperature data logging must be performed to determine if the exhaust temperature profile meets DPF-specific requirements. • Ultra-low-sulfur diesel (ULSD) fuel required (<50ppm). • Passive filters require operating temperatures high enough to initiate combustion of collected soot. Active regeneration uses other heat sources, such as fuel burning or electric heaters. • pDPFs (partial or flow-through filters) are always subject to minimum temperature requirements necessary for periodic regeneration (i.e., combustion of collected PM).
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	Trained personnel required for the installation, approved components to be used.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	• Active/passive regeneration and cleaning system needed (filters require periodic maintenance to clean out non-combustible materials, such as ash). • Since the continuous flow of soot into the filter would eventually block it, it is necessary to 'regenerate' the filter by periodically burning-off the collected particulate. • DPF should incorporate electronic back pressure monitoring equipment to signal vehicle and equipment operators when the device needs to be cleaned.
Durability/lifetime of emission control equipment	No significant performance degradation if properly maintained. Possible failures of retrofitted components with time due to melting/cracking. Monitoring required.
Impacts on safety (users, citizens, …)	Devices need to be maintained by trained personnel to limit exposure to pollutants.
References and Other Points	
Comments or remarks not	• DPF can be combined with Selective Catalytic Reduction (SCR) system or Lean-NO_x Catalyst (LNC) technologies for additional emission reductions.

addressed above	• DPFs are very important to the functionality and effectiveness of an EGR (exhaust gas recirculation) system to ensure that large amounts of particulate matter are not re-circulated to the engine.
Successful examples of implementation	- http://www.dieselretrofit.eu/map.aspx - http://www.epa.gov/cleandiesel/verification/verif-list.htm - http://www.arb.ca.gov/diesel/verdev/vt/cvt.htm - http://www.vert-certification.eu/index.php?option=com_content&view=article&id=77&Itemid=31
References for further details	- http://www.dieselretrofit.eu/technologies_filters.html - http://www.epa.gov/cleandiesel/technologies/retrofits.htm - http://www.meca.org/diesel-retrofit/what-is-retrofit - http://www.meca.org/galleries/files/MECA_diesel_retrofit_white_paper_1009.pdf - http://www.aecc.eu/en/Technology/Filters.html - http://www.aecc.eu/content/pdf/Emissions Control Technologies to meet current and future European vehicle emissions legislation.pdf - http://www1.iaphworldports.org/toolbox%201/cleantech.htm - http://www.corning.com/WorkArea/showcontent.aspx?id=60285

3.2.3 Volatile organic compounds (VOC)

3.2.3.1 Closed Crankcase Ventilation (CCV)

Table 3-13: Summary information for closed crankcase ventilation (CCV)

General Description	
Name of technique	**Closed Crankcase Ventilation (CCV)**
Pollutants addressed	Mainly: VOC, Synergies: PM
Engine/vehicle/vessel types considered	Diesel engines and vehicles: heavy-duty trucks, buses, non-road vehicles (construction and agriculture machinery), trains.
Short description of technique	• Controlling crankcase emissions is part of overall emissions control strategy. While crankcase emissions are not typically a significant source of direct UFPs, they can contribute to the formation of secondary aerosols when oxidized in the atmosphere. Therefore, diesel UFP control strategies should consider both the tailpipe emissions and crankcase emissions from pre-2007 U.S. engines and pre-Euro V engines in the E.U. • In many older diesel engines, crankcase emissions ("blow-by") are released directly from the engine into the atmosphere through a vent or the "road draft tube". CCV systems capture the oil in blow-by gas, return it to the crankcase, then redirect these gaseous emissions back to the intake system for combustion instead of emitting them into the air. • A multi-stage filter is used which is designed to collect, coalesce, and return the emitted lube oil to the engine's sump. Filtered gases are returned to the intake system, balancing the differential pressures involved. Typical systems consist of a filter housing, a pressure regulator, a pressure relief valve and an oil check valve (see figure below[24]). • CCV systems eliminate odor and toxins from vehicle interior (crankcase fumes exit the engine in the engine compartment while exhaust fumes exit through exhaust ductwork); they can help keep engine compartments and components clean, and reduce oil usage (eliminate oil from dripping on to engine block and ground). 
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	Reference technology: Turbocharged compression-ignition engine without crankcase emission control • VOC (and PM) from crankcase emissions (80-95%). • If left open, the crankcase from a pre-2007 diesel engine can contribute 25% of the total VOC and PM emissions from the vehicle. • Therefore, the overall environmental benefit (% reduction of total VOC) is approximately 20-25% (80-95% reduction of crankcase emissions * 25% contribution of crankcase to total VOC from the vehicle).

[24] Source of figure: http://www.meca.org/diesel-retrofit/what-is-retrofit

Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	€250-€3,000 (retrofit)
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	CCV systems reduce engine oil consumption.
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	No specific impact on non-regulated pollutants.
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	No specific limitations in applicability.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	Easy to implement (by trained personnel), approved components need to be used.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	• CCV systems incorporate filter elements that must be periodically replaced. • Maintenance requirements must be reviewed for each manufacturer's product and potentially for each configuration.
Durability/lifetime of emission control equipment	No significant performance degradation if properly maintained.
Impacts on safety (users, citizens, …)	Trained personnel required for installation.
References and Other Points	
Comments or remarks not addressed above	Emissions will be further reduced if the CCV is paired with a DOC or DPF.
Successful examples of implementation	- http://www.arb.ca.gov/diesel/verdev/vt/cvt.htm - K. Trenbath, M.P. Hannigan, J.B. Milford, Evaluation of retrofit crankcase ventilation controls and diesel oxidation catalysts for reducing air pollution in school buses, Atmospheric Environment 43 (2009) 5916–5922. - As EPA's 2007 Highway Heavy Duty Diesel rule requires that engine manufacturers control crankcase emissions as a part of overall emissions control strategy, most highway engines manufactured since 2007 come

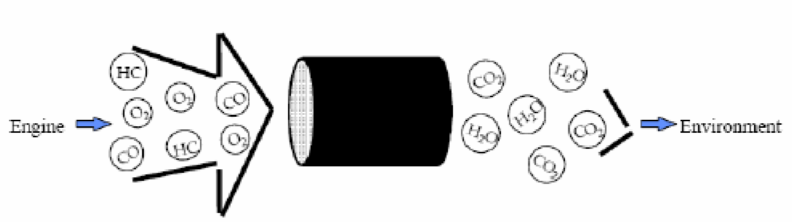
	equipped with CCV systems. - Hundreds of thousands heavy duty vehicles (trucks, buses, new/retrofit) are equipped with crankcase emission control.
References for further details	- http://www.epa.gov/cleandiesel/technologies/retrofits.htm - http://www.meca.org/diesel-retrofit/what-is-retrofit - http://www.meca.org/galleries/files/MECA_diesel_retrofit_white_paper_1009.pdf - https://www.sbeap.org/past_workshops/constructing_clean_air_2009/CCA%20-%20Equipment%20to%20reduce%20emissions%20%28Anderson%29.pdf

3.3 Gasoline engines non-road

3.3.1 Particulate matter (PM) and volatile organic compounds (VOC)

3.3.1.1 Oxidation catalyst

Table 3-14: Summary information for oxidation catalyst

General Description	
Name of technique	**Oxidation catalyst**
Pollutants addressed	PM, VOC, CO
Engine/vehicle/vessel types considered	Small gasoline engines used in non-road applications (small handheld engines and ground-supported engines).
Short description of technique	Oxidation catalysts convert unburned hydrocarbons (HC) and carbon monoxide (CO) to carbon dioxide (CO_2) and water (H_2O) by burning (oxidizing) them (see figure below[25]). 
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	• Up to 50-60% reduction of VOC and CO can be achieved for a conventional two-stroke gasoline engine without aftertreatment control. • PM emissions are primarily the result of excess hydrocarbons; hence, reduction of HC has a direct (and rather proportional) effect to PM as well.
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	• The cost of oxidation catalyst as a replacement part is such that, together with the short lifetime of equipment, make unfavorable the investment in aftertreatment emission control replacement. • Complete replacement of the old higher polluting equipment with newer machinery may be a better solution.
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	Possible increase in fuel consumption due to rich combustion which is required to retain low exhaust temperature (safety concerns).
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	Rich combustion, which is required to retain low exhaust temperature (so that an amount of fuel evaporates, thus decreasing the temperature), increases VOC and CO emissions.
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological	• Increase in exhaust and surface temperatures, thus increasing the risk of skin burns, melting of materials, and lighting up dry grass. This boundary condition poses a significant limitation on the use of catalysts (temperature <246°C is given as a safety threshold). • More appropriate for non heat sensitive applications.

[25] Source of figure: http://www.meca.org/galleries/files/Motorcycle_whitepaper_final_081908.pdf

barriers, behavioral changes, etc.)	
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	Additional cooling air may be needed to address heat increase.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	Possibility for poisoning of active material by missing limit values for oil additives (to be addressed with use of good quality and low additized, e.g. Ca-free and S-free, lubrication oil).
Durability/lifetime of emission control equipment	Lifetime of catalyst may be comparable to the (short) lifetime of the complete equipment, thus making unfavorable the investment in aftertreatment emission control replacement.
Impacts on safety (users, citizens, …)	Technical barriers (from the additional catalyst heat in close to body applications) limit the use of catalyst due to safety hazards.
References and Other Points	
Comments or remarks not addressed above	No other comments or remarks.
Successful examples of implementation	Catalysts are used today in multi million numbers on non heat sensitive applications by many small SI engine manufacturers.
References for further details	- http://www.aecc.eu/en/Technology/Catalysts.html - Lochmann H. (2012), "Small Handheld Nonroad SI Engines", Euromot AECC Workshop, Nov. 2012. - Lochmann H. (2014), "Exhaust emissions of small spark ignited engines", ANDREAS STIHL AG & Co., WG-SSIE-Euromot, Aug. 2014.

3.3.2 All pollutants

3.3.2.1 Engine measures for 2S engines

Table 3-15: Summary information for engines measures for 2S engines

General Description	
Name of technique	**Engine measures for 2S engines**
Pollutants addressed	All pollutants
Engine/vehicle/vessel types considered	Small gasoline 2S engines used in non-road applications
Short description of technique	• Incomplete combustion and scavenging losses of two-stroke engines are addressed by the manufacturers of the engines with improved combustion and measures such as: _ Stratified scavenging, _ Compression wave injection (CWI), _ Direct injection (DI). • These are measures mainly targeted to the small handheld engines, e.g. chainsaws and cut off machines (medium-to-high speed multiposition tools and applications). • Another measure is to enforce the replacement of 2S engines with 4S or 4S hybrid ones.
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	Indicative emission reduction percentages (compared to a conventional 2S engine): _ Stratified scavenging: 45% _ CWI: 45% _ DI: 75% _ 4S: 70% Source: Lochmann H. et al. (2004), “Development of an Emission Aftertreatment System for Hand Held Powertools”, SAE-World-Congress 2004 (2004-01-0149).
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	Possible increase of cost for manufacturers to implement these engine measures.
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	Potential for improvement in fuel consumption.
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	No significant impact on non-regulated pollutants.
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental	Possible increase of cost and weight of the engines.

conditions, fuel specifications, technological barriers, behavioral changes, etc.)	
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	There is not a single technology meeting all requirements.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	Better to use manufacturer recommended lubrication oils of good quality rather than cheap alternatives.
Durability/lifetime of emission control equipment	No significant performance degradation over time if equipment is properly maintained.
Impacts on safety (users, citizens, …)	No safety impacts.
References and Other Points	
Comments or remarks not addressed above	No other comments or remarks.
Successful examples of implementation	Engine measures currently being implemented by manufacturers.
References for further details	- Lochmann H. (2012), "*Small Handheld Nonroad SI Engines*", Euromot AECC Workshop, Nov. 2012. - Lochmann H. (2014), "*Exhaust emissions of small spark ignited engines*", ANDREAS STIHL AG & Co., WG-SSIE-Euromot, Aug. 2014.

3.4 Diesel vessels

3.4.1 Nitrogen oxides (NO_x)

3.4.1.1 Exhaust Gas Recirculation (EGR)

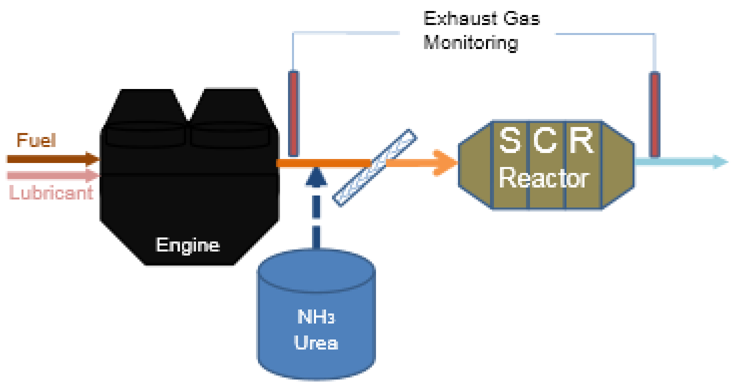
Table 3-16: Summary information for exhaust gas recirculation (EGR)

General Description	
Name of technique	**Exhaust Gas Recirculation (EGR)**
Pollutants addressed	NO_x
Engine/vehicle/vessel types considered	Diesel ships (mainly new ones, many drawbacks for retrofitting).
Short description of technique	• As the name implies, EGR redirects (re-circulates) a portion of engine exhaust back into the engine to cool and reduce peak combustion temperatures and pressures. An intercooler lowers the temperature of the re-circulated gases, which then have higher heat capacity and contain less O_2 than air; hence, combustion temperature in the engine is lowered, thus inhibiting NO_x formation. As such, EGR is a method of primary NO_x control rather than a true exhaust gas treatment system. • EGR systems work very well with DPFs; since EGR requires a clean exhaust supply before the exhaust gases are directed back to the engine, the use of a DPF fulfils this process while reducing PM at the same time. EGR is also compatible with SO_x scrubbers.
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	Reference technology: Conventional compression ignition diesel engine • NO_x (25-80%)
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	High uncertainty in cost analysis for EGR in ships. Some indicative ranges: _ Initial cost (hardware and installation): €0.3m - €2m (in general is considered higher than SCR). _ Operation cost: SFOC penalty, additional auxiliary power, water treatment and sludge handle (in general is considered lower than SCR).
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	• EGR slightly reduces engine power. • Possible fuel penalty 1-2%.
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	PM and SO_x recirculation if not combined with a DPF or SO_x scrubber.
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• EGR, although a mature technology within the automotive market, is new to ships (or under demonstration). • Use of EGR as a retrofit technology in ships is limited with many drawbacks because major engine integration is required. • DPF or SO_x scrubber in the EGR system is necessary to remove SO_x and PM from the re-circulated exhaust, to prevent corrosion and reduce fouling of the EGR system and engine components.

Ease of implementation (technology or expertise required, infrastructural needs, etc.)	Retrofit EGR systems may require major engine integration and careful installation.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	• EGR requires electronic control strategy to ensure operation. • Due to nature of EGR primary engine controls, system malfunction or deviation from normal operation can significantly reduce engine efficiency. • Risk of increased maintenance requirements if the scrubber (used with EGR) does not clean and cool the exhaust gas to the required levels.
Durability/lifetime of emission control equipment	Exhaust cooling may result in engine wear due to excess water vapor.
Impacts on safety (users, citizens, …)	Trained personnel required for installation.
References and Other Points	
Comments or remarks not addressed above	Unlike SCR, fuel sulfur content and low load operation are not constraining factors for EGR systems.
Successful examples of implementation	Examples of experimental testing (or under demonstration) mostly in low-speed diesel engines (concerns about high-speed or medium-speed engines).
References for further details	• EGR for vessels - http://cleantech.cnss.no/air-pollutant-tech/nox/exhaust-gas-recirculation-egr/ - http://www1.iaphworldports.org/toolbox%201/cleantech.htm - http://www.alfalaval.com/campaigns/puresox/documents/documents/Understanding_Exhaust_Gas_Treatment_Systems.pdf - NO_x Abatement Technique for Marine Diesel Engines – Improved Marine SCR Systems. M. Magnusson. PhD thesis, Chalmers University of Technology, Gothenburg, Sweden 2014. • Diesel vessels general - http://www.epa.gov/otaq/marine.htm - http://www.epa.gov/otaq/oceanvessels.htm • EGR general - http://www.epa.gov/cleandiesel/technologies/retrofits.htm - http://www.meca.org/diesel-retrofit/what-is-retrofit - http://www.meca.org/galleries/files/MECA_diesel_retrofit_white_paper_1009.pdf - http://www.corning.com/WorkArea/showcontent.aspx?id=60285

3.4.1.2 *Selective Catalytic Reduction (SCR)*

Table 3-17: Summary information for selective catalytic reduction (SCR)[26]

General Description	
Name of technique	**Selective Catalytic Reduction (SCR)**
Pollutants addressed	Mainly: NO_x, Synergies: VOC, CO, PM
Engine/vehicle/vessel types considered	Wide range of diesel ships, i.e., ferries, supply ships, RoRos, tankers, container ships, icebreakers, cargo ships, workboats, cruise ships, navy vessels.
Short description of technique	• SCR is a proven technology for NO_x emission reduction in diesel vessels and many systems have been installed over the last decades. • SCR reduces the concentration of NO_x in the exhaust gases of the engine to below the emission limits set by IMO Tier III. It is an emission reduction method of NO_x through catalytic aftertreatment technology. • In the presence of high-temperature exhaust gas (> 250°C) and excess O_2, an SCR system uses a catalyst to chemically reduce NO_x (convert NO and NO_2) to elemental nitrogen (N_2) and water, two natural components of the air we breathe, by using ammonia (NH_3) as the selective reducing agent, also known as diesel exhaust fluid - DEF (see figure below[27]).  • Different precursors of ammonia can be used; one of the most common options is a solution of urea in water (e.g. AdBlue®) carefully metered from a separate tank and sprayed into the exhaust system ahead of the SCR catalyst. • AdBlue® is a stable, non-flammable, colorless fluid containing 32.5% urea which is not classified as hazardous to health and does not require any special handling precautions. It is made based on internationally-recognized standards. Urea is used as an artificial fertilizer and is found in products such as cosmetics. The consumption of AdBlue® (urea dosing strategy and desired NH_3-to-NO_x ratio) depends on the amount of NO_x that needs to be converted and the conditions present in the exhaust (gas temperature).
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	Reference technology: Conventional compression ignition diesel engine • NO_x (70-95%), VOC (50-90%), CO (50-90%), PM (20-40%)

[26] Main source of summary information for SCR for ships: IACCSEA (The International Association for Catalytic Control of Ship Emissions to Air, http://www.iaccsea.com/).

[27] Source of figure: J. Briggs and J. McCarney, Field experience of Marine SCR, Paper No. 220, CIMAC Congress 2013, Shanghai http://jmsec.com/Library/Documents/Cimac_2013_Field_Experience_of_Marine_SCR_Full_Paper_No_2201.pdf

Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	A first order economic analysis (cost calculation model) of SCR onboard vessels has been carried out by IACCSEA[28]. For illustrative purposes, the following are two examples of SCR costs derived from the model. The first is for a ship that spends 1,500 hours per annum in a NECA and the second is for a ship that spends 8,000 hours (the whole year) in a NECA: - Engine size = 10 MW Vessel weight = 20,000 DWT Time in NECA = 1,500 hrs/year Capital expenditure costs = €370k Lifetime (25 year) urea cost = €705k Lifetime catalyst recharge cost and maintenance = €445k Back pressure fuel penalty = €130k Potential lifetime fuel savings (2% efficiency gain) = €315k Lifetime ownership cost = €1.3m or €52k p.a. Tonnes NO_x Neutralized (lifetime) = Approx 1,800 - Engine size = 10 MW Vessel weight = 20,000 DWT Time in NECA = 8,000 hrs/year (whole year) Capital expenditure costs = €370k Lifetime (25 year) urea cost = €3.66m Lifetime catalyst recharge cost and maintenance = €780k Back pressure fuel penalty = €665k Potential lifetime fuel savings (2% efficiency gain) = €1.66m Lifetime ownership cost = €3.8m or €155k p.a. Tonnes NO_x Neutralized (lifetime) = Approx 10,000 Notes: _ The abovementioned possible fuel savings are more likely to be achieved for OEM applications, not always guaranteed for retrofitting. _ The initial capital expenditure cost maybe higher (e.g. €500k-800k) depending on ship size.
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	2-4% possible improvement in fuel efficiency (and, therefore, CO_2 benefits) (mainly for OEM applications, not guaranteed for retrofitting).
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	• Risk for ammonia (NH_3) slip, especially as the SCR catalyst degrades over time. Can be controlled e.g. through calibration optimization or introduction of a clean-up catalyst downstream of the SCR catalyst. • SCR reduces the characteristic odor produced by a diesel engine and diesel smoke.
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• Urea additive (as a precursor of ammonia) has to be made widely available. • The catalytic reaction requires certain temperature criteria for NO_x reduction to occur; data logging must be performed to determine if the exhaust gas temperatures meet the specific SCR system requirements. • SCR function at loads below 25% and during slow steaming: - Maintaining sufficiently high temperatures when engines are operating at low loads (<25%) for extended periods of time is a challenge. - Special features to increase exhaust gas temperature (even at very low

28 http://www.iaccsea.com/scr-cost-model/

	loads of 5%) have been introduced by some engine manufacturers (tuning of the engine/SCR system). • SCR performance with high sulfur fuels: - Sulfur is not a poison to conventional SCR catalysts; however, high sulfur content of marine fuels (global average for HFO is 2.4%) presents a challenge to the efficacy of SCR, because at low temperatures, ammonia and sulfuric acid condense as ammonium bisulfate (ABS) which can block/foul the catalyst; ABS formation is reversible, i.e., the ABS deposits may be removed and returned to the gas phase by increasing the temperature. - If vessels use low sulfur fuels in ECAs with fuel sulfur content of 0.1%, this should be sufficiently low to reduce the sensitivity of systems to ABS deposition. For HFO, care must be taken to design system operating temperatures which are high enough to prevent ABS formation. For typical heavy fuel oils, the exhaust temperature would need to be over 300°C to prevent ABS.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	• During the design phase of an engine/SCR system, catalyst suppliers/engine OEMs must ensure that the catalyst is properly sized for the exhaust stream and that there is the correct urea dosage. • SCR units are large, heavy, complex and bulky systems. Urea is handled and stored in designated tanks/lines/fittings/pumps, so as to ensure required cleanliness requirements. • Urea refueling infrastructure is necessary to facilitate the use of SCR: - The total demand for urea solution in marine applications is approximately less than 1% of the total land-based use (yearly consumptions of urea for a vessel are typically between 30-1,000 tonnes, 30 tonnes for smaller fishing vessels, and 1,000 tonnes for large ferries, cruise ships and big deep sea vessels). Marine demand is expected to grow slowly over time. - Urea is produced in over 50 countries and is available across most of the globe including Canada, U.S., Europe, Asia and the Middle East. Distribution systems are expected to expand to major ports in response to urea demand for use on ships. Areas such as the North Sea, English Channel and Baltic Sea already have a well established storage and distribution network for urea, as ships in these areas are already using SCR technology due to the Norwegian NO_x Fond.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	• SCR systems require periodic refilling with urea; on-board systems alert when it is time to top up with urea additive. • Physical blocking of the catalyst with dust from the fuel may diminish the ability to reduce NO_x; it can be addressed through correct choice of catalyst pitch and/or mechanisms to dislodge weakly bound material, e.g. use of dust blowers. • When chemical components in the exhaust bind tightly to the active sites of the catalyst, they are more difficult to dislodge and 'poison' the catalyst. These poisons are generally traceable to either the combustion products of the fuel/lubricant or the thermolysis of urea/ammonia solution. Use of well-considered standards is recommended (e.g. fuel, lubricant and urea) to ensure that the engine/SCR functions adequately for many years.
Durability/lifetime of emission control equipment	• Manufacturers guarantee the useful lifetime of the catalyst depending on its operating conditions, quality of the fuel, etc. (e.g. 16,000 hours of operation). • When a catalyst's performance deteriorates to the extent that Tier III cannot be achieved, the catalyst is removed and can either be collected and processed or regenerated.
Impacts on safety	• Trained personnel required for installation.

<table>
<tr><td>(users, citizens, …)</td><td>• Urea is a nonhazardous material that does not become toxic at any temperature.</td></tr>
<tr><td colspan="2">References and Other Points</td></tr>
<tr><td>Comments or remarks not addressed above</td><td>• SCR can be combined with Diesel Particle Filter (DPF) for additional emission reductions; it has also successfully been demonstrated on LNG carriers which switch between heavy fuel oil and gas.
• Compatibility with SO_x scrubbers and space issues:
- SCR can be used in conjunction with a scrubber (there are examples of vessels with both technologies). Given the temperature range within which SCR operates efficiently, the common view is that the SCR system should be positioned upstream of the scrubber. If the SCR is located downstream, it is necessary to reheat the gas to approximately 250°C (due to low sulfur content), which carries an inherent carbon cost associated with reheating. No negative impact on the catalyst.
- Space should not be an issue as the SCR system is part of the engine and will be integrated as part of the design phase when new Tier III compliant vessels are manufactured. In MARPOL Annex VI, space is, however, considered as an inhibitor to the technology on recreational craft <24m.</td></tr>
<tr><td>Successful examples of implementation</td><td>- http://jmsec.com/Library/Documents/Cimac_2013_Field_Experience_of_Marine_SCR_Full_Paper_No_2201.pdf
- http://www.meca.org/resources/Loco_Marine_Case_Studies_update_0114.pdf</td></tr>
<tr><td>References for further details</td><td>• SCR for vessels
- http://www.iaccsea.com/scr/
- http://www1.iaphworldports.org/toolbox%201/cleantech.htm
- http://www.alfalaval.com/campaigns/puresox/documents/documents/Understanding_Exhaust_Gas_Treatment_Systems.pdf
- http://ec.europa.eu/transport/modes/inland/studies/doc/2013-06-03-contribution-to-impact-assessment-of-measures-for-reducing-emissions-of-inland-navigation.pdf
- NO_x Abatement Technique for Marine Diesel Engines – Improved Marine SCR Systems. M. Magnusson. PhD thesis, Chalmers University of Technology, Gothenburg, Sweden 2014.
• Diesel vessels general
- http://www.epa.gov/otaq/marine.htm
- http://www.epa.gov/otaq/oceanvessels.htm
• SCR general
- http://www.dieselretrofit.eu/technologies_SCR.html
- http://www.meca.org/diesel-retrofit/what-is-retrofit
- http://www.meca.org/galleries/files/MECA_diesel_retrofit_white_paper_1009.pdf
- http://www.aecc.eu/en/Technology/Catalysts.html
- http://www.aecc.eu/content/pdf/Emissions Control Technologies to meet current and future European vehicle emissions legislation.pdf
- http://www.factsaboutscr.com/default.aspx
- http://www.dieselforum.org/about-clean-diesel/what-is-scr-
- http://www.corning.com/WorkArea/showcontent.aspx?id=60285</td></tr>
</table>

3.4.2 Sulfur

3.4.2.1 Scrubbers

Table 3-18: Summary information for scrubbers

General Description	
Name of technique	**Scrubbers** (exhaust gas cleaning systems)
Pollutants addressed	Mainly: SO_x, Synergies: PM, BC
Engine/vehicle/vessel types considered	Diesel ships.
Short description of technique	• Using scrubbers is the main alternative to low sulfur fuel for SO_x emission reduction (a common dilemma for ship owners). A scrubber can operate in: Open-loop: Utilizes seawater to remove SO_x from the exhaust. Exhaust gas enters the scrubber and is sprayed with seawater in three different stages. The sulfur oxide in the exhaust reacts with water and forms sulfuric acid. Chemicals are not required since the natural alkalinity of seawater neutralizes the acid. Ideal for ocean-going ships. Closed-loop: A cost effective alternative to low sulfur content fuels for reducing SO_x emissions. Operates in a closed loop, i.e. the wash water is being circulated within the scrubber. Exhaust gas enters the scrubber and is sprayed with fresh water that has been mixed with caustic soda (NaOH). The sulfur oxides in the exhaust react with this mixture and are neutralized. Ideal for ships in areas with extremely low alkalinity or where zero discharge mode is required. Hybrid mode: The hybrid approach enables operation in closed loop mode when required (for instance in port and during maneuvering using NaOH as a buffer); When at sea, switch can be made to open loop using only seawater. Flexible but more complex system; ideal for ships requiring full flexibility of operations.
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	Reference technology: Conventional compression ignition diesel engine • SO_x (90-95%), PM (70-90%)
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	Detailed cost analysis for scrubbers is not a straightforward task; payback period depends on fuel price, amount of time spent in ECAs, ship size and design; costs are also higher for retrofitting. • Indicative scrubber cost: €0.5m - €9m. • Operational cost: ~1.5-2% of added fuel cost (NaOH 50%: 200 €/t). • Example of ROI: 1,5-2 years based on price difference of 140 €/t HFO/LSFO.
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	Increase in fuel consumption (0.5-3%).
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	No significant impact on non-regulated pollutants.
Limitations and Implementation Issues	
Limitations in its applicability (e.g.	• Documented operational experience of closed loop scrubbers remains very limited.

environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• When retrofitting with scrubbers, there are space, weight and ship stability constraints (design and installation of a scrubber becomes a greater challenge than land applications). • However, scrubbers can work with high sulfur HFO.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	• Scrubbers can be used everywhere and are easy to operate. Some technical issues below: _ Back pressure reduction: A fan can be installed on the cold side to reduce pressure drop through the system. _ Re-oxygenation of the system: Air is added to the discharge water to supplement the oxygen levels (in sensitive areas, such as Alaska, this is often a requirement). _ De-plume: The exhaust is saturated with water and in cold areas this can create a white plume; a de-plume system can provide hot dry air to eliminate this effect.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	If operation in zero discharge mode is requested, the cleaned effluents from a closed loop scrubber can be led to a holding tank for scheduled and periodical discharge (instead of directly being discharged into the sea).
Durability/lifetime of emission control equipment	No significant performance degradation if properly maintained.
Impacts on safety (users, citizens, …)	Wash water from open loop and cleaned effluents from closed loop scrubbers can be safely discharged into the sea with no risk of harm to the environment (ensuring conformity to all applicable discharge criteria).
References and Other Points	
Comments or remarks not addressed above	Scrubbers can be used in conjunction with EGR, SCR.
Successful examples of implementation	- Exhaust Gas Scrubber Washwater Effluent. US EPA Report, EPA-800-R-11-006, November 2011. - Caiazzo, G., Langella, G., Miccio, F., Scala, F., 2012. An experimental investigation on seawater SO_2 scrubbing for marine application. Environmental Progress and Sustainable Energy 27 (4). - Kjølholt, J., Aakre, S., Jürgensen, C., Lauridsen, J., 2012. Assessment of Possible Impacts of Scrubber Water Discharges on the Marine Environment. Environmental Protection Agency, Danish Ministry of Environment.
References for further details	• Scrubbers - http://www.alfalaval.com/campaigns/puresox/documents/documents/Understanding_Exhaust_Gas_Treatment_Systems.pdf - http://www.lloydslist.com/ll/incoming/article418235.ece/BINARY/Scrubbers+survey+big.pdf - http://cleantech.cnss.no/air-pollutant-tech/sox/scrubber/ - http://www.dnv.pl/Binaries/5%20SOx%20reduction%20-%20class%20involvement_tcm144-536397.pdf - S. Brynolf, M. Magnusson, E. Fridell, K. Andersson, Compliance possibilities for the future ECA regulations through the use of abatement technologies or change of fuels. Elsevier Transportation Research Part D 28 (2014) 6–18. - Williams, P.J.l.B., 2010, The natural oceanic carbon and sulfur cycles: implications for SO_2 and CO_2 emissions from marine shipping, International Journal of the Society for Underwater Technology 29 (1), 5-

	19. • Diesel vessels general - http://www.epa.gov/otaq/marine.htm - http://www.epa.gov/otaq/oceanvessels.htm - http://www.dieselforum.org/diesel-at-work/port-and-marine

3.4.3 Particulate matter (PM)

3.4.3.1 Diesel Particle Filter (DPF)

Table 3-19: Summary information for diesel particle filter (DPF)

General Description	
Name of technique	**Diesel Particle Filter (DPF)**
Pollutants addressed	Mainly: PM, PN, BC, Synergies: VOC, CO
Engine/vehicle/vessel types considered	• Diesel ships. • Technology under demonstration (experimental phase), cannot be simply transferred from automotive/NRMM.
Short description of technique	• DPFs are used to trap the harmful PM present in the exhaust of (diesel) engines. PM is trapped in and on a porous ceramic substrate. • Since a filter can fill up over time, a means of burning off or removing accumulated PM must be provided. A convenient means is to burn or oxidize it on the filter when exhaust temperatures are adequate. By burning off trapped material, the filter is cleaned or "regenerated". • DPF can be combined with EGR system for additional NO_x reduction.
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	Reference technology: Conventional compression ignition diesel engine • PM (45-90%), VOC and CO (60-90%) (wall-flow DPF). • Emission reduction may not be as high as in road/non-road vehicles.
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	Still at experimental phase, cannot provide indicative cost ranges.
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	Installation of a filter system may cause a fuel economy penalty ~1-2% (with a corresponding increase in CO_2 emissions).
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	• Concerns that catalyzed DPFs may increase the NO_2 fraction of total NO_x emissions (depending on catalyst formulation). Some DPFs generate NO_2 as a means to help filter regeneration at lower temperatures. • Soot particulates burn-off forms water and CO_2 in small quantity.
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• DPF technology from automotive/NRMM applications cannot be simply transferred to large medium or low speed engines of diesel vessels; it is not entirely ready for commercial operation. • The engine cannot be too polluting for application of DPF (maximum limit 350 mg PM per kWh); furthermore, the exhaust gas should not contain too much oil. This implies that the most 'dirty' engines would need to be replaced first or would need a FWE (fuel-water emulsion) device to reduce the engine-out PM levels. • Low-sulfur fuel required (<5,000ppm). DPF with higher OC (organic carbon) oxidation capability at sulfur insensitivity is needed. • Application of DPF (possibly combined with SCR) increases the exhaust backpressure. For low RPM engines this may require the application of larger aftertreatment systems or, if insufficient space is available, the

	replacement of the engine. On smaller vessels, available space may be a problem due to small engine rooms and small exhaust systems. • Exhaust gas temperature data logging must be performed to determine if the exhaust temperature profile meets DPF-specific requirements. For retrofit, a case-by-case / tailor made approach may be required; first, the condition of the base engine and engine room needs to be verified with respect to the above restrictions and, after mounting the retrofit device, the effectiveness in terms of the reduction levels needs to be verified.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	Trained personnel required for installation, approved components need to be used.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	• Active/passive regeneration and cleaning system needed (filters require periodic maintenance to clean out non-combustible materials, such as ash). Since the continuous flow of soot into the filter would eventually block it, it is necessary to 'regenerate' the filter by periodically burning-off the collected particulate. • Passive filters require operating temperatures high enough to initiate combustion of collected soot. Active regeneration uses other heat sources, such as fuel burning or electric heaters, to raise a DPF temperature sufficiently to combust accumulated PM. • DPF should incorporate electronic back pressure monitoring equipment to signal operators when the device needs to be cleaned.
Durability/lifetime of emission control equipment	Significant performance degradation due to accumulated soot (ash) in 'dirty' engines.
Impacts on safety (users, citizens, …)	Devices need to be maintained by trained personnel to limit exposure to pollutants.
References and Other Points	
Comments or remarks not addressed above	• DPF can be combined with SCR and LNG dual fuel engines for additional emission reductions. • DPFs are very important to the functionality and effectiveness of an EGR (exhaust gas recirculation) system to ensure that large amounts of particulate matter are not re-circulated to the engine.
Successful examples of implementation	- http://www.arb.ca.gov/diesel/verdev/vt/marine.htm - http://www.lav.ethz.ch/nanoparticle_conf/Former/Presentations_L-O.pdf - http://www.meca.org/resources/Loco_Marine_Case_Studies_update_0114.pdf
References for further details	• DPF for vessels - http://www1.iaphworldports.org/toolbox%201/cleantech.htm - http://ec.europa.eu/transport/modes/inland/studies/doc/2013-06-03-contribution-to-impact-assessment-of-measures-for-reducing-emissions-of-inland-navigation.pdf - http://www.worldcargonews.com/htm/w20131017.546041.htm • Diesel vessels general - http://www.epa.gov/otaq/marine.htm - http://www.epa.gov/otaq/oceanvessels.htm • DPF general - http://www.dieselretrofit.eu/technologies_filters.html - http://www.epa.gov/cleandiesel/technologies/retrofits.htm - http://www.meca.org/diesel-retrofit/what-is-retrofit - http://www.meca.org/galleries/files/MECA_diesel_retrofit_white_paper

	_1009.pdf - http://www.aecc.eu/en/Technology/Filters.html - http://www.aecc.eu/content/pdf/Emissions Control Technologies to meet current and future European vehicle emissions legislation.pdf - http://www.corning.com/WorkArea/showcontent.aspx?id=60285

3.5 Aviation

3.5.1 Nitrogen oxides (NO_x)

3.5.1.1 Low NO_x combustion

Table 3-20: Summary information for low NO_x combustion in aviation

General Description	
Name of technique	**Low NO_x combustion in aviation**
Pollutants addressed	NO_x
Engine/vehicle/vessel types considered	Aircrafts
Short description of technique	• Lean premixed combustion, clean combustor design (includes design of fuel injector, thermal liner, dynamics and operability). • Peak temperature and time spent at this temperature is limited.
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	Lower NO_x emissions by 70%.
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	No significant cost increase. Basically R&D costs.
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	Possible fuel savings ~5%.
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	• Smoke formation can be reduced by new lean burn strategies and by increasing air/fuel ratio in the downstream parts of the combustor, so that smoke produced in the primary zone is oxidized. • Lean burn combustion may lead to incomplete combustion and to an increase in CO and unburned hydrocarbons emissions.
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• Not easy to meet all requirements for the design of a low NO_x combustor, e.g. good altitude relight requires large and heavy combustor and, hence, more NO_x emissions. • Fuel-air mixture preparation is a key requirement technology for clean burning. This is difficult during the available time which must decrease with increasing temperature and pressure due to risk of auto-ignition. • Operation on both gaseous and liquid fuels is required in many gas turbines. Pre-mixer is necessary to produce comparable environmental performance between gas and liquid fuels as the latter are more difficult to mix and provide homogeneous fuel/air required for low NO_x combustion.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	• Light weight structures, combustor liners with reduced cooling and improved high temperature durability are necessary. • The lean direct injection concept controls air/fuel premixing with optimized pilot and main stage flame structures to provide low NO_x and weak extinction stability.

Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	No special maintenance requirements.
Durability/lifetime of emission control equipment	• Improved inner and outer liners improve liner life. • Lean combustion eliminates dilution holes. It removes stress concentrations and reduces liner cracking. • Reduced exit temperature variation improves durability of high pressure turbine components.
Impacts on safety (users, citizens, …)	Reliable performance.
References and Other Points	
Comments or remarks not addressed above	Less noise.
Successful examples of implementation	Dry low NO_x combustion systems for GE heavy-duty gas turbines.
References for further details	- Davis, L.B. and Black, S.H., Dry Low NO_x Combustion Systems for GE Heavy-Duty Gas Turbines. GE Power Systems. - Chang CT, Lee CM, Herbon JT, Kramer SK (2013) NASA Environmentally Responsible Aviation Project Develops Next-Generation Low-Emissions Combustor Technologies (Phase I). J Aeronaut Aerospace Eng 2: 116. doi:10.4172/2168-9792.1000116. - Emissions from Combustion and Their Effects. SBAC Aviation and Environment Briefing Papers. http://www.sustainableaviation.co.uk/wp-content/uploads/emissions-from-combustion-and-their-effects-briefing-paper.pdf - Lean Pre-mixed Combustion. http://www.netl.doe.gov/File%20Library/Research/Coal/energy%20systems/turbines/handbook/3-2-1-2.pdf - http://www.nasa.gov/pdf/633344main_12-03_Aeronautics.pdf - Hosoi, J., Hiromitsu, N., Riechelmann, D., Fujii, A. and Sato, J., Simple Low NO_x Combustor Technology. IHI Engineering Review, 41 (1) 2008. - V.D. Bank, R., Berat, C., Cazalens, M. and Harding, S., Strategy For Environmentally Friendly Low Emissions Combustion Development in European Aeronautics, 1st European Air and Space Conference, Deutscher-Luft und Raumfahrt Kongress 2007.

3.5.1.2 *Aircraft design improvements*

Table 3-21: Summary information for aircraft design improvements

General Description	
Name of technique	**Aircraft design improvements**
Pollutants addressed	NO_x
Engine/vehicle/vessel types considered	Aircrafts
Short description of technique	• Reduction of basic aircraft weight. This increases the commercial payload for the same amount of fuel burn. • Improvement of aerodynamics. Reduction of the drag forces and its associated thrust. • Improvement of overall specific performance of the engine. Reduction of the fuel burn per unit of delivered thrust. • Aircraft design that flies at lower altitudes with reduced speed.
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	• NO_x emissions vary with cruise altitude, speed, and shape of aircraft (wide-body, narrow-body). • The improvement of the aerodynamics may lead to NO_x decrease ~4%. • Specific design examples have demonstrated up to 50% NO_x emissions over a baseline design.
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	1-1.5% increase in total operating costs for narrow-body aircrafts and 2-3% increase for wide-body aircrafts.
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	• Large and heavy aircrafts that cruise at low altitudes have large fuel consumption. • The minimum NO_x design has higher fuel consumption rate.
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	30-50% savings in climate impacts for both narrow-body and wide-body aircrafts by varying cruise altitude and improving the design.
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• Reduced speed and altitude for existing aircrafts are associated with larger fuel and operating cost penalties. • Operating an existing aircraft at reduced altitude, increases fuel burn and decreases maximum range.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	Technical difficulties may exist.

Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	No special maintenance requirements.
Durability/lifetime of emission control equipment	No significant impact on aircraft lifetime.
Impacts on safety (users, citizens, …)	No significant safety impacts.
References and Other Points	
Comments or remarks not addressed above	No further remarks.
Successful examples of implementation	Aircraft Technology Improvements. ICAO Environmental Report 2010.
References for further details	- Egelhofer, R., Simplified Aircraft Design Functional Chain. First CEAS European Air and Space Conference, Berlin 2007. - Schwartz Dallara, E. and Kroo, M., Aircraft design: Trading Cost and Climate Impact. 47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition, 5 - 8 January 2009, Orlando, Florida. - Schwartz Dallara, E. and Kroo, I., Aircraft Design for Reduced Climate Impact. 49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, 4 - 7 January 2011, Orlando, Florida.

3.6 Trams, metros, and trolley buses

Trams and trolleybuses are electrically driven public transport vehicles run on rails and powered by electricity usually taken from an overhead wire. They operate in urban, suburban and regional environment. Metropolitan railways (various abbreviators are metro, underground, subway or tube) are electric transport systems with high transport capacity operating on their own – mostly underground - rail network.

Using 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.

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[29,30]. 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.

An indicative list of measures related to the usage of (electric) trams, metros, and trolley buses in order to increase environmental protection and energy efficiency and improve air quality is given below[31].

<u>Fleet and network</u>

- Modernization of existing stock and fleet management optimization
- Increase commercial speed through segregated tracks and traffic management measures
- Inspection and maintenance of rails, fixed installations, etc.

<u>General measures</u>

- Make the usage of trams, metros, and trolleybuses attractive (e.g. by park and ride policies connected to public transport, low fare policies, expansion of network, new routes, etc.)
- Increase intermodality and reduce trip duration
- Use advanced traffic management systems

<u>Technology measures</u>

- Reduce friction by better design and materials
- Eliminate sparking by either mechanical or, most probably, electrical measures

---

[29] Kam, W. et al. 2013. A comparative assessment of $PM_{2.5}$ exposures in light-rail, subway, freeway, and surface streets environments in Los Angeles and estimated lung cancer risk. Environ. Sci.: Processes Impacts 15, 234.

[30] Kam, W. et al. 2011. Chemical characterization of coarse and fine particulate matter (PM) in underground and ground-level rail systems of Los Angeles Metro. Environ. Sci. Technol. 45, 6769.

[31] http://www.caprice-project.info/spip.php?rubrique1

3.7 Horizontal measures

3.7.1 Particulate matter (PM) from component wear and abrasion

3.7.1.1 Tyre, brake, and road surface measures

Table 3-22: Summary information for tyre, brake, and road surface measures

General Description	
Name of technique	**Tyre, brake, and road surface measures**
Pollutants addressed	PM (mainly PM_{10}) primary emissions and resuspension
Engine/vehicle/vessel types considered	All road vehicles
Short description of technique	Tyre measures • Adjustment of tyres. • Avoid using studded tyres. Brake measures • Change brake composition (e.g. ceramic brakes have fewer emissions). • Brake particulate collection system. • Gentle braking. Road surface measures • Adjustment of pavements and gritting material. • Usage of coarser, wear resistant rock aggregates. • Alternative pavements (porous, rubber mixed, concrete). • Dust binding materials. • Wet roads reduce resuspension. • Street sweeping is very effective in reducing resuspension, but completely ineffective in reducing primary emissions.
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	Practical trials of dust binding in Sweden: ~10-40% reductions of PM_{10}.
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	Improved pavement materials and more environmental friendly dust binders are expensive.
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	No significant impact on fuel consumption.
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	Toxic heavy metals contained in brake (as well as tyre) wear are reduced.

Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• The effect of dust binding depends on weather and traffic intensity. • Dust binders reduce friction. • Road sweeping with good techniques, otherwise PM_{10} may increase.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	Different climate conditions among countries must be taken into account.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	Dose problem with dust binding: when, how often, and how much for optimal effect and minimal negative effects?
Durability/lifetime of emission control equipment	The effect of dust binding is short-lived.
Impacts on safety (users, citizens, …)	Avoiding using studded tyres may have negative safety effects.
References and Other Points	
Comments or remarks not addressed above	• In addition to the above, 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. • In any case, optimal combinations of the above abatement measures are expected to have better emission reduction potential.
Successful examples of implementation	Gustafsson M. (2009), "Dust binding: practical trials in Sweden", Air Quality alongside motorways, November 25 – 26, 2009, Rotterdam.
References for further details	- International Workshop Road Transport Wear Emissions, Amsterdam, June 22, 2011. Workshop report available at: http://slb.nu/slb/rapporter/pdf8/ovr2012_005.pdf - Denier van der Gon H.A.C. et al. (2013), "The Policy Relevance of Wear Emissions from Road Transport, Now and in the Future – An International Workshop Report and Consensus Statement", Journal of the Air & Waste Management Association, 63:2, 136-149. - http://www.fleeteurope.com/news/brake-particulate-collection-system-developed

3.7.2 Volatile organic compounds (VOC) from fuel evaporation

3.7.2.1 Activated carbon canister

Table 3-23: Summary information for activated carbon canister

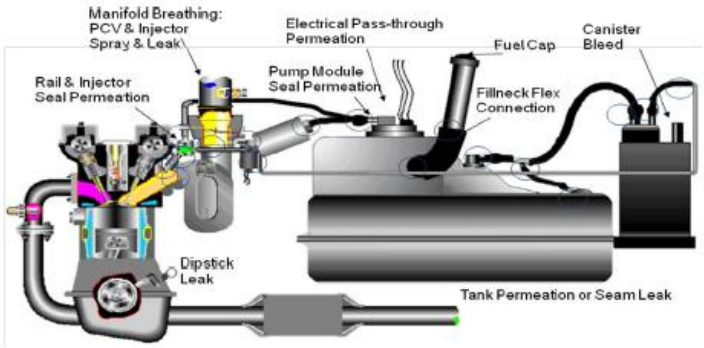
General Description	
Name of technique	**Activated carbon canister**
Pollutants addressed	VOC (from fuel evaporation)
Engine/vehicle/vessel types considered	• All gasoline vehicles (passenger cars, light commercial vehicles, mopeds, motorcycles). • Can be installed in uncontrolled vehicles (retrofitting) or as replacement of smaller canisters (e.g. for meeting stricter limits).
Short description of technique	• One of the essential components of evaporative emission control system is carbon canister. It consists of a plastic housing containing high surface area carbon adsorbent material. Hydrocarbon molecules are attracted to the non-polar surface of the activated carbon and stored within the pores by physical adsorption or physisorption. Canister filling occurs during diurnal events and refueling. • Canisters come in many shapes and sizes and are proportional to the volume of vapor generated in fuel tank (see figure below[32]). At the core of the canister function is the activated carbon that is charged inside the chambers. Carbon is available in different particle sizes and working capacities. The particle size or granule size controls the back pressure whereas the working capacity is a function of surface area and porosity. Vapor migration into the carbon particle occurs via gas phase and surface diffusion of the hydrocarbon molecules. 
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	Reference technology: No evaporation control • Up to 99% of breathing losses depending on carbon quality, age, purging strategy, ambient temperature. • No effect on other evaporation losses (due to permeation, leakages and refueling).
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	€40–€50 (indicative cost as a replacement part – carbon canister, hoses, purge valve).
Environmental Side Effects	
Impact on fuel consumption	No significant impact (if any, only small amounts of fuel saved).

32 Source of figure: http://www.meca.org/galleries/files/MECA_Evap_White_Paper_Final.pdf

(positive/negative impact and typical % effect)	
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	No effects.
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• Canister has to be properly purged for maintaining its working capacity. • For correct dimensioning a number of parameters should be taken into consideration: fuel tank size, fuel specifications, climatic conditions, type of application. • Adsorption efficiency may decrease with ethanol content in the fuel.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	Easy to install for new vehicles. Space concerns for mopeds and small motorcycles. More complicated for retrofits as an automation to purge the system is required.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	• No additional maintenance required. • Malfunctioning purge valve (venting fuel vapor to the engine), and leaks in vent and vacuum hoses may be detected by OBD (in new cars). • Evaporation-related problems/failures do not have any impact on vehicle drivability.
Durability/lifetime of emission control equipment	Deterioration of canister performance with mileage.
Impacts on safety (users, citizens, …)	Only trained personnel should maintain the canister.
References and Other Points	
Comments or remarks not addressed above	• For an effective control of evaporative emissions, an activated carbon canister should be combined with low-permeability fuel tank and hoses. • In addition to the quantity of carbon contained in canister, carbon quality is also important. There are typically two classes of durability of carbons: - Low Degradation Carbons: they lose about 4% to 9% of their capacity over the lifetime of the vehicle, due to repeated cycling with gasoline. - High Degradation Carbons: they lose about 12% to 20% of their capacity over vehicle lifetime, due to repeated cycling with gasoline.
Successful examples of implementation	- http://www.meca.org/galleries/files/MECA_Evap_White_Paper_Final.pdf
References for further details	- Estimating the Costs and Benefits of Introducing a New European Evaporative Emissions Test Procedure. JRC Scientific and Policy Reports, EUR 26057 EN, 2013. - Joint EUCAR/JRC/CONCAWE Programme on: Effects of gasoline vapor pressure and ethanol content on evaporative emissions from modern cars. Final report to DG Joint Research Centre. EUR 22713 EN, Luxembourg: Office for Official Publications of the European Communities, 2007.

3.7.2.2 *Low permeability tank*

Table 3-24: Summary information for low permeability tank

General Description	
Name of technique	**Low permeability tank**
Pollutants addressed	VOC (from fuel evaporation)
Engine/vehicle/vessel types considered	All gasoline vehicles (passenger cars, light commercial vehicles, mopeds, motorcycles), small handheld and non-handheld machinery (e.g. in lawn and garden applications), and boat/recreational craft engines.
Short description of technique	• Low permeability tanks are used to control evaporative emissions – losses due to permeation (see figure below[33], where a typical fuel system is depicted). They reduce the permeability of plastics and polymers to gasoline in either the liquid or vapor phase; this can be accomplished through both design and selection of materials. Advanced tanks consist of coextruded, multilayer construction with a barrier layer of ethylene vinyl alcohol and fluoropolymers to reduce permeation. Furthermore, polymers can be treated via sulfonation or fluorination to further reduce permeability.  • Special challenges in permeation emissions and materials compatibility have resulted since the introduction of ethanol blends in gasoline. Newest vehicles (FFV) are equipped with the lowest permeation materials, while older vehicles (spark-ignited off road engines like those used in lawn equipment, boats, recreational motorcycles and ATVs) still use conventional fuel system materials which are not compatible with ethanol levels above 10%. There is a concern that if this equipment and vehicles are fueled with ethanol-gasoline blends greater than E10 they will result in significant emissions of hydrocarbons into the atmosphere. Furthermore, these engines are not calibrated to operate on higher ethanol blends.
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	Reference technology: Fluorinated fuel tank with monolayer structure • Up to 70% of permeation losses depending on materials used, no effect on other evaporation (e.g. breathing) losses. • If contribution of permeation losses is ~20% of total VOC, then the overall environmental benefit of a low permeability tank (% reduction of total VOC) is ~14% (70% reduction of permeation losses * 20% contribution of permeation losses to total VOC from the vehicle).
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	Typical installation cost: 200-250€.

[33] Source of figure: http://www.meca.org/galleries/files/MECA_Evap_White_Paper_Final.pdf

Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	No significant impact (if any, only small amounts of fuel saved).
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	No critical emissions of unregulated pollutants.
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• Metal tanks add weight and limit the shape necessary to meet stringent packaging requirements (although they offer the highest barrier to permeation). • Permeation and compatibility issues with ethanol blends above 10% for older vehicles (spark-ignited off road engines like those used in lawn equipment, boats, recreational motorcycles and ATVs); concerns for significant emissions of hydrocarbons.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	Easy to install by trained personnel.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	• No additional maintenance required. • Evaporation-related problems/failures do not have any impact on vehicle drivability.
Durability/lifetime of emission control equipment	Trouble free operation.
Impacts on safety (users, citizens, …)	• Only trained personnel should install the tank. • Reducing evaporative emissions also reduces the risk of fires.
References and Other Points	
Comments or remarks not addressed above	For an effective control of evaporative emissions, a low permeability tank should be combined with an activated carbon canister.
Successful examples of implementation	- http://www.meca.org/galleries/files/MECA_Evap_White_Paper_Final.pdf
References for further details	- Estimating the Costs and Benefits of Introducing a New European Evaporative Emissions Test Procedure. JRC Scientific and Policy Reports, EUR 26057 EN, 2013. - Joint EUCAR/JRC/CONCAWE Programme on: Effects of gasoline vapor pressure and ethanol content on evaporative emissions from modern cars. Final report to DG Joint Research Centre. EUR 22713 EN, Luxembourg: Office for Official Publications of the European Communities, 2007. - Effect of Proposed Evaporative Emission Standards for Boat Owners. EPA FAQ, EPA420-F-02-009, July 2002.

3.7.3 Fuels, fuel switching, alternative powertrains

Gasoline related fuels

3.7.3.1 Liquefied Petroleum Gas (LPG)

Table 3-25: Summary information for liquefied petroleum gas (LPG)

General Description	
Name of technique	**Liquefied Petroleum Gas (LPG)**
Pollutants addressed	VOC, CO
Engine/vehicle/vessel types considered	Gasoline vehicles (mainly: passenger cars and light commercial vehicles, secondarily: buses and trucks)
Short description of technique	• LPG is produced by natural gas extraction (60%) and crude oil refining (40%). It consists of propane and butane molecules. It is composed of simple hydrocarbons and it is free of lead and additives. • High octane number enables optimization of spark timing, hence more efficient engine and more power generated at the same amount of fuel. • Its gaseous nature eliminates the cold/start problems related to liquid fuels. Easier start, smoother acceleration, efficient burning, less unburned hydrocarbons in the exhaust. • LPG may be combusted in a normal gasoline engine that has to be adjusted to the fuel specifications. Most such engines are suitable for conversion; LPG can also be used in bi-fuel engines which can run on both LPG and gasoline and, as such, have two independent fuel systems and tanks.
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	• Properly adjusted stoichiometric OEM LPG vehicles little differ in terms of their regulated emissions compared to new gasoline ones. • A ~10% reduction in CO and total VOC may be observed (negligible evaporative emissions due to gas-tight seals required on the fuel system). • As a retrofit, there is no clear evidence that significant emission reductions can be achieved.
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	• Typical conversion cost: 800-2,000€. • Fuel cost savings: 400-900€ per year, depending on mileage driven (because of lower LPG price compared to gasoline)[34].
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	• In general, LPG has ~80% of the energy content of gasoline per liter. • Reduction in brake specific fuel consumption of about 20-30 % compared to gasoline.
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	Higher NO_x emissions of LPG retrofit.
Limitations and Implementation Issues	
Limitations in its applicability (e.g.	• Fuel availability. • Gas tank limits the car storage space when conversion is applied.

[34] Indicative example: http://www.racq.com.au/motoring/cars/car_advice/car_fact_sheets/lp_gas

environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• A retrofitted bi-fuel vehicle may be inferior (in emissions) compared to an OEM single LPG fuelled vehicle.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	• LPG conversion involves fitting an additional fuel tank, fuel lines and associated components; very sturdy tank and cylinders are needed for its storage. Installation may also be performed at new vehicles by the original manufacturer. • Refueling infrastructure must be expanded.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	Longer service life and reduced engine maintenance costs (due to its vapor condition at the engine combustion chamber, it does not strip oil from cylinder walls or dilute the oil when the engine is cold).
Durability/lifetime of emission control equipment	Reduced tear and wear on the engine due to absence of carbon deposits and acids.
Impacts on safety (users, citizens, …)	LPG conversion to be made by trained personnel only.
References and Other Points	
Comments or remarks not addressed above	Petroleum dependency remains.
Successful examples of implementation	- http://apem-journal.org/Archives/2011/APEM6-2_087-094.pdf - In 2012 there were approximately 5.9 million LPG passenger cars, 2,000 LPG buses and 262,000 LCVs in the EU.
References for further details	- Liu, E., Yue, S.Y., Lee, J., A study on LPG as a Fuel for Vehicles, 1997. Research and Library Services Division Legislative Council Secretariat. Hong Kong. - Pundkar A. H., Lawankar S.M., Deshmukh S., Performance and Emissions of LPG Fueled Internal Combustion Engine: A Review. International Journal of Scientific & Engineering Research Volume (3) 3 (2012), ISSN 2229-5518. - Saraf R.R., Thipse S.S. and Saxena P.K., Comparative Emission Analysis of Gasoline/LPG Automotive Bifuel Engine. World Academy of Science, Engineering and Technology (3) (2009). - Yang HH, Chien SM, Cheng MT, Peng CY., Comparative study of regulated and unregulated air pollutant emissions before and after conversion of automobiles from gasoline power to liquefied petroleum gas/gasoline dual-fuel retrofits. Environ Sci Technol. (41) 24 (2007), 8471-8476. - Lanje A.S., and Deshmukh M.J., Performance and Emission Characteristics of SI Engine using LPG-Ethanol Blends: A Review. International Journal of Emerging Technology and Advanced Engineering, (2) 10 (2012). - Europia White Paper on Fuelling EU Transport (2011). Available at: http://www.endseurope.com/docs/110427b.pdf - Ntziachristos L. and Dilara P., Sustainability Assessment of Road Transport Technologies. JRC Scientific and Policy Reports, EUR 25341 EN, Joint Research Centre – Institute for Energy and Transport, (2012) doi:10.2788/28167. - Autogas in Europe, The sustainable Alternative. An LPG Industry Roadmap. Available at: http://www.aegpl.eu/media/16300/autogas%20roadmap.pdf - JEC well-to-wheels study - version 3, (2008). Assessment of a wide range of

	automotive fuels and powertrains relevant to Europe in 2010 and beyond. Available at: http://iet.jrc.ec.europa.eu/sites/about-jec/files/documents/V3.1_TTW_Report_07102008.pdf - Mamidi, T. and Suryawnshi, J.G., Investigations on S.I. Engine Using Liquefied petroleum Gas (LPG) As an Alternative Fuel. International Journal of Engineering Research and Applications (IJERA), (2) 1 (2012), 362-367. - Salhab, Z., Qawasmi, M.G., Amro, H., Zalloum, M., Qawasmi, M.S. and Shaeawi, N., Comparative Performance and Emission Properties of Spark-Ignition Outboard Engine Powered by Gasoline and LPG. Jordan Journal of Mechanical and Industrial Engineering, (5) 1 (2011), 47-52.

3.7.3.2 Ethanol (EtOH)

Table 3-26: Summary information for ethanol (EtOH)

General Description	
Name of technique	**Ethanol (EtOH)**
Pollutants addressed	PM, NO_x, VOC (from fuel evaporation), Synergies: CO
Engine/vehicle/vessel types considered	Gasoline road vehicles (mainly passenger cars and light commercial vehicles), FFVs (Flexi-Fuel Vehicles)
Short description of technique	• Ethanol is an alcohol-based fuel for vehicles that can be used as neat fuel or blended with gasoline. It is produced either from starch-sugar based crops or by cellulosic feed stocks with biochemical or thermo chemical procedures. • Because of its high oxygen content, ethanol is cleaner burning than gasoline. It can be used blended with gasoline as e.g. E85, which is composed of 85% ethanol and 15% gasoline (formulated for FFVs), or E10, which is composed of 10% ethanol and 90% gasoline (formulated for conventional gasoline vehicles) or other blends. • High combustion speed and high octane number that allows higher compression ratios (hence, anti-knock quality and more thermally efficient engine). • High latent heat of evaporation (hence, decreased compressed gas temperature). The combustion products also decrease combustion temperature and reduce cooling heat loss (these lead to increased torque and thermal efficiency).
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	In general, environmental benefit mainly depends on ethanol blend. Some indicative ranges for E85 emission reductions (compared to pure gasoline) are given below: • PM (10-20%) • NO_x (10-15%) • VOC from fuel evaporation (10-20%) (E85 is less volatile than gasoline) • CO (20-40%)
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	• FFVs are priced the same as gasoline-only vehicles, offering drivers the opportunity to buy an E85 capable vehicle at no additional cost. • Conventional vehicles can be upgraded for use with lower percentage blends simply changing the parts that are under risk of corrosion (€350-€700) and by engine retuning. • Usually, lower price for E85 fuel compared to gasoline, but no significant fuel cost savings (e.g. per year) because of decreased fuel economy.
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	Fuel economy of vehicles using ethanol blends depends on the engine type and driving conditions. In general, E85 reduces fuel economy and range by about 20-30%, meaning an FFV will travel fewer km on a tank of E85 than on a tank of gasoline. This is because ethanol contains less energy than gasoline.
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	• Increased unburned ethanol and acetaldehyde emissions. • Using E85 may provide significant reductions in emissions of many harmful toxics.
Limitations and Implementation Issues	
Limitations in its applicability (e.g.	• Severe issues with cold startability and drivability; can be solved with additives or by lowering the blend percentage.

environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• At conventional gasoline vehicles, specific proportions of ethanol/gasoline blends are allowed. Above these limits, corrosion may occur at specific parts of the vehicles.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	• The use of pure ethanol requires some modifications to SI engines. • Appropriate calibration of the lambda sensor is required to retain stoichiometry with ethanol. • E85 cannot be used in a conventional, gasoline-only engine. Vehicles must be specially designed to run on it. • Conventional vehicles can be upgraded simply changing the parts that are under risk of corrosion.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	Maintenance for ethanol-fueled vehicles is very similar to that of regular cars. However, owners should identify the car as an FFV when ordering replacement parts.
Durability/lifetime of emission control equipment	Clogging of fuel lines due to ethanol deposits when using ethanol blends of E10 and beyond.
Impacts on safety (users, citizens, …)	Ethanol is safe for storage and transportation; safety and storage regulations are generally the same as gasoline regulations.
References and Other Points	
Comments or remarks not addressed above	• Performance of vehicles running on ethanol/gasoline blends is similar to that of pure gasoline powered vehicles. • Ethanol usage may drive up the food cost, so it may not constitute an adequate solution to the energy problem.
Successful examples of implementation	About 39 million FFVs worldwide (23m in Brazil, 10m in US, 600k in Canada, 230k in Sweden).
References for further details	- Nakata, K., Utsumi, S., Ota, A., Kawatake, K. et al., The Effect of Ethanol Fuel on a Spark Ignition Engine. SAE Technical Paper 2006-01-3380, (2006), doi:10.4271/2006-01-3380. - Li, L., Liu, Z., Wang, H., Deng, B. et al., Combustion and Emissions of Ethanol Fuel (E100) in a Small SI Engine. SAE Technical Paper 2003-01-3262, (2003), doi:10.4271/2003-01-3262. - Ethanol Internal Combustion Engines. IEA ETSAP – Technology Brief T06 – June 2010. - Curtis, S., Owen, M., Hess, T. and Egan, S. Effect of Ethanol Blends on a Spark Ignition 4-Stroke Internal Combustion Engine. Bringham Young University, Provo, Utah (2008). - Arcoumanis C., A technical Study on Fuels Technology related to the Auto-Oil II Programme. European Commission DG Energy, Final Report, Volume II: Alternative Fuels, (2000). - Masum, B.M., Masjuki, H.H., Kalam, M.A. and Rizwanul Fattah, I.M., Effect of ethanol-gasoline blend on NO_x emission in SI engine. Renewable and Sustainable Energy Reviews 24 (2013), 209-222. - Kumar, J., Trivedi, D., Mahara, P. and Butola, R., Performance Study of Ethanol Blended Gasoline Fuel in Spark Ignition Engine. IOSR Journal of Mechanical and Civil Engineering, (7) 3 (2013), 71-78. - Argakiotis, C., Mishra, R., Stubbs, C., and Weston, B., The Effect of using an Ethanol blended fuel on Emissions in an SI Engine. Renewable Energy and Power Quality Journal, Issue (12), 2014, ISSN 2172-038 X (In Press).

	- Zhai H, Frey HC, Rouphail NM, Gonçalves GA and Farias TL., Comparison of flexible fuel vehicle and life-cycle fuel consumption and emissions of selected pollutants and greenhouse gases for ethanol 85 versus gasoline. Journal of the Air & Waste Management Association, 59 (8) (2009), 912-924. - E85 and Flex Fuel Vehicles. US EPA Technical Highlights, Office of Transportation and Air Quality, EPA-420-F-10-010a, May 2010. - http://about.bnef.com/press-releases/cellulosic-ethanol-heads-for-cost-competitiveness-by-2016/ - http://www.meca.org/technology/technology-details?id=28&name=Alternative%20Fuels - http://www.ffv-awareness.org/faqs.html - http://www.afdc.energy.gov/vehicles/flexible_fuel.html

3.7.3.3 Methanol (MtOH)

Table 3-27: Summary information for methanol (MtOH)

General Description	
Name of technique	**Methanol (MtOH)**
Pollutants addressed	• No significant impact on PM and NO_x compared to gasoline. • Reduction of aromatic and polyaromatic hydrocarbons (PAHs).
Engine/vehicle/vessel types considered	• Gasoline road vehicles (mainly passenger cars and light commercial vehicles). • (Bio)methanol is reported in individual studies as an alternative liquid biofuel in applications such as e.g. in buses and ships (instead of LNG), but the experience is limited.
Short description of technique	• Methanol is a natural gas derivative. It can be produced from natural gas, coal gasification, or biogas, using various synthesis techniques. • It offers much higher volumetric energy content than natural gas, and ease of handling for refueling and storage on board the vehicle. • Actually, MtOH is one of the first alternative fossil fuels used in transport already since the 1970s (in particular in US as a gasoline replacement). • It can be used as a neat fuel or in blends with gasoline. It has a high natural octane rating (>105) and offers additional efficiency gains due to its high heat of vaporization.
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	• Methanol is ignited in cylinder by a spark, in an identical process to gasoline combustion. Hence, emissions are usually controlled by a three way catalyst and a similar profile of conventional pollutants as gasoline is to be expected. • In general, the use of methanol instead of gasoline as a fuel on new specifically designed vehicles is not expected to lead to substantially different levels of pollutants, as long as oxygenated compounds are satisfactorily dealt with.
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	• Methanol powered vehicles may be €150-€350 more expensive than corresponding gasoline ones. • Fuel cost savings can be achieved because of lower methanol fuel price (calculated in energy equivalence to gasoline and diesel)[35]. • Extra costs for the lubricants are required, but maintenance costs might be reduced due to clean burn characteristics of methanol.
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	The energy content of methanol is less than that of gasoline (almost half), so higher fuel consumption would be theoretically predicted for blends of methanol with gasoline.
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	• Similar to ethanol and other alcohols, oxygenated organic compounds like aldehydes and ketones can be a problem when methanol is combusted. • On the other hand, its use may result to a reduction of aromatic and polyaromatic products of gasoline combustion. • Adding methanol to gasoline increases vapor pressure. Light blends have high evaporative emission issues. • Methanol can be aggressive to some of the engine parts, if no proper care is given, thus creating additional failures and, possibly, secondary air emission impacts.

[35] http://emsh-ngtech.com/methanol/methanol-pricing

Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• More difficult to handle than ethanol due to toxic and poisonous nature, hence its use in IC engines is of limited interest. It may be more interesting as a fuel in fuel cells (direct methanol fuel cells - DMFCs). • Use of methanol in existing vehicles may lead to slight departures from stoichiometry, in a similar way to LPG retrofits. • The solubility of methanol in gasoline is decreased in lower temperatures and solubilizers (higher alcohols) may need to be added to the fuel. • Methanol/gasoline blends result in higher vapor pressures that can lead to vapor lock problems, difficulties with hot starts, poor acceleration.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	Engine modifications are not necessary, but this depends on the percentage of methanol considered. If M100 is used, then certain modifications to the vehicle may be needed.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	• Special lubricants are required. • Methanol blends are likely to cause permeation emissions. Special treatment of the fuel tanks is necessary to reduce permeation losses. • Large canisters can be used for accumulating the evaporating emissions.
Durability/lifetime of emission control equipment	• Corrosion of the fuel system parts and compatibility problems when methanol blends or methanol fuel is used, shortening the engine's life. • Long-term durability of alcohol retrofit vehicle is questionable.
Impacts on safety (users, citizens, …)	Less flammable than gasoline. However, it burns with an invisible flame hard to detect for vehicle owners and operators.
References and Other Points	
Comments or remarks not addressed above	Equal power can be obtained by vehicles powered either with MtOH or with gasoline at stoichiometric air to fuel ratios. Power is increased in vehicles with richer mixtures.
Successful examples of implementation	- http://www.methanol.org/energy/transportation-fuel.aspx - http://www.afdc.energy.gov/fuels/emerging_methanol.html - http://www.eri.ucr.edu/ISAFXVCD/ISAFXVAF/MTFLBLF.pdf - http://www.methanol.org/Health-And-Safety/Safety-Resources/Health---Safety/Methanex-TISH-Guide.aspx
References for further details	- Nichols, R.J., The Methanol Story: A Sustainable Fuel for the Future. Journal of Scientific & Industrial Research, 62 (2003), 97-105. - Bechtold, R.L., Goodman, M.B. and Timbario, T.A., Use of Methanol as Transportation Fuel. The Methanol Institute, Arlington, VA (2007). - L. Bromberg, and W. K. Cheng, Methanol as an Alternative Transportation Fuel in the U.S.: Options for Sustainable and/or Energy-Secure Transportation, Massachusetts Institute of Technology (2010). - Cassady, P.E., The use of methanol as a motor vehicle fuel. Mathematical Sciences Northwest, Inc. Symposium on Alternate Fuel Resources. Proceedings, 1976, p. 257-272. - Faiz, A., Weaver, C.S. and Walsh, M.P., Air Pollution from Motor Vehicles: Standards and Technologies for Controlling Emissions, (1996). The World bank Washington, D.C. - Sperling, D., New Transportation Fuels: A Strategic Approach to Technological Change. University of California Press, 1990. - Cohn, D., Super Efficient Methanol Engines, Promsus Workshop, Gothenburg, Sweden, 2014. Available at: http://marinemethanol.com/publications/category/5-promsus-workshop

	- Clean Alternative Fuels: Methanol. United States Environmental Protections Agency. Transportation and Air Quality Transportation and Regional Programs Division, EPA420-F-00-040, (2002). - http://www.openfuelstandard.org/2011/05/what-is-methanol.html

3.7.3.4 Gasoline components

Table 3-28: Summary information for gasoline components

General Description	
Name of technique	**Gasoline components – Aromatic free (alkylate) gasoline**[36]
Pollutants addressed	Mainly: VOC, CO, Synergies: PAHs, benzene, toxicity of exhaust emissions
Engine/vehicle/vessel types considered	• Small gasoline engines for non-road applications (handheld and ground-supported engines) both 2-stroke and 4-stroke. • High power output non-automotive engines like snowmobiles.
Short description of technique	• 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). • Because of the rather simplistic fuel system of small engines, that allows increased fuel evaporation, use of aromatic free and benzene free gasoline will have a significant positive impact on VOC and CO, as well as on PAHs, benzene, and toxicity (including mutagenicity) of exhaust emissions. • Moreover, alkylate gasoline improves the startability and the long term operation of such engines.
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	Significant positive impact on VOC and CO.
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	Significant price difference with conventional gasoline may exist (e.g. more expensive ~0.3-0.4 €/l) but the overall additional cost is minor since typical use of small gasoline engine is less than 10 l/year/user.
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	No significant impact on fuel consumption.
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	Significant positive impact on PAHs, benzene, and toxicity (including mutagenicity) of exhaust emissions.
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• No harmonized fuel markets since no European wide fuel standard exists (this would increase availability and use of the fuel). • Sweden has a national standard and some countries have national regulations (Sweden, Finland, and Norway).
Ease of implementation (technology or	No difficulties in implementation (production exists).

[36] Main source of summary information for aromatic free gasoline: Neste Oil (http://www.nesteoil.com/).

expertise required, infrastructural needs, etc.)	
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	• Less maintenance of the engines is required. • Improvement in startability and long term operation.
Durability/lifetime of emission control equipment	Lifetime of the engine may increase.
Impacts on safety (users, citizens, …)	Less health risks when engines refueled from canisters (less volatile hydrocarbons, less fuel odor, no benzene vapors).
References and Other Points	
Comments or remarks not addressed above	As an example, VOC and CO of a lawn mower can be as high as of 20 modern cars per hour. CO of a chain saw can be as high as 20 modern cars and VOC as high as of 100 modern cars per hour.
Successful examples of implementation	Used commonly in Sweden and Finland, to some extent in Germany and Switzerland.
References for further details	Swedish standard SS 15 54 61 with some updates could be used as a baseline for a European wide small engine gasoline standard.

Diesel related fuels

3.7.3.5 Dimethyl Ether (DME)

Table 3-29: Summary information for dimethyl ether (DME)

General Description	
Name of technique	**Dimethyl Ether (DME)**
Pollutants addressed	PM, BC, NO_x
Engine/vehicle/vessel types considered	• Heavy duty road vehicles (trucks, buses), NRMM/rail. • General use is difficult, maybe more appropriate for dedicated fleets, where the fuel distribution is probably easier. • The experience in DME-fuelled vehicles is very limited.
Short description of technique	• DME is a natural gas derivative. It can be produced from natural gas, biomass or coal (through gasification and then the synthetic gas is catalyzed to produce DME). It can also be formed by dehydration of methanol. • It offers much higher volumetric energy content than natural gas (therefore, easier handling for refueling and storage on board the vehicle). • It has low boiling point, hence it vaporizes easily and improves combustion. • Low auto-ignition temperature, high cetane number (55-60), so highly appropriate for CI engines. • Easier engine start in cold weather conditions.
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	• PM: DME combustion results to soot levels that can meet Euro VI limits without the need of a DPF (due to molecular structure of DME). • NO_x benefits can be achieved compared to diesel engines (especially the oldest ones).
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	Comparable to conventional diesel (marginal cost differences may exist).
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	In general, higher fuel consumption is expected due to lower DME energy density per unit volume than diesel.
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	Higher formaldehyde (CH_2O) emission than diesel, especially in high speeds and medium-to-high loads of working conditions.
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• Fuel availability (distribution network is limited). • Its low viscosity is responsible for leakage problems from the fuel supply system and for poor lubricity. • Due to high vapor pressure, it tends to cavitate to the fuel injection system and prevent stable fuel injection operation.

Ease of implementation (technology or expertise required, infrastructural needs, etc.)	• Engine modifications may not be necessary when DME/diesel blends are used; this may not be true for neat DME in CI engines (in any case, retrofit is possible). • DME can be transported in pressurized liquid form (a pressurized fuel system is required to maintain DME in liquid state).
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	Not compatible with most elastomers used in diesel fuel system due to its corrosiveness, so replacement by compatible materials may be necessary.
Durability/lifetime of emission control equipment	Low lubricity can cause surface wear of moving parts within the fuel injection system.
Impacts on safety (users, citizens, …)	• Non-toxic, environmentally benign. Blue visible flame. • Wide flammability limits require the adoption of rigorous procedures for safer operation.
References and Other Points	
Comments or remarks not addressed above	• DME can substitute conventional diesel, LPG or be reformed into hydrogen for fuel cells (direct DME fuel cell - DDMEFC). • Engine combustion noise is lower than that of a diesel engine.
Successful examples of implementation	- http://www.aboutdme.org/
References for further details	- Greszler, A., DME from Natural Gas or Biomass: A Better Fuel Alternative, Volvo Group Truck Technology. SAE 2013 Government / Industry meeting (2013). Available at: http://www.sae.org/events/gim/presentations/2013/greszler_anthony.pdf - Kalyuzhnyi, S., Dimethylether as a motor fuel of the 21st century. Department of Chemical Enzymology, Moscow State University, Russia. Available at: http://www.cpi.umist.ac.uk/eminent/publicFiles/brno/MSU_Dimethyl_Ether.pdf - Patil, K. R. and Thipse, S. S., The Potential of DME-Diesel Blends as an Alternative Fuel for CI Engines, International Journal of Emerging Technology and Advanced Engineering, (2) 10 (2012), 35-41. Available at: http://www.ijetae.com/files/Volume2Issue10/IJETAE_1012_06.pdf - Erdener, H., Arinan, A. and Orman, S., Future Fossil Fuel Alternative; Di-methyl Ether (DME) A review, International Journal of Renewable Energy Research, (1) 4 (2011), 252-258. Available at: http://www.ijrer.org/index.php/ijrer/article/viewFile/78/pdf - Kowalewicz, A and Wojtyniak, M., New Alternative Fuels for IC Engines – A Review, Journal of KONES Internal Combustion Engines, (11) 1-2 (2004), 358-368. Available at: http://ilot.edu.pl/KONES/2004/01/42.pdf - Arcoumanis C., A technical Study on Fuels Technology related to the Auto-Oil II Programme. European Commission DG Energy, Final Report, Volume II: Alternative Fuels, (2000). - Semelsberger, T. A., Borup, R. L. and Greene, H. L., Dimethyl Ether (DME) as an Alternative Fuel, Journal of Power Sources, (156) 2 (2006), 497-511. - Yu-sheng, Z., Chun-lan, M., Hai-ying, S., and Shao-ren, Z., Study on Formaldehyde Emission in a DME-Fueled Direct-Injection Diesel Engine, SAE Technical Paper 2007-01-1909, 2007, doi:10.4271/2007-01-1909.

	- Hansen, K.R., Application of Dimethyl Ether in Compression Ignition Engines. PhD Thesis. Department of Mechanical Engineering, Nils Koppels Allé, Building 403, DK-2800 Kgs. Lyngby, Denmark, 2012. - Shukla, M.K., Bhaskar, T., Jain,A.K., Singal, S.K. and Garg, M.O., Bio-Ethers as Transportation Fuel: A Review. Automotive Fuels and Lubricants Application Division, Indian Institute of Petroleum Dehradum.

3.7.3.6 Biodiesel

Table 3-30: Summary information for biodiesel

General Description	
Name of technique	**Biodiesel**
Pollutants addressed	PM, VOC, CO
Engine/vehicle/vessel types considered	Diesel engines and vehicles: cars, light commercial vehicles, trucks, buses, non-road construction and agriculture machinery, trains.
Short description of technique	• Biodiesel can be produced from new and used vegetable oils and animal fats by reacting with methanol or ethanol to produce a lower-viscosity fuel that is similar in physical characteristics to diesel. • It can be used neat or blended with petroleum diesel for use in a diesel engine. It is commonly blended at low levels, i.e., 20% (B20) or less.
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	Low biodiesel blends (up to B20) can reduce PM (10-15%), VOC and CO (5-10%).
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	Comparable to conventional diesel (marginal cost differences may exist).
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	Increase in fuel consumption, proportionally to the blend considered.
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	Possible increase in NO_x (2-3%).
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• Current regulations in Europe limit blends to B7 and only gradually move towards higher blending ratios. • Higher blends are allowed in controlled captive fleets (e.g. buses) where maintenance intervals and practices, as well as engine materials, can be adjusted to the fuel properties. • Incompatibility with some older engines.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	• Blends of 20% biodiesel with 80% petroleum diesel (B20) can be used in unmodified diesel engines. • Biodiesel can be used in its pure form (B100), but may require certain engine modifications to avoid maintenance and performance problems. Pure blends of biodiesel may not be suitable for cold climates.
Maintenance and operation (additional maintenance requirements,	• More often maintenance necessary. • When used for the first time, biodiesel can release deposits accumulated on tank walls and pipes from previous diesel fuel, initially causing fuel filter clogs. Hence, fuel filter must change after the first tank of biodiesel.

monitoring requirements, …)	
Durability/lifetime of emission control equipment	Biodiesel can degrade rubber fuel system components, such as hoses and pump seals (especially with higher-percentage blends and older vehicles).
Impacts on safety (users, citizens, …)	Safe, non-toxic, biodegradable.
References and Other Points	
Comments or remarks not addressed above	Retrofit DOCs and DPFs can operate effectively on vehicles using a biodiesel blend fuel up to B20 provided that this biodiesel blend conforms to appropriate biodiesel specifications and that the biodiesel blend meets the fuel sulfur specification required by the retrofit technology supplier.
Successful examples of implementation	- The Route to Cleaner Buses: A guide to operating cleaner, low carbon buses. Energy Saving Trust, UK, 2003. - Clean Vehicles in Europe – An overview of vehicles, fuels and national strategies, Trendsetter Report No 2003: 2, October 2003. - IEA Advanced Motor Fuels, Annual Report 2003. - Clean Fuels for Road Public Transport, International Association of Public Transport (UITP), 2004. - Clean Buses – Experiences with Fuel and Technology Options, Clean Fleets project, February 2014. Available at: http://www.clean-fleets.eu/fileadmin/files/Clean_Buses_-_Experiences_with_Fuel_and_Technology_Options_2.1.pdf - http://www.vtt.fi/inf/pdf/technology/2012/T46.pdf
References for further details	- Charles C. et al., Biofuels – At What Cost? A review of costs and benefits of EU biofuel policies, International Institute for Sustainable Development, April 2013. - Ntziachristos L. and Dilara P., Sustainability Assessment of Road Transport Technologies. JRC Scientific and Policy Reports, EUR 25341 EN, Joint Research Centre – Institute for Energy and Transport, (2012) doi:10.2788/28167. - http://www.epa.gov/cleandiesel/technologies/fuels.htm - http://www.meca.org/technology/technology-details?id=28 - http://www.fueleconomy.gov/feg/biodiesel.shtml - http://www.dieselnet.com/tech/fuel_biodiesel.php - http://www1.iaphworldports.org/toolbox%201/cleantech.htm - http://www.theicct.org/sites/default/files/publications/ICCT_HDV_in-use_20130802.pdf - http://advancedbiofuelsusa.info/wp-content/uploads/2011/03/11-0307-Biodiesel-vs-Renewable_Final-_3_-JJY-formatting-FINAL.pdf

3.7.3.7 Renewable diesel

Table 3-31: Summary information for renewable diesel

General Description	
Name of technique	**Renewable diesel**
Pollutants addressed	NO_x, PM, BC, VOC, CO
Engine/vehicle/vessel types considered	Diesel engines and vehicles: cars, light commercial vehicles, trucks, buses, non-road construction and agriculture machinery, trains.
Short description of technique	• Renewable diesel is produced: a) by hydrotreating (and not esterification) of vegetable oil (HVO), b) thermal conversion process (TCP), c) biomass to liquid (BTL). • Neat renewable diesel has several advantages over fuels produced with the transesterification process, such as reduced waste and by-products, higher energy density and better cold flow properties. • It has superior oxidation stability compared to biodiesel and it can also be used as an additive to increase cetane number.
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	• Renewable diesel can reduce NO_x (5-10%), PM and BC (15-25%), VOC (20-40%), and CO (15-30%). • Benefits are lower when used as an additive.
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	Comparable to conventional diesel (marginal cost differences may exist).
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	Possible increase in fuel consumption.
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	Free of aromatics, low aldehyde and mutagenic emissions, decrease of engine smoke (neat renewable diesel).
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	Fuel availability.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	Adjustments in the electronic control of the engine may be required, and additives to address the lubricity issues.

Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	Fewer repairs and less maintenance required.
Durability/lifetime of emission control equipment	• Ash free fuel with zero sulfur content leads to longer lifetimes. • No deposit formation in engines, fuel systems or injectors.
Impacts on safety (users, citizens, …)	No safety impacts.
References and Other Points	
Comments or remarks not addressed above	Since existing farm based feedstocks compete with food production, non-food oils such as algae oil need to be made available.
Successful examples of implementation	- Clean Fuels for Road Public Transport, International Association of Public Transport (UITP), 2004. - Clean Buses – Experiences with Fuel and Technology Options, Clean Fleets project, February 2014. Available at: http://www.clean-fleets.eu/fileadmin/files/Clean_Buses_-_Experiences_with_Fuel_and_Technology_Options_2.1.pdf - http://www.vtt.fi/inf/pdf/technology/2012/T46.pdf
References for further details	- Aatola, H., Larmi, M., Sarjovaara, T., and Mikkonen, S., Hydrotreated Vegetable Oil (HVO) as a Renewable Diesel Fuel: Trade-off between NO_x, Particulate Emission, and Fuel Consumption of a Heavy Duty Engine, SAE Int. J. Engines 1(1) (2009): 1251-1262, doi:10.4271/2008-01-2500. - Mikkonen, S., Hartikka, T., Kuronen, M. and Saikkonen, P., HVO, Hydrotreated Vegetable Oil – A Premium Renewable Biofuel for Diesel Engines, Neste Oil Corporation, (June 2012). - No, S.Y., Application of Hydrotreated Vegetable Oil from Triglyceride Based Biomass to CI Engines – A Review, Fuel 115 (2014) 88-96. - Lindfors, L.P., High Quality Transportation Fuels from Renewable Feedstock, XX1st World Energy Congress, Montreal, Canada (2010). Neste Oil Corporation. - Gill, S., Tsolakis, A., Dearn, K. and Rodrígues-Fernández, J., Combustion Characteristics and Emissions of Fischer-Tropsch Diesel Fuels in IC Engines, Progress in Energy and Combustion Science, 37 (4) 2011: p. 503-523. - Crepeau, G., Gaillard, P., van der Merve, D. and Schaberg, P. Engine Impacts and Opportunities of Various Fuels Including GTL and FAME: Toward Specific Engine Calibration. - Pflaum, H., Hofmann, P., Geringer, B., and Weissel, W., Potential of Hydrogenated Vegetable Oil (HVO) in a Modern Diesel Engine, SAE Technical Paper 2010-32-0081, 2010, doi:10.4271/2010-32-0081. - Mizushima, N., Sato, S., Kawano, D., Saito, A. et al., A Study on NO_x Emission Characteristics When Using Biomass-derived Diesel Alternative Fuels, SAE Int. J. Fuels Lubr. 5(2):892-899, 2012, doi:10.4271/2012-01-1316 - http://advancedbiofuelsusa.info/wp-content/uploads/2011/03/11-0307-Biodiesel-vs-Renewable_Final-_3_-JJY-formatting-FINAL.pdf - http://www.dieselforum.org/files/dmfile/RenewableFuelsFactSheet_01.30.13.pdf

3.7.3.8 Emulsified diesel

Table 3-32: Summary information for emulsified diesel

General Description	
Name of technique	**Emulsified diesel**
Pollutants addressed	NO_x, PM
Engine/vehicle/vessel types considered	Diesel engines and vehicles: cars, light commercial vehicles, trucks, buses, non-road construction and agriculture machinery, trains.
Short description of technique	• Emulsified diesel is a blended mixture of diesel fuel, water, and other additives (with milky appearance) that lowers combustion temperatures and reduces emissions of PM, as well as NO_x. • The water is suspended in droplets within the fuel, creating a cooling effect in the combustion chamber that decreases NO_x emissions. A fuel-water emulsion creates a leaner fuel environment in the engine, lowering PM emissions. The additives also prevent water from contacting the engine.
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	Emulsified diesel can reduce NO_x (10-20%) and PM (50-60%).
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	_ For light duty vehicles: • €120–€160 per year (e.g. assuming 2,000 l of fuel per year, 20% increase in fuel consumption because of emulsified diesel use, and 0.06 €/l additional fuel cost, the cost of this option is 144 € per year). _ For heavy duty and non-road vehicles: • €1,200–€1,600 per year (e.g. assuming 20,000 l of fuel per year, 20% increase in fuel consumption because of emulsified diesel use, and 0.06 €/l additional fuel cost, the cost of this option is 1,440 € per year).
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	The addition of water reduces the energy content of the fuel, so there is some reduction in power and fuel economy of the vehicle (increase of fuel consumption).
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	No significant impact on non-regulated pollutants.
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• Decrease in power and fuel economy due to the addition of water. • Fuel availability.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	• It can be used in any new or existing engine. • No specific tanking installations are needed. Existing tanks can be used after careful washing and rinsing.

Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	Possible increase in maintenance requirements.
Durability/lifetime of emission control equipment	Over time the water can settle out of the emulsified fuel and may cause performance problems.
Impacts on safety (users, citizens, …)	No safety impacts.
References and Other Points	
Comments or remarks not addressed above	The practice of emulsifying fluids in diesel is not new, however the science of using additive chemistry and blending techniques to specifically address the air quality characteristics of diesel exhaust emissions is new and evolving, with a number of US based and international companies taking a lead role in its advancement.
Successful examples of implementation	An emulsified diesel + oxidation catalyst system has been verified as a retrofit technology option under both the EPA and ARB verification programs.
References for further details	- The Route to Cleaner Buses: A guide to operating cleaner, low carbon buses. Energy Saving Trust, UK, 2003. - Clean Fuels for Road Public Transport, International Association of Public Transport (UITP), 2004. - http://www.epa.gov/cleandiesel/technologies/fuels.htm - http://www.meca.org/diesel-retrofit/what-is-retrofit - http://www1.iaphworldports.org/toolbox%201/cleantech.htm

3.7.3.9 Low-sulfur fuel (for ships)

Table 3-33: Summary information for low-sulfur fuel (for ships)

General Description	
Name of technique	**Low-sulfur fuel (for ships)**
Pollutants addressed	SO_x, PM
Engine/vehicle/vessel types considered	Diesel vessels.
Short description of technique	• The most straightforward method of reducing SO_x emissions is to simply reduce fuel sulfur content. • IMO Marpol Annex VI obliges a reduction of the fuel sulfur limit from the current 3.5% to 0.5% by 2020. • Distillates like MGO can be used, known as light fuel oil. Maximum sulfur content ~0.1%. Does not contain any residuals and is free from organic and inorganic acids.
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	• SOx (75-90%), PM (20-60%). • SO_x can be reduced directly with distillates because of reduced sulfur content (0.1%). • Reduction of PM emissions can be achieved since some of the particulates are sulfur compounds.
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	• Negligible initial capital cost. • High operating cost especially in SECAs (because of higher fuel price).
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	Low sulfur, low viscosity fuels have low density compared to heavy fuels, so less energy per volume of fuel. Hence more fuel is needed to be supplied in order to maintain equivalent power.
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	No significant impact on non-regulated pollutants.
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• Higher fuel price. • Availability of fuel.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	• Engine should be adjusted for the combustion of LSF with the necessary modifications to the fuel oil system and boiler. • Special training to the crew is necessary for the operation of the boiler with LSF. • Any modifications on existing vessels should be certified.

Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	• Increased oil fuel supply inspections for the detection and repair of fuel leaks should be performed due to low viscosity that favors leaks and evaporation. • Operational challenges imposed by fuel switch. • Low viscosity, reduced lubrication ability.
Durability/lifetime of emission control equipment	The low viscosity reduces the film thickness of the fuel valves leading to excessive wear and possible sticking causing failure of the fuel pump.
Impacts on safety (users, citizens, …)	Wrong handling of operating media may cause safety issues.
References and Other Points	
Comments or remarks not addressed above	Best alternative (with low technology entry barrier) if retrofitting a SO_x scrubber or conversion to LNG are technically (or economically) not attractive options.
Successful examples of implementation	Currently low-sulfur fuel is an option that is used for complying with the growing restrictions on SO_x emissions.
References for further details	- http://cleantech.cnss.no/air-pollutant-tech/sox/low-sulphur-fuel/ - Limits on Sulfur Content In Marine Fuels. Operational Hazards Related to Maintenance of Diesel Engines and Fired Auxiliary Boilers. PRS Machinery Department (2009). Available at: http://www.prs.pl/__files/parent175/informacja_eng.pdf - Guidelines for Operation on Distillate Fuels. The Swedish Club (2009). Available at: http://www.swedishclub.com/upload/Loss%20Prevention726/Member-Alert-Distillate-Fuels.pdf - Fuel Switching Advisory Notice, ABS. Available at: http://www.eagle.org/eagleExternalPortalWEB/ShowProperty/BEA%20Repository/References/ABS%20Advisories/FuelSwitchingAdvisory

Gasoline-Diesel related fuels

3.7.3.10 Compressed Natural Gas (CNG)

Table 3-34: Summary information for compressed natural gas (CNG)

General Description	
Name of technique	**Compressed Natural Gas (CNG)**
Pollutants addressed	PM, BC, NO_x, CO, NMVOC
Engine/vehicle/vessel types considered	• All gasoline/diesel road vehicles (except mopeds/motorcycles): passenger cars, light commercial vehicles, buses, trucks. • Diesel NRMM/rail.
Short description of technique	• Compressed natural gas (CNG) consists mainly of methane. It can be used in OEM applications or as a retrofit. • In SI engines, the conversions are bi-fuel and the driver switches between NG and gasoline and vice versa during engine operation. • In CI engines, the conversions are dual-fuel where the engine runs with a mixture of NG and diesel. This is because CNG has long ignition delay times and cannot be used directly as a fuel in a CI engine; hence, ignition aid is required and dual fuel is a practical way to use NG in such diesel engines.
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	Environmental benefit of CNG depends on comparison to a gasoline/diesel vehicle, OEM/retrofit, light/heavy duty, etc. Some generic results are: • Properly adjusted stoichiometric OEM NG vehicles little differ in terms of their regulated emissions compared to new gasoline ones. • Retrofitting may lead to uncontrollably high NO_x emissions in some cases. • Compared to gasoline, CNG vehicles do not suffer from evaporation emissions, due to the high-pressure sealed tanks used. • Significant environmental benefit (mainly for PM) can be achieved comparing CNG with diesel vehicles (especially the oldest and heaviest ones). Indicative ranges of emission reduction in this case: _ PM (85-95%), NO_x (20-60%), CO (70-95%), NMVOC (75-85%).
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	• Typical conversion cost (one-off): _ 2,000-3,000€ (for light duty vehicles), _ 12,000-15,000€ (for heavy duty vehicles). • Fuel cost savings: 100-1,000€ per year, depending on mileage driven (because of lower CNG price compared to gasoline/diesel).
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	Volumetric energy content is low (~5 times less than gasoline).
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	• Increase of CH_4 emissions. • Not so effective in PN as DPF. • 20-25% (10-20%) less CO_2 compared to a similar gasoline (diesel) vehicle. • No benzene and 1,3 butadiene toxins emitted as by diesel engines.
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel	• Strong impact on climate change upon CH_4 release (catalysts with high loading of catalytic components required to maximize CH_4 oxidation). • Fuel availability. • More difficult to store: gas tank limits the vehicle storage space (especially

specifications, technological barriers, behavioral changes, etc.)	for passenger cars) and adds extra weight to the vehicle. • Low volumetric energy content leads to limitations on carrying sufficient quantity of fuel on board the vehicle; as a result, the driving range may decrease (less overall energy can be stored in tanks of same size). • Limited experience in retrofit long term performance. • Bi-fuel vehicles may suffer from power loss and drivability issues, and may have lower energy efficiency and acceleration performance.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	• May require significant changes to fueling infrastructure and maintenance facilities. • More complicated bi-fuel conversion (gas carburetor/mixer, regulator, shut-off valves, control system, fuel storage tanks needed).
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	• Requires less maintenance than conventional fuels; no filters or additives required. • Refueling time is longer than gasoline/diesel. • Water content should be limited, since water vapor is absorbed and it might freeze under certain conditions.
Durability/lifetime of emission control equipment	Reduced engine wear and longer lifetime ('cleaner' fuel).
Impacts on safety (users, citizens, …)	• Natural gas vehicles are as safe as conventional vehicles. • Non-toxic and will not contaminate if spilled.
References and Other Points	
Comments or remarks not addressed above	• Energy independence for countries with high natural gas reserves. • Natural gas engines significantly reduce noise emissions and vibrations.
Successful examples of implementation	- http://www.vacleancities.org/ - http://www.iangv.org/ - http://www.ngvaeurope.eu/ - http://www.vtt.fi/inf/pdf/technology/2012/T46.pdf - The Route to Cleaner Buses: A guide to operating cleaner, low carbon buses. Energy Saving Trust, UK, 2003. - 2012: ~768,000 NG passenger cars, 8,700 NG buses, 87,500 NG LCVs (EU).
References for further details	- Verbeek R.et al., Natural gas in transport – An assessment of different routes, TNO-ECN-CE Delft Report, May 2013. Available at: http://www.fuelswitch.nl/files/files_news/natural_gas_in_transport_tno_ce_delft_ecn_4818.pdf - Rosli S., Bakar A., A technical Review of Compressed Natural Gas as an Alternative Fuel for Internal Combustion Engines. American Journal of Engineering and Applied Sciences, (1) 4 (2008), 302-311. - Rosli Abu Bakar et al., Application of Natural Gas for Internal Combustion Engines, Dr. Hamid Al-Megren (2012) (Ed.). Available at: http://www.intechopen.com/books/advances-in-natural-gas-technology/application-of-natural-gas-for-internal-combustion-engines - Arcoumanis C., A technical Study on Fuels Technology related to the Auto-Oil II Programme. European Commission DG Energy, Final Report, Volume II: Alternative Fuels, (2000). - Bhandari K., Bansal a., Shukla A. and Khare M., Performance and emissions of natural gas fueled internal combustion engine: A review. Journal of Scientific & Industrial Research, 64 (2005), 333-338. - Haeng Muk Cho and Bang-Quan He, Combustion and Emission

	Characteristics of a Natural Gas Engine under Different Operating Conditions. Environmental Engineering Research, (14) 2 (2009), 95-101.

3.7.3.11 Liquefied Natural Gas (LNG)

Table 3-35: Summary information for liquefied natural gas (LNG)

General Description	
Name of technique	**Liquefied Natural Gas (LNG)**
Pollutants addressed	PM, BC, NO_x, SO_x, NMVOC
Engine/vehicle/vessel types considered	• Diesel vessels. • Diesel road and non-road vehicles (trucks, buses, NRMM, rail).
Short description of technique	• LNG differs from CNG only to the way that the fuels are stored on board the vehicle/vessel. The combustion of the two forms of natural gas is identical; this results to identical emission profiles. • LNG engines can be of a mono fuel type, or of a dual fuel type. • LNG is pure methane and it has higher volumetric energy content than CNG; hence, it may be more economical e.g. for ship transport. • By requiring smaller volume for storage, it may also be a good option for medium-long distance road transportation (in order to achieve the requested mileage on a limited chassis space).
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	• PM (75-95%), NO_x (50-85%), SO_x (90-100%), NMVOC (75-85%). • Negligible amounts of evaporative emissions.
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	Making a detailed cost analysis for LNG conversion of a ship is not a straightforward task and depends on many factors, such as the ship size and design, engine type (dual-fuel or single LNG engine), size of fuel tank, and even geographic location and ECA (Emission Control Area) exposure. Some indicative cost ranges are given below, while more detailed information can be found e.g. in - http://www.epa.gov/region5/water/npdestek/badger/pdfs/application/badger-appz.pdf - http://ec.europa.eu/transport/modes/inland/studies/doc/2013-06-03-contribution-to-impact-assessment-of-measures-for-reducing-emissions-of-inland-navigation.pdf - http://www.mandieselturbo.com/files/news/filesof17541/5510-00122-0ppr_low.pdf In general, the cost for a newly built LNG fuelled vessel may be comparable to the cost of converting a similar existing one; hence, LNG may be more attractive for new ships. • €500k - €5.5m initial capital investment (conversion) cost per ship (for example, the €5.5m initial capital will cost €702k annually for principle and interest payments at 5% interest and a 10 year amortization). • Indicative LNG fuel price: 380-420€/t (15-20% lower than HFO and ~40% lower than MGO).
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	In vessels, it has been reported that dual-fuel engines consume marginally more energy than marine diesel oil engines and a few less than residual fuel oil engines.
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	• Increase of CH_4 emissions. • 20% reduction of CO_2 due to lower carbon content.

Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• Strong impact on climate change upon CH_4 release (catalysts with high loading of catalytic components may be required to maximize methane oxidation). For example, in Verbeek R.et al. (2013) it is mentioned that methane emissions from natural gas use in ships may result to 'loss of GHG gains' versus diesel application from a given value (6 g/kWh) onwards. • Fuel availability. • More difficult to store: gas tank limits the vehicle/vessel storage space and adds extra weight. Substantial modifications are needed and sufficient storage capacity for the fuel is required. • The high price of natural gas vehicles (due to insulation device for LNG vehicles) hinders its deployment beyond public transportation and carrier services.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	• Refueling infrastructure must be expanded; significant amount of investment may be needed for fueling stations and infrastructure. • Construction of LNG facilities gives rise to numerous social, environmental and economic effects. LNG tanks and components should comply with international regulations and standards regarding the design integrity and the operational performance to avoid explosions and failures.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	• LNG needs heavy and highly insulated fuel tanks to retain the fuel at the desired temperature to maintain its liquid form (a temperature of -162^{o}C is required). • Limited periodic tank inspections and reduced engine maintenance costs (in comparison to oil engines, due to a more clean and efficient system and a longer lifetime of the machinery).
Durability/lifetime of emission control equipment	Due to its cleaner burning characteristics, LNG results in longer engine lifetime.
Impacts on safety (users, citizens, …)	• Only trained personnel should make any modifications and services. • Flammable, explosive, non-corrosive, non-toxic, odorless. • Special preparation for safe handling LNG cargo.
References and Other Points	
Comments or remarks not addressed above	• Questionable if LNG is finally an alternative fuel for sustainable energy future, due to energy needed to liquefy, transport and re-gasify LNG. • Acceptance of LNG as a fuel depends on policy concerns and availability of alternatives in different regions. • No big differences between LNG and diesel vehicles in operation and performance.
Successful examples of implementation	- Liquefied Natural Gas, Case Study. Green Truck Partnership. Available at: http://www.rms.nsw.gov.au/documents/about/environment/air/case-study-lng.pdf - Liquefied Natural Gas (LNG), Clean North Sea Shipping. Available at: http://cleantech.cnss.no/air-pollutant-tech/nox/liquefied-natural-gas-lng/
References for further details	- Verbeek R.et al., Natural gas in transport – An assessment of different routes, TNO-ECN-CE Delft Report, May 2013. Available at: http://www.fuelswitch.nl/files/files_news/natural_gas_in_transport_tno_ce_delft_ecn_4818.pdf - Consistent methodology for estimating greenhouse gas emissions from Liquefied Natural Gas (LNG) operations. The LEVON Group, LLC, Pilot Draft, (2013). Available at: http://www.api.org/~/media/Files/EHS/climate-change/API-LNG-GHG-Emissions-Guidelines-Pilot-Draft-21JUL2013.pdf - Kavalov B., Petric A., and Georgakaki A., Liquefied Natural Gas for Europe - Some Important Issues for Consideration. JRC Reference Reports, (2009). - Kofod, M. and Stephenson, T., Well-to Wheel Greenhouse Gas Emissions of

	LNG Used as a Fuel for Long Haul Trucks in a European Scenario. SAE Technical Paper 2013-24-0110, 2013, doi:10.4271/2013-24-0110. - Cost and benefits of LNG as ship fuel for container vessels. Key results from a GL and MAN joint study, (2011). Germanischer Lloyd. - Choi DooHo, The effect of shale gas revolution on oil industry. International Electrical Engineering Journal (2013). - Susan L. Sakmar, Esq, The Globalization and Environmental Sustainability of LNG: Is LNG a Fuel for the 21st Century? World Energy Congress, Montreal, Canada (2010). - Lowell D., Bradley ML., Wang H. and Lutsey N., Assessment of the Fuel Cycle Impact of Liquefied Natural Gas as Used in International Shipping. White Paper, International Council on Clean Transportation (2013). - LNG: Benefits and Risks of Liquefied Natural Gas. Available at: http://vehicles.ltgovernors.com/lng-benefits-and-risks-of-liquified-natural-gas.html - Faiz, A., Weaver, C.S. and Walsh, M.P., Air Pollution from Motor Vehicles: Standards and Technologies for Controlling Emissions, (1996). The World bank Washington, D.C. - Chiotopoulos, A. and Ellefsen, A., A Crazy Idea? Retroffiting cruise ships to LNG by elongation. DNV-GL. Available at: http://www.dnv.com/binaries/LNG_RetrofitCruise_2014-03-L03_tcm4-596302.pdf

Alternative powertrains

3.7.3.12 Hybridization

Table 3-36: Summary information for hybridization

General Description	
Name of technique	**Hybridization** (replacement of an old vehicle with a new hybrid one)
Pollutants addressed	Practically all (or most of) pollutants
Engine/vehicle/vessel types considered	Practically all (or most of) vehicles and engines (road and non-road).
Short description of technique	• In hybrid vehicles (off-vehicle or on-vehicle charging) power is provided by two alternative powertrain systems, a reciprocating internal combustion engine combined with an electric motor. The two powertrain systems may be arranged in different configurations, i.e. "power-split" or series hybrid. • Plug-in hybrids can be charged directly from an electric grid and emit no exhaust pollutants when in an electric only mode. • Hybrids are expected to emit lower than their conventional counterparts and show better cold-start behavior when compared to gasoline vehicles.
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	20-50% emission reduction can be achieved in practically all pollutants (compared to a similar non-hybrid vehicle/engine).
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	• LDVs: €5,000-€12,000 marginal cost* (one-off) minus €500-€1,500 energy and maintenance cost benefits per year. • HDVs and NRMM: €50,000-€100,000 marginal cost* (one-off) minus €5,000-€10,000 energy and maintenance cost benefits per year. * Additional cost required to buy a new hybrid vehicle compared to buying a conventional diesel one in replacement of an older vehicle.
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	High fuel consumption benefits.
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	• Similar decrease in practically all (or most of) pollutants. • Low PM resuspension, especially taking off from bus stops.
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• More suitable for buses in urban applications. Experience in diesel hybrid LDVs is limited. Trucks and NRMM not at mass production yet. • High initial capital cost, possible decrease in driving range, and recharging.
Ease of implementation (technology or expertise required,	Plug-in hybrids basically involve additional batteries and modification of the control system to allow higher speed operation under only electrical power before calling on the combustion power system.

infrastructural needs, etc.)	
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	Less maintenance required than conventional counterparts.
Durability/lifetime of emission control equipment	Typically, plug-in hybrids can operate up to ~170km under purely electric power and can be recharged by plugging into a domestic power source.
Impacts on safety (users, citizens, …)	No safety impacts.
References and Other Points	
Comments or remarks not addressed above	Low noise.
Successful examples of implementation	- The Route to Cleaner Buses: A guide to operating cleaner, low carbon buses. Energy Saving Trust, UK, 2003. - Clean Vehicles in Europe – An overview of vehicles, fuels and national strategies, Trendsetter Report No 2003: 2, October 2003. - IEA Advanced Motor Fuels, Annual Report 2003. - Clean Fuels for Road Public Transport, International Association of Public Transport (UITP), 2004. - Clean Buses – Experiences with Fuel and Technology Options, Clean Fleets project, February 2014. Available at: http://www.clean-fleets.eu/fileadmin/files/Clean_Buses_-_Experiences_with_Fuel_and_Technology_Options_2.1.pdf - http://www.vtt.fi/inf/pdf/technology/2012/T46.pdf
References for further details	- Ntziachristos L. and Dilara P., Sustainability Assessment of Road Transport Technologies. JRC Scientific and Policy Reports, EUR 25341 EN, Joint Research Centre – Institute for Energy and Transport, (2012) doi:10.2788/28167. - Carslaw, D.C., Rhys-Tyler, G., 2013. New insights from comprehensive on-road measurements of NO_x, NO_2 and NH_3 from vehicle emission remote sensing in London, UK. Atmospheric Environment 81, 339-347. - Robinson, M.K., Holmen, B.A., 2011. Onboard, real-world second-by-second particle number emissions from 2010 hybrid and comparable conventional Vehicles. Transportation Research Record, 63-71. - Wei, Q., Porter, S., 2011. Evaluation of solid particle emissions from hybrid and conventional gasoline vehicles. SAE International Journal of Engines 4, 619-638. - http://www.meca.org/technology/technology-details?id=21&name=Alternate%20Fuel%20and%20Advanced%20Technology%20Vehicles - http://www.nextgreencar.com/hybrid-cars/car-costs.php

3.7.3.13 Electrification

Table 3-37: Summary information for electrification

General Description	
Name of technique	**Electrification** (replacement of an old vehicle with a new electric one)
Pollutants addressed	Practically all pollutants
Engine/vehicle/vessel types considered	Mainly passenger cars and buses in urban applications.
Short description of technique	• Battery electric (BEV) and fuel cell electric (FCEV) 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. • BEVs: In these vehicles, energy is stored in batteries on board the vehicle. • FCEVs: Energy is stored in liquid form, e.g. in the form of hydrogen. The energy carrier is converted to electricity in a fuel cell, also on board the vehicle. The electricity produced is then used to power the wheels in a more or less identical fashion to the one implemented in BEVs. The main advantage of a fuel cell in comparison to a battery is that it is not so much confined by capacity limitations, e.g. the same range of a battery electric vehicle can be achieved with a fuel cell electric one with ~1/5 of total weight for energy storage. The second advantage is that it can refill within a few minutes, i.e. in approximately the same time it takes to refill a conventional vehicle. • FCEVs may also operate on alternative to hydrogen fuels in two different pathways. One option is to use methanol directly in a specially designed fuel cell (direct methanol fuel cell), which operates similarly to the hydrogen one but with a lower efficiency overall. The second option is to use almost any conventional fossil hydrocarbon fuel on a reformer where fuel reacts with steam over a catalyst to separate hydrogen from carbon atoms. Hydrogen is then used in a conventional fuel cell. Demonstration vehicles of both these concepts have appeared.
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	No tailpipe emissions.
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	• Initial price of a BEV is almost double the price of a conventional powertrain vehicle. • Significant savings from lower operational cost.
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	Hydrogen or other fuel (e.g. methanol) needed for fuel cells.
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	No tailpipe emissions.

Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• Technology used in niches, not many commercial applications exist. • BEVs: Batteries have been so far the limiting factor in the growth of the BEV market due to their inferior energy density compared to liquid fuel, high cost, and question-marks on their long-term performance. Decrease in driving range (typical autonomy range of ~100-200km), excess weight of ~200kg, recharging required. • FCEVs: The limiting factor in FCEV technology is the non-availability of hydrogen, both with regard to its production and refueling infrastructure. Hydrogen is not a primary energy source but has to be produced utilizing one of the existing power sources. It then has to be distributed locally, and then stored on board the vehicle.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	• Specifically designed powertrain system is required. • Battery technology still under development. • Refueling infrastructure for hydrogen.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	Easy to operate, less maintenance required.
Durability/lifetime of emission control equipment	Battery or fuel cell durability (compared to the lifetime of the vehicle) may be a limiting factor.
Impacts on safety (users, citizens, …)	There are safety concerns for hydrogen as a fuel in FCEVs.
References and Other Points	
Comments or remarks not addressed above	• BEVs: A significant real world penetration of electric vehicles will only take place when the technical and cost competitiveness of batteries improves. Technological maturity and material limitations delay this. New breakthroughs in battery technology will be required. • In designing an integrated air quality policy involving electric vehicles, it is necessary to consider energy and fuel production associated emissions (either on-board the vehicle or upstream ones) and not just make the usual simplification that electric vehicles are zero emitters.
Successful examples of implementation	• Electric cars and prototype fuel cell buses as demonstrators. • Small fuel cell bus fleets already operate in different parts of the world.
References for further details	- Boulanger, A., Chu, A., Maxx, S. and Waltz, D., Vehicle Electrification: Status and Issues, Proceedings of the IEEE,99 (6) 2011: 1116-1138. - Ntziachristos L. and Dilara P., Sustainability Assessment of Road Transport Technologies, JRC Scientific and Policy Reports, EUR 25341 EN, Joint Research Centre- Institute for Energy and Transport, (2012) doi: 10.2788/28167. - Faiz, A., Weaver, C.S. and Walsh, M.P., Air Pollution from Motor Vehicles: Standards and Technologies for Controlling Emissions, (1996). The World bank Washington, D.C. - Eudy L., Chandler K., and Gikakis C. (2007), "Fuel Cell Buses in U.S. Transit Fleets: Summary of Experiences and Current Status", NREL/TP-560-41967, National Renewable Energy Laboratory. Available at: http://www.nrel.gov/hydrogen/pdfs/41967.pdf

3.7.3.14 Hydrogen

Table 3-38: Summary information for hydrogen

General Description	
Name of technique	**Hydrogen**
Pollutants addressed	Practically all (or most of) pollutants
Engine/vehicle/vessel types considered	Fuel cell electric vehicles (FCEVs), mainly passenger cars and buses in urban applications.
Short description of technique	• Hydrogen is an energy carrier. It stores and delivers energy. • It can be produced using diverse, domestic resources like fossil fuels, coals (with carbon sequestration), natural gas, biomass, or using nuclear energy and renewable sources (wind, solar, geothermal power to split H_2O). • It can be used as a fuel in fuel cell electric vehicles (FCEVs) or combusted in an IC engine.
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	• Hydrogen as a fuel in IC engines results to similar performance characteristics to those of gasoline. • Free of CO. • Any traces of HC emissions are due to lube oil consumption. • NO_x emissions can be significant due to the high combustion temperature of H_2; hence, specifically tuned combustion and coupled NO_x aftertreatment is required.
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	Indicative cost of a hydrogen car (OEM): €30k-€60k.
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	Low volumetric energy density makes necessary to store enough fuel onboard to have a comparable driving range to gasoline vehicles.
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	Near zero net GHG with hydrogen production through gasification.
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• Still used in niches, prototype applications. • Due to low volumetric energy density of hydrogen compared to other fuels, transportation, storage and delivery is expensive. • Due to high cost of production, lack of storage reserves, and the large scale production that is required for hydrogen to be used as a motor fuel, it is unlikely that hydrogen will be a cost effective fuel in the near future.
Ease of implementation (technology or expertise required, infrastructural needs,	Large scale production and refueling infrastructure is missing, significant investment needed.

etc.)	
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	Easy to operate, less maintenance required.
Durability/lifetime of emission control equipment	Fuel cell durability must increase in order to compete with other (e.g. gasoline) vehicles.
Impacts on safety (users, citizens, …)	There are safety concerns for hydrogen as a fuel in FCEVs.
References and Other Points	
Comments or remarks not addressed above	Hydrogen could be considered as an alternative aviation fuel. Issues for consideration: thorough study of the materials of the fuel system, insulation system, check hydrogen leaks, study of load structure and aerodynamics due to large volumes needed for hydrogen storage.
Successful examples of implementation	• Prototype hydrogen cars. • Hydrogen fueled taxis in London and buses in different parts of the world.
References for further details	- http://www.greenfuelonline.com/hydrogen - http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/fct_h2_production.pdf - http://www.afdc.energy.gov/fuels/hydrogen.html - http://heshydrogen.com/hydrogen-fuel-cost-vs-gasoline/ - http://www.fueleconomy.gov/feg/fcv_challenges.shtml - http://www.energy.ca.gov/2007publications/CEC-600-2007-004/CEC-600-2007-004-F.PDF - Ntziachristos L. and Dilara P., Sustainability Assessment of Road Transport Technologies, JRC Scientific and Policy Reports, EUR 25341 EN, Joint Research Centre- Institute for Energy and Transport, (2012) doi: 10.2788/28167. - Faiz, A., Weaver, C.S. and Walsh, M.P., Air Pollution from Motor Vehicles: Standards and Technologies for Controlling Emissions, (1996). The World bank Washington, D.C. - Contreras, A., Yigit, S., Ozay, K. and Veziroglou, T.N., Hydrogen as Aviation Fuel: A Comparison with Hydrocarbon Fuels, International Journal of Hydrogen Energy, 22 (10/11) 1997, 1053-1060.

3.8 Non-technical measures

3.8.1.1 Environmental zones (EZs)

Table 3-39: Summary information for environmental zones (EZs)

General Description	
Name of technique	**Environmental Zones (EZs) or Low Emission Zones (LEZs)**
Pollutants addressed	Practically all pollutants
Engine/vehicle/vessel types considered	• Road vehicles in urban areas • A similar concept for ships is ECA (Emission Control Area) or SECA (Sulfur Emission Control Area).
Short description of technique	• 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 the following: _ Access restrictions to vehicles that do not comply with set emission standards (e.g. Euro standards). _ Access restrictions based on the vehicle registration plate to days, pick hours or areas (not very costly to implement and usually easier to enforce). _ Non-compliant vehicles entering the zone are charged with penalty fines.
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	Real environmental impact of implementing a LEZ is not always easy to quantify and cannot be generalized, since it depends on the specific access restrictions applied. Some indicative ranges from specific examples of implementation (e.g. in Berlin, London, Stockholm, Rome) are given below: • PM (5-35%), NO_x (5-20%).
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	• Difficult to quantify initial set up and operation costs. Indicative ranges: €10m - €60m initial cost to set up and €1m - €10m a year to run. • Indicative penalty fine for non-compliant vehicles: €50-€250 per day.
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	Impact on fuel consumption (and CO_2 emissions) depends on the impact of the environmental zone on the traffic volume. Not easy to quantify.
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	Usually positive impact on non-regulated pollutants by accelerating natural fleet turnover, forcing owners of polluting vehicles to retrofit with upgraded aftertreatment equipment, or use hybrid vehicles, etc.
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• Police enforcement maybe necessary. • LEZs may face strong political and societal opposition (they are overly burdensome to economically disadvantaged operators of older vehicles). This opposition may be overcome by the introduction of retrofit or replacement subsidies for noncompliant vehicles. • For greatest health benefit, zones should cover a large geographical area (e.g. whole city) and affect the whole fleet.

Ease of implementation (technology or expertise required, infrastructural needs, etc.)	• A lot of preparatory work is necessary before implementing an environmental zone (e.g. distinguish vehicles into classes according to their Euro standard, aftertreatment equipment, etc). • Fixed or mobile cameras may be necessary to read vehicle number plate while driving within the LEZ and check it against the database of registered vehicles (in that way it is indicated automatically whether the vehicle meets the LEZ emissions standards).
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	Possible maintenance requirements e.g. if cameras are used.
Durability/lifetime of emission control equipment	The impact of environmental zones on emission reduction can be evaluated e.g. every one or two years and make any necessary changes (e.g. tighten emission limits).
Impacts on safety (users, citizens, …)	Improvement in road safety if environmental zone results in lower traffic volumes and less congestion.
References and Other Points	
Comments or remarks not addressed above	Possible other benefits: _ Owners of polluting vehicles are forced to retrofit with filters, traps, etc. _ Bus (and trucks) operators may start thinking of replacing their fleet with cleaner vehicles (e.g. natural gas, hybridization, etc). _ More parking spaces within the zone, cleaner mobility, less congestion, less noise, better accessibility.
Successful examples of implementation	- http://urbanaccessregulations.eu/low-emission-zones-main - http://www.iaqm.co.uk/text/resources/reports/lez_aq_impacts.pdf - http://www.epcplc.com/clients/tfl/lez/home.php - http://www.tfl.gov.uk/modes/driving/low-emission-zone - http://www.tfl.gov.uk/cdn/static/cms/documents/health-impact-assessment.pdf - http://www.tfl.gov.uk/cdn/static/cms/documents/lez-impacts-monitoring-baseline-report-2008-07.pdf - http://www.gtkp.com/assets/uploads/20091121-162039-2749-Env%20Zones%20EU.pdf
References for further details	- http://www.healtheffects.org/Slides/AnnConf2013/Barratt-MonPM.pdf - http://ec.europa.eu/transport/themes/urban/doc/ump/swd%282013%29526-communication.pdf - http://ec.europa.eu/transport/themes/urban/studies/doc/2010_12_ars_final_report.pdf - http://www.tdm-beijing.org/files/Fact_Sheet_Environmental_Zones.pdf - F. Kelly et al. The London low emission zone baseline study. Research Report 163, Health Effects Institute, Boston, Massachusetts, November 2011.

3.8.1.2 Intelligent transport systems (ITS)

Table 3-40: Summary information for intelligent transport systems (ITS)

General Description	
Name of technique	**Intelligent Transport (and communication) Systems (ITS)**
Pollutants addressed	Practically all (or most of the) pollutants
Engine/vehicle/vessel types considered	All modes of transport (here, discussed for road)
Short description of technique	ITS can be divided in three categories: • Systems in the vehicle _ Driver behavior systems such as the start-stop system, the tyre pressure monitoring system, the gear shift indicator system etc. _ Advanced driver assistance systems (ADAS) such as the night vision system, the lane keeping system, the emergency braking system, the (adaptive) cruise control system, platooning, intelligent speed adaption system. _ Driver condition monitoring system. • Navigation and information systems _ Systems used before the trip such as the eco trip planning system and the eco information system. _ Systems used during the trip such as the in vehicle information systems, the outside of the vehicle systems, and the eco driving support system. _ Systems used after the trip. • Management and traffic control systems
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	Difficult to quantify environmental benefit, but, in general, positive impact is expected. Two indicative examples are given below. • Transit signal priority system in Helsinki, Finland. A pilot project designed to provide real-time passenger information and signal priority to tram and bus lines. Automated vehicle location (AVL) and computer assisted dispatch (CAD) systems were installed on a tram and bus line. In addition, transit signal priority was provided on each route, and real-time schedule information was displayed at each transit stop. Reductions: NO_x 4.9%, PM 1%, VOC 1.2%, CO 1.8%. • Automated speed control system in Torino, Italy. Automatically adjust vehicle following distances, real time signal control timing data to regulate intersection approach speeds, optimize travel speeds between green lights to improve travel times. Vehicles were provided with adaptive cruise control (ACC), stop & go (S&G) functions, and traffic light approach control (TLC) systems. Reductions: NO_x (7.9-11.3%), VOC (4.2-6.9%).
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	• Depends on application (from a few hundreds of € per vehicle to millions of € required for the installation of an advanced ITS). • Investment is expected to be paid back by savings from fuel consumption, emissions reduction, reduced travel times and better mobility, less accidents, etc.
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	ITS that help reduce vehicles dynamics (accelerations and deceleration) may reduce fuel consumption (and CO_2 emissions) by approximately 3-15%.

Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	Positive impact is expected on GHGs.
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• Implementation cost. • User acceptance (in-vehicle displays, behavioral changes, privacy issues). • Need for more standardized systems.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	• Technical difficulties may arise. • Significant investment in infrastructure may be required, depending on application.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	Frequent and careful maintenance of the various systems is required.
Durability/lifetime of emission control equipment	Depends on application.
Impacts on safety (users, citizens, …)	Safety is improved.
References and Other Points	
Comments or remarks not addressed above	ITS reduce traffic congestion and enhance mobility of people and goods.
Successful examples of implementation	• From March 2005 until February 2008, INTRO was implemented in Sweden under the coordination of the Swedish Road and Transport Research Institute. INTRO combined innovative use of new and existing sensor technologies in pavements and bridges with data from moving cars in order to provide operators, maintenance authorities and road users with rapid warning of emerging problems. The total budget of this project was €3.5 millions. • MOTOROLA implemented in Israel a system under the name REACT that senses natural and infrastructure conditions of suitably-equipped vehicles, transmits real-time date to a central server where it can be analyzed by sophisticated prediction and decision-making models and generates safety alerts, speed and route recommendations to individual drivers, plus relevant information for road and law enforcement authorities. The project budget was €3.7 million and lasted from January 2005 to December 2006. • An experiment of the Intelligent Speed Adaptation (ISA) was applied in 20 vehicles with equipment for speed recording for 6 months in Leeds, UK, during which the system was deactivated the first month (base case), then activated for four months and then deactivated for the last month. For the emission calculations data of the base case where used and compared to

	those of the second phase. The results showed that in the second phase the vehicle average speed increased in comparison to the period when the system was deactivated, the accelerations decreased significantly and, consequently, the CO_2 emissions decreased as well by about 6% (near the average speed). • http://www.wiseride.gr
References for further details	- European Commission, DG Enterprise & Industry, special study No. 02/2009, the potential of Intelligent Transport Systems for reducing road transport related greenhouse gas emissions, a sectoral e-business watch study by SE consult, final report, version 1.2, December 2009. - Intelligent Transportation Systems Benefits, Costs, Deployment, and Lessons Learned: 2008 Update, Robert P. Maccubbin, Barbara L. Staples, Firoz Kabir, Cheryl F. Lowrance, Michael R. Mercer, Brian H. Philips, Stephen R. Gordon (Oak Ridge National Laboratories), U.S Department of Transportation, Research and Innovative Technology Administration. - Intelligent Transport Systems, EU-funded research for efficient, clean and safe road transport, European Commission, Directorate General for Research Transport, EUR 24504 EN, 2010. - Reduction of fuel consumption and exhaust pollutant using intelligent transport systems, Mostofa Kamal Nasir, Rafidah Md Noor, M. A. Kalam and B. M. Masum, February 2014. - Lehtonen and Kulmala, "The Benefits of a Pilot Implementation of Public Transport Signal Priorities and Real-Time Passenger Information", 81st Annual Meeting of the Transportation Research Board, Washington, DC, 13-17 January 2002. - International Journal of Innovative Research in Technology & Science (IJIRTS), intelligent driver assist and fuel consumption system for road transport using ubiquitous RFID (Radio Frequency Identification). - What have we learned about intelligent transportation systems?, U.S. Department of Transportation, Federal Highway Administration, December 2000. - Assessing the emissions and fuel consumption impacts of Intelligent Transportation Systems (ITS), Energy and Transportation Sectors Division, Office of Policy, U.S. Environmental Protection Agency, December 2008. - Policy framework for Intelligent Transport Systems in Australia, Standing Council on Transport and Infrastructure, 2012. - EU transport GHG: Routes to 2050?, modal shift and decoupling options: paper 5, Huib van Essen (CE Delft), Xander Rijkee (CE Delft), Gijs Verbraak (CE Delft), Hans Quak (TNO), Isabel Wilmink (TNO), 22 December 2009. - Thesis on the effect of Intelligent Transport Systems in energy consumption and emissions of road transport, Sokrates Mamarikas, Thessaloniki 2012. - http://www.mlit.go.jp/road/ITS/Policy/h12/2.html

3.8.1.3 Enhanced inspection and maintenance (I/M) schemes

Table 3-41: Summary information for enhanced inspection and maintenance (I/M) schemes

General Description	
Name of technique	**Enhanced inspection and maintenance (I/M) schemes**
Pollutants addressed	Practically all (or most of the) pollutants
Engine/vehicle/vessel types considered	All road vehicles
Short description of technique	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 national and/or international standards. These tasks are accomplished with visual checks, emission measurements, and use of various technical means/devices. A short categorization of I/M types is the following: • 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) system 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. When a potential problem is detected, a dashboard warning light called malfunction indicator light (MIL) is illuminated to alert the driver. By giving vehicle owners this early warning about poor performance, high emissions or poor fuel economy, OBD protects not only the environment, but also consumers, detecting minor problems early before they become major repair bills and avoid costly repairs. In addition to the above, remote sensing devices (RSD) can also be used to measure emissions in the exhaust stream.
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	A reduction ~15-35% in most of pollutants can be achieved.
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	Indicative cost per vehicle €300-€500 based on the following analysis: (10 remote sensing facilities * €250,000 each + 500 technical inspection centers * €50,000 for every smoke meter + 500 persons * €1,000 training per person + 10% * 100,000 vehicles * €1,000 maintenance cost + €5,000,000 management cost) / 100,000 vehicles = 430 € (cost per vehicle)
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	Usually positive impact on fuel consumption (and CO_2 emissions).
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	Usually positive impact on non-regulated pollutants.

Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• The idle test, which is typically performed, does not reflect real driving conditions; it does not measure acceleration or deceleration modes, which greatly affects the volatile organic compound level. • Possible false reading of actual emission levels.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	• Police enforcement may be necessary. • Infrastructural changes (retooling of I/M stations, education of personnel). • Suitability of locations for remote sensing.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	• Vehicles that fail the inspection are not repaired to the point of reducing emissions but only to pass re-inspection. • No incentive for vehicle owners to purchase repairs to reduce emissions, only those that result in passing the inspection.
Durability/lifetime of emission control equipment	Vehicle lifetime increases and performance improves.
Impacts on safety (users, citizens, …)	Safety of vehicles is improved.
References and Other Points	
Comments or remarks not addressed above	Road traffic accidents may decrease.
Successful examples of implementation	- http://www.unep.org/transport/pcfv/pdf/dataapchina.pdf - http://www.muni.org/departments/health/admin/environment/im/Pages/default.aspx
References for further details	- http://ec.europa.eu/environment/archives/pollutants/inusecars1.pdf - http://www.epa.gov/otaq/consumer/14-insp.pdf - http://www.epa.gov/otaq/documents/cfa-air.pdf - http://www.epa.gov/otaq/regs/im/im-tsd.pdf - http://www.epa.gov/obd/questions.htm - http://www.epa.gov/oms/consumer/15-remot.pdf - http://www.arb.ca.gov/msprog/obdprog/obdprog.htm - http://www2.gtz.de/dokumente/bib/05-0520.pdf - http://www.crcao.org/reports/recentstudies2011/E-90-2a/CRC_E-90-2a_021811.pdf - An environmental analysis of vehicle inspection and maintenance programs, Pauline Easley, Applied Research Projects, Texas State University-San Marcos, Dept. of Political Science, Public Administration Program, Paper 368, Fall 2011.

3.8.1.4 Accelerated scrappage schemes

Table 3-42: Summary information for accelerated scrappage schemes

General Description	
Name of technique	**Accelerated scrappage schemes**
Pollutants addressed	Practically all pollutants
Engine/vehicle/vessel types considered	• In-use (mainly road) vehicles (oldest, most polluting ones). • Can be expanded to all mobile sources.
Short description of technique	• Older, 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 established by every country's government usually by giving grants to vehicles owners. • These schemes are quite likely to achieve: _ Environmental benefits, since newer vehicles meet more stringent emission standards _ Fuel savings • Replacing an entire vehicle (or equipment) 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.
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	Significant emission reductions may be achieved but difficult to quantify. Indicative range of average emission reduction that can be achieved: • PM, NO_x (5-20%) with the largest effect in the first year(s) of the scheme.
Costs for implementation and operation (order-of magnitude estimations per unit or any other metric)	• There is no limit on how much an early retirement program may cost in total (€ from a few millions to hundreds of millions). • Indicative incentive range for a single vehicle: €500-€3,000 for a light duty road vehicle.
Environmental Side Effects	
Impact on fuel consumption (positive/negative impact and typical % effect)	Usually positive impact on fuel consumption (and CO_2 emissions).
Non-regulated pollutants and trade-offs (e.g. NH_3 or N_2O emissions, NO_2 formation, PM/NO_x trade-offs, etc.)	Usually positive impact on non-regulated pollutants.
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• Response to a scrappage scheme is not always 100% guaranteed. It depends on the incentives provided, adequate information and dissemination of the program, etc. • Owners/operators of older vehicles are typically economically disadvantaged. Therefore, fiscal policies, carefully tailored to ensure proper balance between environmental goals and economic fairness, are important to successful programs. • The environmental benefit may be very poor if there is no scrappage verification (e.g. if old vehicles are exported to other countries or just moved outside of cities' limits and continue to pollute other areas).

	• Furthermore, the benefits of a scrappage/replacement program may be much smaller than anticipated if the new vehicles are used or driven considerably more than the scrapped vehicles would have been, or if the new vehicles have substantially more power than the replaced vehicles.
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	Infrastructure for dismantling old vehicles is required.
Maintenance and operation (additional maintenance requirements, monitoring requirements, …)	Significant benefits in vehicle maintenance costs.
Durability/lifetime of emission control equipment	The impact of a scrappage program on emission reduction can be evaluated e.g. after one or two years and make any necessary changes (e.g. provide more incentives).
Impacts on safety (users, citizens, …)	Improvement of vehicle safety and reliability.
References and Other Points	
Comments or remarks not addressed above	• A scrappage scheme can be combined with additional financial incentives, e.g. lower taxes and tolls. • Possible other benefits: _ Less engine noise levels. _ Owners of old vehicles may decide to buy a new one with alternative powertrain or cleaner fuel (hybrid, LPG, CNG).
Successful examples of implementation	- http://www.arb.ca.gov/msprog/moyer/guidelines/cmp_guidelines_part1_2.pdf - http://livingingreece.gr/2011/02/21/car-withdrawal-greece/ - http://www.scrapit.ca/ - http://heros2.org/
References for further details	- http://www.sustainable-mobility.org/resource-centre/month-issue/scrappage-schemes-in-europe-an-assessment.html?section=0 - http://www.theicct.org/sites/default/files/publications/ICCT_HDV_in-use_20130802.pdf

4 Assessment of best available techniques (BAT)

In this section, the BAT candidates presented earlier are assessed for each one of the categories shown below:

- Road vehicles
  - Spark-ignition (gasoline) road vehicles
    - Mopeds and motorcycles
    - LDVs (cars, vans, light commercial vehicles)
  - Diesel road vehicles
    - LDVs (cars, vans, light commercial vehicles)
    - HDVs (trucks, buses)
- Non-road mobile machinery (NRMM)
  - Gasoline engines
  - Diesel engines (including rail)
- Waterborne transport
  - Gasoline boats and recreational crafts
  - Diesel vessels

Wherever this is considered relevant, the assessment is made following the evaluation scheme described in section 2, in order to be consistent with the methodology proposed there. However, there are some categories (e.g. gasoline road vehicles and gasoline non-road engines) where such a ‘strictly defined’ evaluation scheme is 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 such as GDI vehicles, measures which are incomparable, etc). In such cases, a simplified descriptive assessment (i.e. without detailed cost-benefit comparisons) of various emission reduction techniques is provided with a clear distinction between BAT for new and in-use vehicles/engines.

Below we describe how the detailed evaluation scheme and methodology of section 2 is implemented in practice.

Assessment based on the evaluation scheme of section 2

For a given mobile source (e.g. diesel LDVs, diesel HDVs, etc.) and specific pollutant addressed (e.g. NO_x or PM), the available emission control techniques are summarized in a comparative table. The techniques are organized in the following categories:

- Engine measures (e.g. EGR)
- Exhaust aftertreatment (e.g. DPF, DOC, SCR, LNT)
- Cleaner fuels and alternative powertrains (e.g. conversion to natural gas, biodiesel, renewable diesel, emulsified diesel, hybridization)

The following main characteristics are given for each technique to assist in the evaluation:

- Emission reduction potential for the pollutant addressed (indicative percentage range – “expected environmental effect”) compared to the reference technology
- Cost per vehicle (indicative additional cost relative to reference technology, required for implementation and operation, order of magnitude estimate)

- Environmental side effects (positive / negative) and synergies
- Limitations in applicability
- Implementation and other issues

The two key criteria (environmental benefit and cost) are used to make a cost-effectiveness comparison of BAT candidates and provide a relative placement of them on the evaluation grid of Figure 2-5. Based on this, the final evaluation and BAT assessment is performed by examining in a more qualitative manner the remaining criteria (synergies and side effects, technical limitations, implementation issues), as proposed in the flow chart diagram of Figure 2-6, to identify potential bottlenecks in applicability of each technique.

Some clarifications (notes) related to the assessment methodology are given below.

- *Note on cost of a technique:* The cost for implementation and operation of a technique is provided for an 'average cost' vehicle/machine (that is, a vehicle/machine whose total cost, i.e. purchase price, is neither 'too low' nor 'too high'). Hence, comparing the cost of a technique to the total cost of a vehicle/machine does not substantially affect the outcome of the evaluation methodology adopted here. Moreover, when considering mobile sources of different categories (car vs. truck vs. NRMM vs. train) the cost of e.g. an aftertreatment technology (catalyst, filter, etc.), as an order of magnitude estimate, may increase almost proportionally to the total cost of the vehicle/machine. As a result, this parameter (cost of technique compared to total vehicle cost) is not an important element in establishing the economic viability of a technique in the framework of the evaluation methodology used in this study.
- *Note on placement of techniques within the boxes of the evaluation grid:* The placement of techniques within the boxes of the evaluation grid is indicative and relative, based on order of magnitude estimates, not absolute values; hence, should not be scaled. The important for each technique is the box, not the placement within the box. Additional cost per vehicle is assessed (to the degree possible) for an indicative period of 10 years, e.g. 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.

  Latest and recent Euro (or other) emission standards are placed on the environmental benefit axis for reference. Similarly to the positioning of techniques within the boxes of the evaluation grid, the placement of emission standards on the environmental benefit axis is indicative and relative and, as such, should not be scaled. Furthermore, it should not directly be concluded that emission standards on the vertical axis 'are equal to' (can be achieved with) specific BAT techniques within the boxes in all cases, because this depends on specific application considered.
- *Note on definition of reference technology and distinction between BAT for new and in-use vehicles/engines:* The environmental problem related to the mobile sources examined is different in each case. The definition of reference technology and its current usage conditions/popularity provide an indication about how 'big' the problem is. A characteristic example is the well known NO_x problem with diesel LDVs, which exhibit an individualistic pattern compared to other vehicle types and pollutants (more on this below). In this case, the emission level of the reference technology is representative for the entire range of diesel LDV emission technologies (emission standards) and the BAT candidates which are assessed in this section are for both

new and existing vehicles. In order to avoid any misunderstandings, a clearer distinction and justification of specific BAT recommendations for OEM/retrofit applications (new/in-use vehicles) is provided in the summary section 5.

- *Note on non-technical measures:* Non-technical measures are complementary to the technical ones in order to assist in further emission reductions. Mixing technical and non-technical measures in the evaluation scheme and directly comparing them could give misleading results. Therefore, non-technical measures can rather be considered as ‘good practices’ and are referenced wherever deemed necessary (in this section and in summary section 5). For details on the implementation of individual non-technical measures, the reader is referred to the descriptions of section 3. It is not the intention of this report to analyze the policy and societal impacts of non-technical measures.

  In addition to the non-technical measures analytically described in section 3, various implementations may differ in practice and be combined with specific funds and incentives schemes, tax exemption or tax reductions, etc. Incentives and policies to promote modal shift to cleaner public transportation systems is also 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).

4.1 Road vehicles

4.1.1 Mopeds and motorcycles

Gasoline powered mopeds and motorcycles have traditionally been significant emitters of VOC and CO, due to their engine and performance calibration (Ntziachristos et al., 2009). 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 to urban air pollution where these vehicles are in use has been historically increasing. This is especially noticed in densely populated (urbanized) areas of the world that rely on mopeds and motorcycles as an essential means of transportation.

BAT for new vehicles

Typical exhaust emission control considered as BAT

Current production mopeds and motorcycles have to comply with latest emission limits and the technology used to meet these limits is considered (assumed) as BAT for new vehicles. This includes 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.

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.

Two-stroke engines: Two-stroke engine is another combustion technology used for the propulsion of some moped models. Two-stroke vehicles have historically been notorious emitters of VOC mostly for two reasons, i.e., the use of lubricant oil directly in the cylinder (in the absence of a crankcase sump), and the excess scavenging losses due to the overlap in the exposure of inlet and outlet cylinder ports during charging. Despite emission problems, two stroke engines were popular in the past because they were lightweight, easy to construct and maintain, and had an extremely good power-to-mass ratio. However, meeting the new emission limits means significant investments in the emission control of such engines. This includes electronically controlled fuel injection directly in the cylinder for precise metering of the quantity and the timing of the fuel supplied, secondary air injection in the exhaust line and an oxidation catalyst to control hydrocarbon 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. Therefore, two-stroke engines have started to disappear – a trend not expected to revert in the future.

Fuel evaporation control

The purpose of evaporative control systems is to reduce or eliminate the release of NMVOC emissions escaping from the vehicle’s fuel system. Evaporative emissions control on motorcycles consists of carbon canisters connected to the fuel system to capture and recycle HC vapors back to the intake of the engine to be combusted. Low permeability tanks are also used to control evaporative emissions, 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.

BAT for in-use vehicles

Reference technology and current usage conditions / popularity

Mopeds: As a reference technology for mopeds we have selected a light two-wheel powered vehicle with a two-stroke gasoline engine without aftertreatment control, cylinder capacity <50 cm^3, maximum design speed not exceeding 45 km/h, and maximum continuous or net power ≤4,000 W. Such a vehicle may typically emit in the range of 2.8-3.5 g/km VOC, 3-4.5 g/km CO, and 0.17-0.18 g/km NO_x, depending on age of vehicle, driving conditions, speed, etc. These reference emission levels correspond to (old technology) Euro 2 and older vehicles. An indicative estimate of the mopeds that may in practice emit in the range of reference technology is ~68% of total mopeds fleet in EU28[37].

Motorcycles: As a reference technology for motorcycles we have selected a two-wheel powered vehicle with a four-stroke gasoline engine without aftertreatment control, cylinder capacity ~100-250 cm^3, maximum design speed exceeding 45 km/h, and maximum continuous or net power >4,000 W. Such a vehicle may typically emit in the range of 0.7-1.2 g/km VOC, 4-10 g/km CO, and 0.25-0.30 g/km NO_x, depending on age of vehicle, driving conditions, speed, etc. These reference emission levels correspond to Euro 2 and older vehicles. An indicative estimate of the motorcycles that may in practice emit in the range of reference technology is ~50% of total motorcycles fleet in EU28.

The small displacement engines used in the majority of mopeds/motorcycles population complicates emission control issues due to space limitations and simple design characteristics of small engine technology. Hence, retrofitting a catalytic converter in general cannot be recommended as BAT for existing vehicles. In fact, 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:

a) *Emission control system maintenance*

   To ensure compliance with applicable exhaust emission standards, a vehicle inspection and maintenance (I/M) program should be implemented. A program requiring annual inspections of all two-wheel vehicles subject to emissions regulations is recommended. I/M programs consist of measuring motorcycle emissions and requiring consumer repairs when those emissions exceed specified levels.

b) *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.

[37] EMISIA COPERT data 2013. Available at: http://www.emisia.com/content/copert-data

Assessment of alternative fuels and powertrains as BAT candidates

In general, an alternative strategy for emission reduction is the introduction of alternative fuels and new powertrain concepts. Some examples that have been demonstrated in mopeds/motorcycles include electrification, hybridization, LPG, natural gas, and biofuels such as ethanol. Some of these options have the potential to achieve reductions in both GHG and air pollutants. However, the use of alternative fuels and powertrains presents specific challenges on two-wheeled vehicles with respect to packaging and safety/space constraints for storage of such fuels on board the motorcycle; hence, additional system requirements may be needed to facilitate their use. A discussion/assessment of the available options is given below (MECA, 2008).

a) *LPG and CNG*

   Using LPG or CNG on two-stroke vehicles requires the installation of a lubricating oil pump since it is not possible to manually mix oil and fuel. A CNG system typically consists of a high pressure fuel tank, a pressure regulator, and a gaseous carburetor. The use of LPG in motorcycles is conceptually similar to that of CNG although it can be stored as a liquid and thus eliminates some of the space constraints of CNG. LPG tanks tend to be cylindrical for safety reasons and this tends to limit their application on two-wheeled motorcycles since most of the available space is irregular in shape.

b) *Ethanol*

   Use of ethanol (or other biofuels) on motorcycles requires minor fueling system upgrades to ensure that potential negative impacts on elastomers are avoided and permeation properties are addressed within the fuel delivery system.

c) *Electric and hybrid vehicles*

   Electric or hybrid electric motorcycles have the potential to provide significant air quality benefits, while exhibiting even greater challenges than automobiles in terms of weight and space constraints. Lately, electric power two wheelers have started to become popular in several markets, but wider penetration of such vehicles may only be achieved when technical and cost competitiveness of batteries improves and issues related to vehicle weight and range are adequately addressed.

Based on the above discussion/assessment and on the technical descriptions of alternative fuels/powertrains in section 3, and considering the constraints of the two-wheeled vehicles, the only option that can be considered to have a future potential as BAT for mopeds and motorcycles is electrification. This is the only concept that could be more easily accepted as a really ‘clean’ technology.

4.1.2 Spark-ignition (gasoline) light duty vehicles (cars, vans, and light commercial vehicles)

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. These engines are characterized by high power to weight ratio, smooth operation, and possibility to build them in different sizes and configurations.

BAT for new vehicles

Current production light duty vehicles have to comply with latest emission limits and the technology used to meet these limits is considered (assumed) as BAT for new vehicles (state-of-the-art).

There are two main combustion concepts of such engines, with distinct characteristics. The most widespread one is the so-called port-fuel injection (PFI) engine, where the fuel is injected in the intake manifold, upstream of the combustion chamber. This allows time for the fuel to evaporate and mix with the intake air and, hence, creates an almost homogenous (premixed) mixture that forms relatively limited pollutants upon combustion.

The second concept is the gasoline direct injection (GDI) one, where the fuel is injected directly in the cylinder. This allows precise metering of the fuel injected per stroke and cylinder, and better adjustment of the combustion parameters, such as compression ratio and valve and injection timings. This also leads to decreased pumping losses. As a result, fuel efficiency improves. The drawback is that the fuel is not thoroughly mixed with the intake air. Liquid fuel may impinge on the cold walls of the piston and the combustion chamber, thus, leading to higher emissions, in particular PM and VOC. Because of their distinct performance, these two concepts need to be considered separately.

Typical exhaust emission control considered as BAT in PFI engines

For their emission control, PFI engines are calibrated stoichiometrically, which means that the quantity of fuel injected is precisely proportional to the air intake. This is combined with a closed-loop three way catalyst (TWC) in the exhaust which oxidizes CO and HC and reduces NO_x. Typically, the exhaust system also includes an oxygen sensor (or air:fuel ratio sensor) that monitors the oxygen content of the exhaust and continuously adjusts the fueling to match the operation conditions. This also ensures that the system alternates rapidly between slightly fuel-lean and slightly fuel-rich conditions. In this way, both the oxidation functions (conversion of CO and HC to CO_2 and water) and the chemical reduction function (NO_x to nitrogen) can operate simultaneously.

The above technology has been proven very efficient over the years and may lead to a pollutant reduction that exceeds 99%. Recent developments with regard to catalyst formulation, substrate optimization, and positioning of the catalytic converter in relation to the engine outlet have extended the performance and the useful lifetime of such systems. Such a configuration may achieve the lowest emission levels of all conventional vehicle technologies today.

BAT for gasoline direct injection (GDI) engines

GDI is a much more recent technology on spark-ignition engines, introduced to improve engine fuel economy and power by directly injecting fuel into the cylinder rather than upstream of the intake valve. This allows the engine to operate in a diesel-like lean combustion mode at light engine loads (cruising situations where little acceleration is required) or in stoichiometric combustion mode similar to PFI engines in other situations. Today, most of the GDI engines operate stoichiometrically over their complete operation range, but engines that combine both modes in different load regions are also available.

NO_x control: Stoichiometric GDI NO_x emissions do not substantially differ from conventional PFI stoichiometric 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 (instead of conventional TWC which is used in stoichiometric combustion mode). This operates by adsorbing NO_x over the lean phase on the catalyst surface and by reducing upon release over short cycles of rich operation. 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: Directly injecting the fuel in the cylinder decreases the time that the fuel has to mix with the air, and can induce wall impingement of fuel droplets. Both mechanisms may lead to an increase in PM (and UFP - ultra fine particles) formation due to the incomplete combustion caused by heterogeneous mixing and cold flame phenomena on the wall, respectively. PM (and PN) emissions can be controlled by modified injection strategy and an improved fuel system (engine measures). 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 GPF technology draws from the large experience accumulated on diesel particle filters (DPFs), which are also based on wall-flow filter technology.

Fuel evaporation control

Non-methane volatile organic compounds (NMVOC) originate from fuel escaping both the combustion process and the fuel system. NMVOC emissions from the vehicle's fuel system are called evaporative emissions and occur as a result of fuel volatility combined with the variation in ambient temperature and the temperature changes in the vehicle's fuel system.

The *activated carbon canister* is an essential component of the evaporative emission control system. 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 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; this can be accomplished through both design and selection of materials. Advanced tanks consist of coextruded, multilayer construction with fluoropolymers to reduce permeation. Special challenges in materials compatibility have resulted since the introduction of ethanol blends in gasoline, due to the corrosive character of ethanol.

BAT for in-use vehicles

Reference technology and current usage conditions / popularity: The majority of gasoline cars on the road today are already equipped with three-way catalysts 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 urban air pollution. Experience shows that accelerated replacement schemes boosted by financial incentives are very effective in removing these older vehicles from the road.

The following techniques are proposed as BAT options for TWC equipped vehicles:

a) *Emission control system maintenance*

The emission reduction effectiveness of the catalyst may be severely degraded over time. Excessive vibration or shock, excessive heat, lack of proper vehicle maintenance, or improper vehicle operation each can cause catalyst failures. The catalyst can also be damaged if the engine is not properly tuned and excess fuel enters the catalyst. Moreover, fuel/air ratio adjustment may fail with time for a variety of reasons (lambda sensor failure, injectors plugging, etc).

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 are also adequate but can be further enhanced to be more effective (e.g. including measurement of NO_x levels). Finally, OBD related identification technique can be plausible. Once a malfunction has been identified, maintenance may include component replacement (e.g. catalyst), re-calibration, or cleaning (e.g. injectors).

b) *Fuel evaporation control*

Despite some technical difficulties, retrofitting activated carbon canisters and low permeability tanks can be considered as BAT to reduce evaporative emissions. Compatibility issues with ethanol blends above 10% for older vehicles may exist. Moreover, no inspection techniques exist for the efficiency of the canister and no manufacturer maintenance schedule includes canister replacement. Replacing the canister can be considered a BAT for older vehicle types.

Assessment of alternative fuels and powertrains as BAT candidates

An alternative strategy to introducing engine measures and aftertreatment control for emission reduction is the introduction of alternative fuels and new powertrains concepts (e.g. LPG, natural gas, ethanol, methanol, hybrid and electric vehicles)[38]. Some of these options have the potential to achieve reductions in both GHG and air pollutants. Although it is not to be expected that such concepts will constitute the majority of vehicles sold in Europe in the near future, certainly a wider diversification with regard to powertrain technologies and fuels is to be anticipated. A discussion/assessment of the available options is given below.

a) *Liquefied petroleum gas (LPG)*

LPG can be used either as a single fuel or in bi-fuelled vehicles that can operate both on gasoline and LPG in order to increase vehicle range and security (if LPG refueling stations cannot be found in a particular area). It is stored in pressurized tanks on board the vehicle in liquid form (to benefit from the increased volumetric energy content compared to its gaseous form) and it may be combusted in a normal gasoline type of engine that has to be adjusted to the specifications of the fuel. With proper tuning, LPG engine operation and emission performance is hardly distinguishable to gasoline. With

[38] Communication 'COM(2013) 17 final' from the European Commission to the Parliament designates the main alternative energy sources for transport, and road transport in particular, to be LPG, natural gas, electricity, liquid biofuels and hydrogen. All of these fuels are already used in road transport, in various extents and degrees of success.

LPG usage petroleum dependency remains. However, its use has been promoted for cost reasons, as its normalized price per unit of energy delivered is lower than gasoline.

Retrofits: LPG retrofits on existing gasoline vehicles is a widespread practice in several countries, as drivers aim at benefiting from the substantial price difference compared to gasoline. Converting a gasoline engine to LPG is so easy that can be made in any local car repair shop. Due to the ease of conversion and the lower cost of LPG at the pump, many gasoline vehicles have been converted to LPG around the world using commercially available retrofit kits. Traditional large fleets in Europe include Poland, the Netherlands and Italy, and lately Greece. Outside of Europe, LPG cars constitute a large fraction of Korean and Australian fleets.

b) *Compressed natural gas (CNG)*

Despite its energy content disadvantage compared to liquid fuels, natural gas is currently in the focus of the automotive industry as an alternative fuel. The main advantages are energy security (alternative energy pathway to oil), lower CO_2 yield per unit of energy delivered, and the ability to directly substitute it by biomethane, i.e., the product of biomass conversion. In light duty vehicles, natural gas is burned in conventional stoichiometric gasoline-type of engines and produces a similar profile of regulated pollutants compared to gasoline (with the exception of higher hydrocarbon content, primarily consisting of methane, the key ingredient in natural gas). Once stoichiometry has been established, the TWC in the exhaust line should lead to a very efficient reduction of CO, HC, and NO_x. Due to the low reactivity of methane from CNG engines, a dedicated TWC would be required for sufficient reduction of the methane part of HC.

Currently, natural gas is still a niche fuel (~1.5% share worldwide), but it has great potential for considerable growth in the future, especially as the main constraints are expected to be gradually solved (initial technology cost, vehicle range, performance, refueling infrastructure). European natural gas vehicle markets are still with diverse state of development depending on the existence or not of national promotional policies.

Retrofits: Converting current gasoline vehicles to CNG is much more difficult than LPG due to the specific characteristics of natural gas (e.g. high pressure of storage and handling, vehicle space considerations, distance of fuel combustibility relative to gasoline, etc.). As a result, retrofitted vehicles have also appeared but not to the extent of LPG retrofits. In any case, the drivers can benefit from the substantial price difference compared to gasoline (as with LPG), although the initial cost for conversion is quite high.

c) *Ethanol and FFVs*

Ethanol is mostly used blended in gasoline (e.g. E10 formulated for conventional gasoline vehicles consisting of 10% ethanol, E85 formulated for flexi-fuel vehicles consisting of 85% ethanol, other intermediate blends) 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. E85 cannot be used in a conventional gasoline-only engine (vehicle must be specially designed to run on it). In any case, the environmental benefit from ethanol use is very low.

d) *Methanol*

Methanol is one of the first alternative fossil fuels used in transport already since the 1970s (in particular in US as a gasoline replacement). It can be used as a neat fuel or in blends with gasoline. Methanol is ignited in cylinder by a spark, in an identical process to gasoline combustion. Hence, emissions are usually controlled by a TWC and a similar profile of regulated pollutants as gasoline combustion is to be expected. Use of methanol in existing vehicles may lead to slight departures from stoichiometry, in a similar way to LPG retrofits. Methanol can also be aggressive to some of the engine parts, if no proper care is given, thus creating additional failures and, possibly, secondary air emission impacts. In general, 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 - DMFCs).

Based on the above discussion/assessment of alternative fuels and their technical descriptions in section 3, the following remarks can be made concerning whether these fuels can be considered as BAT for gasoline replacement in road vehicles.

- Through subsequent regulations of fuel specifications, gasoline grades of today are high quality products with a chemical character which well serves the needs of advanced combustion and aftertreatment systems used in road vehicles. As a result, current gasoline fuels enable technologies that can lead to extremely low emissions of air pollutants. With the current status of aftertreatment technology, no additional significant emission reductions of regulated pollutants can be expected by further control of conventional fuel specifications, with perhaps the exception of the fuel performance in cold (sub-zero) conditions. Hence, in general the above fuels cannot be considered as BAT 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.
- Especially for retrofits (e.g. LPG/CNG), they are only approved by authorities for their safety. In terms of emission performance they are only checked in oversimplified inspection and maintenance tests. The latter have been designed to check whether original fueled vehicles behave as they should and not to test whether alternative fuels deliver a similar performance level. Most importantly, NO_x emission levels are not at all checked. Evidence shows that the lambda sensor used for retaining stoichiometry may slightly drift when an alternative fuel is used and, by that, significantly degrading the performance of emission control systems, leading to uncontrollably high NO_x emissions in some cases. It can now safely be considered that possible NO_x air quality problems from LPG (and CNG) retrofits are not at all recognized. More checks on retrofitted vehicles are required and depending on the extent of the problem, specific interventions need to be planned (Ntziachristos, 2014).

The following concepts are advanced technology vehicle types having the potential to achieve significant GHG and air pollutant emission reductions in the future[39]. Currently, these concepts have penetrated the market in various degrees, depending on the concept, due to various limitations (technical, economical, infrastructural, etc).

e) *Hybrid vehicles*

Hybrid vehicles combine an electric motor and an internal combustion engine, most frequently powered by gasoline, in various configurations to power the wheels. This combination primarily aims at reducing energy consumption and greenhouse gas emissions, but studies have shown that some gasoline hybrids can also achieve impressive reductions in air pollutants compared to conventional powertrains. Vehicle sales statistics show that more than 30 hybrid vehicle models were available in Europe

[39] They may be considered for replacement of both gasoline and diesel vehicles in the future and, hence, the discussion is not repeated again for diesel vehicles below.

in 2013, although they make only some 1.4% of total sales (ICCT, 2014). However, this percentage is more than twice as high as two years ago and, in any case, it is deemed to increase as more and more models are offered.

f) *Battery and fuel cell electric vehicles*

Battery electric (BEV) and fuel cell electric (FCEV) vehicles are advanced technology vehicle types that have been considered to reduce greenhouse gas 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.

BEVs: In these vehicles, energy is stored in the form of electricity in batteries on board the vehicle. Batteries have been so far the limiting factor in the growth of the BEV market due to their inferior energy density compared to liquid fuel, high cost, and concerns regarding their long-term performance. Charging considerations and the associated infrastructural and behavioral changes of vehicle owners also provide an obstacle in widening the popularity of BEVs. On the other hand, electric vehicles offer low operational costs, ease of operation, driving and noise comfort. A significant real world penetration of electric vehicles will therefore only take place when the technical and cost competitiveness of batteries improves. Technological maturity and material limitations delay this. New breakthroughs in battery technology will be required.

FCEVs: In order to overcome some of the issues of BEVs, energy can be stored in liquid form in FCEVs. Most often, energy is stored on board the vehicle in the form of hydrogen, either compressed in high pressure bottles or adsorbed on a storage material. The energy carrier is converted to electricity in a fuel cell, also on board the vehicle. The electricity produced is then used to power the wheels in a more or less identical fashion to the one implemented in BEVs. The main advantage of a fuel cell in comparison to a battery is that it is not so much confined by capacity limitations, e.g. the same range of a battery electric vehicle can be achieved with a fuel cell electric one with ~1/5 of total weight for energy storage (Ntziachristos, 2012). The second advantage is that it can refill within a few minutes, i.e. in approximately the same time it takes to refill a conventional vehicle. The limiting factor in FCEV technology is the non-availability of hydrogen, both with regard to its production and refueling infrastructure. Hydrogen is not a primary energy source but has to be produced utilizing one of the existing power sources. It then has to be distributed locally, and then stored on board the vehicle. The whole process is technically demanding due to the diffusivity and safety concerns of hydrogen fuel. Significantly advancing the presence of FCEVs on the road will need significant investments in the so-called hydrogen economy front, which includes production, distribution, storage, and refueling considerations. FCEVs may also operate on alternative to hydrogen fuels in two different pathways. One option is to use methanol directly in a specially designed fuel cell (direct methanol fuel cell), which operates similarly to the hydrogen one but with a lower efficiency overall. The second option is to use almost any conventional fossil hydrocarbon fuel on a reformer where fuel reacts with steam over a catalyst to separate hydrogen from carbon atoms. Hydrogen is then used in a conventional fuel cell. Demonstration vehicles of both these concepts have appeared.

Remark: Electric vehicles have zero tailpipe emissions (locally). However, in rightly estimating the environmental footprint of electric vehicles, one needs to take into account the energy mix and the processes involved for electricity production. Some studies have shown that in countries with significant share of solid fuels in total electricity production, electric vehicles are overall not cleaner than conventional ones. In designing an integrated air quality policy involving electric vehicles, it is necessary to consider energy and fuel production associated emissions (either on-board the vehicle or upstream ones) and not just make the usual simplification that electric vehicles are zero emitters. The exact local energy generation mix, the technology used for energy conversion as well as the proximity of power generation stations to cities – where most of the air quality problems reside – are different dimensions of the issues that have to be considered in this process.

g) *H_2 combustion*

Apart from being used as a fuel in fuel cell electric vehicles, an alternative pathway for utilization of hydrogen is that of its combustion in an internal combustion engine. Although this approach is heavily criticized in terms of sustainability, the small number of commercial vehicles produced demonstrate that H_2 combustion can result 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. However, NO_x emissions can be significant due to the high combustion temperature of H_2; hence, specifically tuned combustion and coupled NO_x aftertreatment is required. With such advanced technology implemented, even H_2 combustion can be a very low (practically zero) contributor to air pollutant emissions (Wallner et al. 2008). However, hydrogen combustion should not be considered ‘clean’ by definition, especially in terms of NO_x.

4.1.3 Diesel road vehicles

4.1.3.1 NO_x reduction in diesel light duty vehicles (cars, vans, and light commercial vehicles)

Table 4-1 summarizes the different options for NO_x control in diesel LDVs. The techniques are placed according to their environmental effect and the cost per vehicle in the evaluation grid of Table 4-2. Based on this relative cost-effectiveness comparison and the limitations of each technique, the final evaluation and BAT assessment are performed.

Reference technology

Regarding nitrogen oxides (NO_x) control in diesel LDVs, we have selected a typical base diesel engine without aftertreatment as a reference technology (turbocharged compression-ignition engine with high-pressure fuel injection). Different versions of this reference technology may exist, for example with direct or indirect injection, intercooled or not, etc. Moreover, some of the engines may be equipped with exhaust gas recirculation. However, all these technology variants are relevant for the order of magnitude of NO_x produced and can all be considered to typically emit in the order of 0.5-1.5 g/km, depending on the size and age of vehicle, driving conditions, speed, etc.

Current usage conditions / popularity of reference technology

NO_x emission levels of diesel LDVs exhibit an individualistic pattern compared to other pollutants and vehicles types. Specifically, real-world NO_x emission levels have not been dropping with latest emission standards in Europe, as several studies have confirmed (Carslaw, 2011 and Franco, 2014), despite the significant corresponding reductions in type-approval values. This exceedance of type approval standards 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. In fact, this undesirable performance has led to activities currently taken at a European level to regulate the Real Drive Emissions of LDVs. Therefore, the emission level suggested here as a reference is representative for the entire range of diesel LDV emission technologies (emission standards).

It should also be clarified that several of the emission control technologies used in recent technology LDVs do have the potential to lead to significant emission reductions, when properly calibrated, even over real world operation. This is why several of these technologies are presented below as candidates for BAT.

Table 4-1: Comparison of techniques for NO_x reduction in diesel light duty vehicles (cars, vans, and light commercial vehicles)

	BAT candidates for NO_x reduction in diesel light duty vehicles (cars, vans, and light commercial vehicles)						
	Technique	**"Expected effect"**	**Cost per vehicle (Euro)**	**Environmental side effects and synergies (positive**	**/ negative)**	**Limitations in applicability**	**Implementation and other issues**
Engine measures	A. Exhaust Gas Recirculation (EGR)	25-45%	150-250 (indicative manufacturer cost)	n.a.	• Slightly reduces engine power • Risks by PM recirculation if not combined with a DPF	Electronic control strategy required to ensure operation	• Major engine integration when retrofitted • Exhaust cooling may result in engine wear due to excess water vapour
Aftertreatment	B. Selective Catalytic Reduction (SCR)	70-95%	350-500 (indicative manufacturer cost) +50 urea +50 maintenance -80 possible fuel savings (OEM) per year (*)	• Reduction of PM (20-40%), VOC and CO (50-90%) • 3-5% possible fuel consumption benefits (OEM applications) • Reduction of the characteristic odor produced by a diesel engine and smoke	Risk for "ammonia slip" (careful urea injection strategy and clean-up catalyst required)	• Urea additive must be available (infrastructure required) • Certain temperature criteria for NO_x reduction to occur (data logging) • Lower efficiency in low-load city driving (low exhaust gas temperatures)	• Limited potential for retrofitting (technical difficulties, limited space) • More suitable for OEM large vehicles (e.g. >1.8l) • Periodic refilling with urea required (on-board dosing unit)
Aftertreatment	C. Lean NO_x Trap (LNT)	70-85%	300-500 (indicative manufacturer cost)	n.a.	• Fuel economy penalty (~2%) • NH_3 is generated during the rich regeneration phase (give up trapped NO_x)	Ultra Low Sulfur Diesel (ULSD) fuel required <10ppm	• Limited potential for retrofitting (technical difficulties, limited space) • Periodic "desulfation" cycle to remove any adsorbed sulfur compounds • High temperatures required for "$DeSO_x$" regeneration procedure
Alternative fuels and powertrain	D. Conversion to natural gas (CNG)	20-50%	2,000-3,000 (one-off for conversion) minus 100-500 fuel cost benefits per year	• Reduction of PM and BC (70-85%), NMVOC (75-85%), CO (70-95%) • Lower CO_2 emissions due to lower carbon content	• Low volumetric energy content • Not so effective in PN as DPF • Increase of CH_4 emissions	• Availability of fuel • Gas tank limits storage space and increases vehicle weight • Driving range may decrease (better for urban applications)	• May require significant changes to fueling infrastructure and maintenance facilities • Limited experience in retrofitting
Alternative fuels and powertrain	E. Emulsified diesel	10-20%	120-160 per year (**)	Reduction of PM (50-60%)	Decrease in power and fuel economy	Availability of fuel	Over time the water can settle out of the emulsified fuel and may cause performance problems
Alternative fuels and powertrain	F. Renewable diesel	5-10%	Comparable to conventional diesel (***)	• Reduction of PM and BC (15-25%), VOC (20-40%), CO (15-30%) • Free of aromatics, low mutagenic emissions and engine smoke (neat renewable diesel)	Possible increase in fuel consumption	Availability of fuel	• Adjustments in the electronic control of the engine may be required • Additives to address the lubricity issues
Alternative fuels and powertrain	G. Hybridization (off-vehicle or on-vehicle charging)	20-40%	5k-12k marginal cost (one-off) (****) minus 500-1,500 energy and maintenance cost benefits per year	• High fuel consumption benefits • Similar decreases in practically all pollutants • Low noise and PM resuspension	n.a.	• Recharging necessary for off-vehicle charging vehicles • Driving range may decrease (better for urban applications)	Limited experience in diesel hybrids

* E.g. assuming 2,000 l of fuel per year, 3% fuel economy because of SCR use, and 1.38 €/l diesel price, fuel savings is 83 €; if AdBlue® is 4% of fuel consumption, and 0.6 €/l is AdBlue® price, the urea cost is 48 €.

** E.g. assuming 2,000 l of fuel per year, 20% increase in fuel consumption because of emulsified diesel use, and 0.06 €/l additional fuel cost, the cost of this option is 144 € per year.

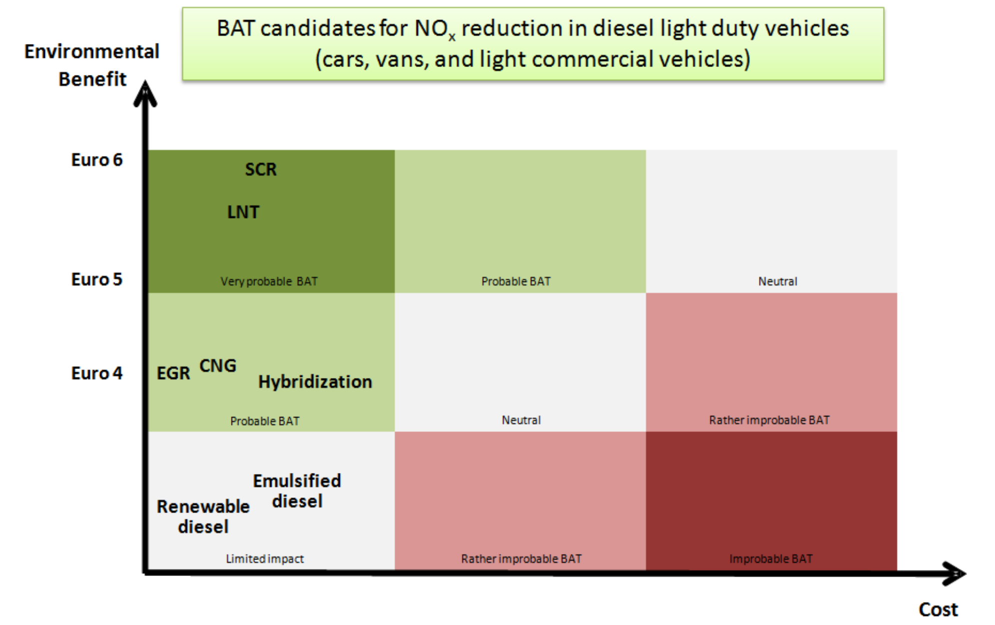
*** Marginal cost differences compared to conventional diesel may exist, but these do not affect the assessment made here.

**** Additional cost required to buy a new hybrid vehicle compared to buying a conventional diesel one in replacement of an older vehicle.

Table 4-2: BAT assessment for NO_x reduction in diesel light duty vehicles (cars, vans, and light commercial vehicles)

Relative cost-effectiveness comparison of BAT candidates

Pollutant	NO_x
Application	Diesel LDVs (PCs, LCVs)
Reference Technology	Turbocharged compression-ignition engine with high-pressure fuel injection
Reference emission level	0.5-1.5 g/km
Techniques	SCR LNT CNG Hybridization EGR Emulsified diesel Renewable diesel



Summary BAT assessment

SCR	• SCR is a cost-effective technology to reduce NO_x from diesel LDVs (passenger cars, light commercial vehicles), achieving high % reduction (70-95%). It also reduces PM, VOC, CO. • SCR is ideal for OEM applications, providing possible fuel consumption benefits. SCR units are usually large, heavy, complex, and bulky systems, and, therefore, may not be suitable for small diesel cars (e.g. <1.4l). • Urea additive has to be made widely available, since periodic refilling is required (on-board dosing unit). Risk for "ammonia slip" can be controlled with careful urea injection strategy (calibration optimization) or introduction of a clean-up catalyst downstream of the SCR catalyst. • In general, SCR is a BAT for new vehicles, having some limitations that need to be taken into account (urea infrastructural needs, space limitations, lower efficiency in low-load city driving). As a retrofit, it has limited potential due to technical difficulties and limited space available for installation.
LNT	• LNT achieves satisfactory NO_x reduction (70-85%). An environmental side-effect is the generation of ammonia during the rich regeneration phase, while there may also be a fuel economy penalty ~2%. • Other technical limitations are the requirement for low sulfur fuel (<10ppm) and periodic "desulfation" cycle (regeneration at high temperatures) to remove any adsorbed sulfur compounds. • In general, LNT is a BAT when low sulfur fuel is available and it appears to be the best alternative to SCR for NO_x reduction, e.g. in OEM applications with limited space or in which urea usage is difficult. Retrofit has limited potential due to technical difficulties.
CNG	• Conversion of a light duty vehicle to natural gas can lead to some NO_x reduction (20-50%) with additional PM, BC, NMVOC, CO benefits. CO_2 emissions are lower due to lower carbon content. • However, technical complications for conversion to NG, fuel availability, and high initial costs are limiting factors. Moreover, gas tank may limit storage space and increase vehicle weight, while the driving range of the vehicle may decrease. • An environmental side-effect is the increase of CH_4 emissions. • Hence, CNG is considered as BAT especially for OEM applications, providing an alternative energy pathway to oil, that promotes energy security, and offering fuel cost savings because of lower fuel price. As a retrofit, it has limited potential.
Hybridization	• Hybridization (replacement of old vehicle with a new hybrid one) can reduce NO_x (20-40%) and practically offer similar decrease in most pollutants with additional high fuel consumption benefits. • Initial capital costs are high, although fuel efficiency improvements may lead to cost benefits in the long run. Recharging for off-vehicle charging vehicles is a limiting factor, while the driving range may decrease. • In general, hybridization can be considered as BAT with potential to be further established in the future. Currently, the experience in diesel hybrid LDVs is limited.

EGR	• EGR exhibits NO_x reduction efficiency of 25-45% which is modest compared to the above options. • It slightly reduces engine power, while exhaust cooling may result in engine wear due to excess water vapor. Major engine integration effort is required when retrofitted. • In general, EGR has limited potential due to technical difficulties integrating this on existing engines.
Emulsified diesel	• Emulsified diesel exhibits low NO_x reduction efficiency (10-20%) with some additional PM benefits; it can be used in any new or existing diesel engine. • However, there is a decrease in power and fuel economy due to the fact that addition of water reduces fuel energy content. Fuel availability is also an issue. • It is evaluated as technique with 'limited impact' because there are better options for significantly higher NO_x reduction.
Renewable diesel	• Renewable diesel offers low NO_x emission reduction (5-10%) with some additional PM, BC, VOC, and CO benefits. The reduction is even lower when used as an additive. Neat renewable diesel is free of aromatics and it produces low mutagenic emissions and engine smoke. • The main issues concerning its use are fuel availability, adjustments in the electronic control of the engine, and additives to address the lubricity issues. • It is evaluated as technique with 'limited impact' because there are better options for significantly higher NO_x reduction.

4.1.3.2 PM reduction in diesel light duty vehicles (cars, vans, and light commercial vehicles)

Table 4-3 summarizes the different options for PM control in diesel LDVs. The techniques are placed according to their environmental effect and the cost per vehicle in the evaluation grid of Table 4-4. Based on this relative cost-effectiveness comparison and the limitations of each technique, the final evaluation and BAT assessment are performed.

Reference technology

Regarding particulate matter (PM) control in diesel LDVs, we have selected a typical base diesel engine without aftertreatment as a reference technology (turbocharged compression-ignition engine with high-pressure fuel injection). Different versions of this reference technology may exist, for example with direct or indirect injection, intercooled or not, etc. Moreover, some of the engines may be equipped with exhaust gas recirculation. However, all these technology variants are relevant for the order of magnitude of PM produced and can all be considered to typically emit in the order of 0.03-0.12 g/km, depending on the size and age of vehicle, driving conditions, speed, etc.

Current usage conditions / popularity of reference technology

The above reference PM emission level corresponds to Euro 3 and older vehicles (official type-approval) or even to Euro 4 for vehicles of categories N1-II/III. In practice, even the Euro 4 certified passenger cars (non-DPF-equipped) may emit more than 0.03 g/km PM (European Environment Agency, 2013a). Hence, the reference technology considered here for BAT assessment is a very popular one. A rough estimate of vehicles that may in practice emit PM in the range of the reference technology is ~72% of total diesel passenger cars fleet and ~85% of total diesel light commercial vehicles fleet in EU28[40].

[40] EMISIA COPERT data 2013. Available at: http://www.emisia.com/content/copert-data

Table 4-3: Comparison of techniques for PM reduction in diesel light duty vehicles (cars, vans, and light commercial vehicles)

	BAT candidates for PM reduction in diesel light duty vehicles (cars, vans, and light commercial vehicles)						
	Technique	"Expected effect"	Cost per vehicle (Euro)	Environmental side effects and synergies (positive	/ negative)	Limitations in applicability	Implementation and other issues
Aftertreatment	A. Diesel Particle Filter (DPF)	80-95%	250-450 (indicative manufacturer cost) plus 100-400 additional fuel and maintenance costs per year	Reduction of VOC (85-95%), CO (50-90%), BC	• Fuel economy penalty (1-2%) • NO_2 formation, in particular for catalyzed DPFs	• Ultra Low Sulfur Diesel (ULSD) required <50ppm • High temperatures required for regeneration	• Regeneration and cleaning system needed • Periodic maintenance to clean out non-combustible materials • Limited potential for retrofitting (technical difficulties, limited space)
Aftertreatment	B. Diesel Oxidation Catalyst (DOC)	20-40%	50-100 (indicative manufacturer cost)	Reduction of VOC (40-70%), CO (40-60%)	NO_2 formation	Ultra Low Sulfur Diesel (ULSD) required <50ppm	Little or no maintenance required
Alternative fuels and powertrain	C. Conversion to natural gas (CNG)	70-85%	2,000-3,000 (one-off for conversion) minus 100-500 fuel cost benefits per year	• Reduction of NO_x (20-50%), NMVOC (75-85%), CO (70-95%), BC • Lower CO_2 emissions due to lower carbon content	• Low volumetric energy content • Not so effective in PN as DPF • Increase of CH_4 emissions	• Availability of fuel • Gas tank limits storage space and increases vehicle weight • Driving range may decrease (better for urban applications)	• May require significant changes to fueling infrastructure and maintenance facilities • Limited experience in retrofitting
Alternative fuels and powertrain	D. Emulsified diesel	50-60%	120-160 per year (*)	Reduction of NO_x (10-20%)	Decrease in power and fuel economy	Availability of fuel	Over time the water can settle out of the emulsified fuel and may cause performance problems
Alternative fuels and powertrain	E. Renewable diesel	15-25%	Comparable to conventional diesel (**)	• Reduction of NO_x (5-10%), VOC (20-40%), CO (15-30%), BC • Free of aromatics, low mutagenic emissions and engine smoke (neat renewable diesel)	Possible increase in fuel consumption	Availability of fuel	• Adjustments in the electronic control of the engine may be required • Additives to address the lubricity issues
Alternative fuels and powertrain	F. Low biodiesel blends (up to B20)	10-15%	Comparable to conventional diesel (**)	• B20: Reduction of VOC (10%), CO (10%) • Proportional reduction of GHGs	• Possible increase in NO_x (2-3%) • Increase in fuel consumption, proportionally to the blend considered	• Current regulations in Europe limit blends to B7 • Higher blends are allowed in controlled captive fleets (e.g. buses)	• More often maintenance necessary • Incompatibility with some older engines
Alternative fuels and powertrain	G. Hybridization (off-vehicle or on-vehicle charging)	20-40%	5k-12k marginal cost (one-off) (***) minus 500-1,500 energy and maintenance cost benefits per year	• High fuel consumption benefits • Similar decreases in practically all pollutants • Low noise and PM resuspension	n.a.	• Recharging necessary for off-vehicle charging vehicles • Driving range may decrease (better for urban applications)	Limited experience in diesel hybrids

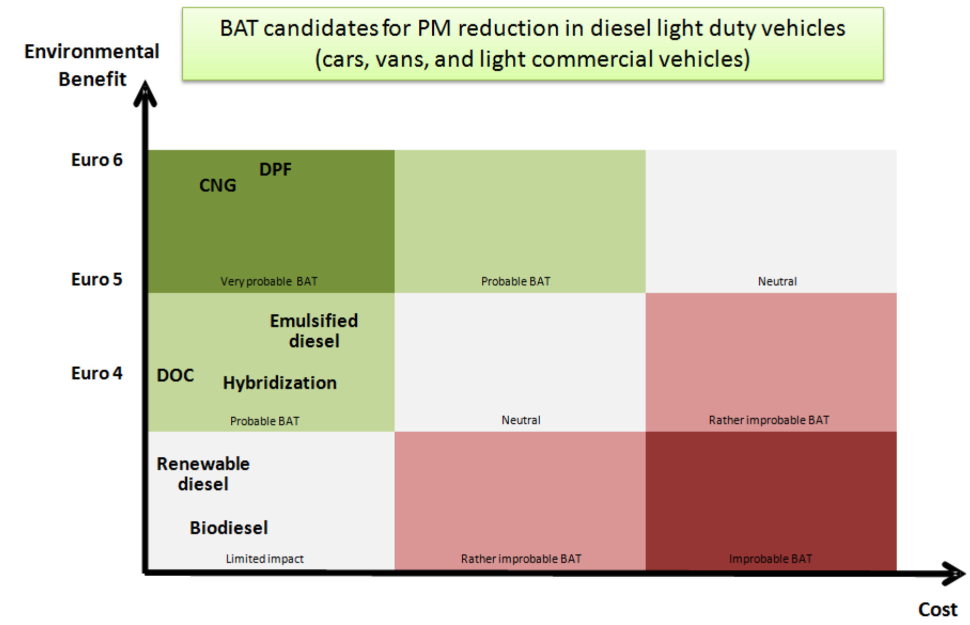
* E.g. assuming 2,000 l of fuel per year, 20% increase in fuel consumption because of emulsified diesel use, and 0.06 €/l additional fuel cost, the cost of this option is 144 € per year.

** Marginal cost differences compared to conventional diesel may exist, but these do not affect the assessment made here.

*** Additional cost required to buy a new hybrid vehicle compared to buying a conventional diesel one in replacement of an older vehicle.

Table 4-4: BAT assessment for PM reduction in diesel light duty vehicles (cars, vans, and light commercial vehicles)

Relative cost-effectiveness comparison of BAT candidates	
Pollutant	PM
Application	Diesel LDVs (PCs, LCVs)
Reference Technology	Turbocharged compression-ignition engine with high-pressure fuel injection
Reference emission level	0.03-0.12 g/km
Techniques	DPF CNG DOC Hybridization Emulsified diesel Renewable diesel Biodiesel



Summary BAT assessment	
DPF	• DPF is a cost-effective technology to reduce PM from diesel LDVs (passenger cars, light commercial vehicles), achieving high % reduction (80-95%). It also reduces BC, VOC, CO. • DPFs are ideal for OEM applications. Regeneration at high temperatures and periodic maintenance with cleaning system are required. • Attention should be given to increase of NO_2 from some DPF implementations (catalyzed DPFs), while there is also a fuel economy penalty (1-2%). • DPF is a BAT for new vehicles when low sulfur fuel (<50ppm) is available. As a retrofit, it has limited potential due to technical difficulties and limited space available for installation.
CNG	• Conversion of a light duty diesel vehicle to natural gas can lead to high PM (and BC) reductions (70-85%) with additional NO_x, NMVOC, CO benefits. CO_2 emissions are lower due to lower carbon content. • However, technical complications for conversion to NG, fuel availability, and high initial costs are limiting factors. Moreover, gas tank may limit storage space and increase vehicle weight, while the driving range of the vehicle may decrease. • An environmental side-effect is the increase of CH_4 emissions, while CNG is not so effective in PN as DPF. • Hence, CNG is considered as BAT especially for OEM applications, providing an alternative energy pathway to oil, that promotes energy security, and offering fuel cost savings because of lower fuel price. As a retrofit, it has limited potential.
DOC	• DOC exhibits PM reduction efficiency of 20-40% which is modest compared to the above options. It also reduces VOC, CO, but there are concerns that it may increase the NO_2 fraction of total NO_x emissions. • It has low cost and there are no particular limitations or maintenance requirements. • Hence, DOC may be considered as BAT (especially in large-scale applications), being more tolerant to fuel sulfur than DPF and when other technical factors exclude the applicability of DPFs.
Hybridization	• Hybridization (replacement of old vehicle with a new hybrid one) can reduce PM (20-40%) and practically offer similar decrease in most pollutants with additional high fuel consumption benefits. • However, initial capital costs are high, although fuel efficiency improvements may lead to cost benefits in the long run. Recharging for off-vehicle charging (OVC) vehicles is a limiting factor, while the driving range may decrease. • In general, hybridization can be considered as BAT with potential to be further established in the future. Currently, the experience in diesel hybrid LDVs is limited.

Emulsified diesel	• Emulsified diesel can achieve satisfactory PM reduction (50-60%) with some additional NO_x benefits; it can be used in any new or existing diesel engine. • However, there is a decrease in power and fuel economy due to the fact that addition of water reduces fuel energy content. Fuel availability is also an issue. • In general, emulsified diesel has limited potential due to decrease in power and fuel economy and possible performance issues.
Renewable diesel	• Renewable diesel offers low PM emission reduction (15-25%) with some additional BC, NO_x, VOC, and CO benefits. The reduction is even lower when used as an additive. Neat renewable diesel is free of aromatics and it produces low mutagenic emissions and engine smoke. • The main issues concerning its use are fuel availability, adjustments in the electronic control of the engine, and additives to address the lubricity issues. • It is evaluated as technique with 'limited impact' because there are better options for significantly higher PM reduction.
Biodiesel	• Use of low biodiesel blends reduces PM (10-15%), VOC, CO, and GHGs; it may increase NO_x (2-3%) and fuel consumption, proportionally to the blend considered. • Current regulations in Europe limit blends to B7 and only gradually move towards higher blending ratios. Higher blends are allowed in controlled captive fleets where maintenance intervals and practices, as well as engine materials, can be adjusted to the fuel properties. • It is evaluated as technique with 'limited impact' because there are better options for significantly higher PM reduction.

4.1.3.3 NO_x reduction in diesel heavy duty vehicles (trucks, buses)

Table 4-5 summarizes the different options for NO_x control in diesel HDVs. The techniques are placed according to their environmental effect and the cost per vehicle in the evaluation grid of Table 4-6. Based on this relative cost-effectiveness comparison and the limitations of each technique, the final evaluation and BAT assessment are performed.

Reference technology

Regarding nitrogen oxides (NO_x) control in diesel HDVs, we have selected a typical base diesel engine without aftertreatment as a reference technology (turbocharged compression-ignition engine with high-pressure fuel injection). Different versions of this reference technology may exist, for example with direct or indirect injection, intercooled or not, etc. Moreover, some of the engines may be equipped with exhaust gas recirculation. However, all these technology variants are relevant for the order of magnitude of NO_x produced and can all be considered to typically emit in the order of 4-16 g/km, depending on the size and age of vehicle, driving conditions, speed, etc.

Current usage conditions / popularity of reference technology

The above reference NO_x emission level corresponds to Euro III and older vehicles (official type-approval)[41]. In practice, even some Euro IV certified (or newer) vehicles (e.g. rigid/articulated trucks with more than 20t GVW and buses) may emit more than 4 g/km NO_x, especially in urban conditions (European Environment Agency, 2013a). Hence, the reference technology considered here for BAT assessment is a very popular one. A rough estimate of vehicles that may in practice emit NO_x in the range of the reference technology is ~63% of total heavy duty trucks fleet and ~81% of total buses fleet in EU28[42].

[41] Converting emission factors from g/km to g/kWh (and vice versa) is not a straightforward task (it depends on the size/mass of the vehicle, engine used, brake specific fuel consumption, speed, etc). For a very rough estimate, it is assumed that an operating heavy duty vehicle is producing ~3.3kWh of output per litre of fuel consumed. Assuming a typical diesel fuel consumption of 30litres/100km, we have ~1kWh per km. Hence, 1 g/km may be considered to be approximately equal to 1 g/kWh.

[42] EMISIA COPERT data 2013. Available at: http://www.emisia.com/content/copert-data

Table 4-5: Comparison of techniques for NO_x reduction in diesel heavy duty vehicles (trucks, buses)

	BAT candidates for NO_x reduction in diesel heavy duty vehicles (trucks, buses)						
	Technique	"Expected effect"	Cost per vehicle (Euro)	Environmental side effects and synergies (positive	/ negative)	Limitations in applicability	Implementation and other issues
Engine measures	A. Exhaust Gas Recirculation (EGR)	25-45%	400-700 (indicative manufacturer cost)	n.a.	• Slightly reduces engine power • PM recirculation if not combined with a DPF	Electronic control strategy required to ensure operation	• Major engine integration when retrofitted • Exhaust cooling may result in engine wear due to excess water vapour
Aftertreatment	B. Selective Catalytic Reduction (SCR)	70-95%	5k-10k retrofit installation (one-off) +500 urea +200 maintenance -800 possible fuel savings (OEM) per year (*)	• Reduction of PM (20-40%), VOC and CO (50-90%) • 3-5% possible fuel consumption benefits (OEM applications) • Reduction of the characteristic odor produced by a diesel engine and smoke	Risk for "ammonia slip" (careful urea injection strategy and clean-up catalyst required)	• Urea additive must be available • Certain temperature criteria for NO_x reduction to occur (data logging) • Lower efficiency in low-load city driving (low exhaust gas temperatures)	• Requires infrastructure for urea additive • Periodic refilling with urea required (on-board dosing unit) • SCR units are large, heavy, complex and bulky systems
Alternative fuels and powertrain	C. Conversion to natural gas (CNG)	20-50%	12k-15k (one-off for conversion) minus 500-1,000 fuel cost benefits per year	• Reduction of PM and BC (85-95%), NMVOC (75-85%), CO (70-95%) • Lower CO_2 emissions due to lower carbon content	• Low volumetric energy content • Not so effective in PN as DPF • Increase of CH_4 emissions	• Availability of fuel • Gas tank limits storage space and increases vehicle weight • Driving range may decrease (better for urban applications)	• Changes to fueling infrastructure and maintenance facilities maybe required • Limited experience in retrofit long term performance • Truck applications still at experimental scale
	D. Dimethyl ether (DME)	40-60%	Comparable to conventional diesel (**)	• Reduction of PM and BC (85-95%) • Higher volumetric energy content than NG (easier handling for refueling and storage on board the vehicle)	• Increase in fuel consumption (compared to diesel) • Possible higher CH_2O emissions	• Availability of fuel • Production and distribution issues	• General use is difficult and experience is limited • More appropriate for dedicated fleets (e.g. buses) or for use in fuel cells • Leakage problems and poor lubricity due to low viscosity
	E. Emulsified diesel	10-20%	1,200-1,600 per year (***)	Reduction of PM (50-60%)	Decrease in power and fuel economy	Availability of fuel	Over time the water can settle out of the emulsified fuel and may cause performance problems
	F. Renewable diesel	5-10%	Comparable to conventional diesel (**)	• Reduction of PM and BC (15-25%), VOC (20-40%), CO (15-30%) • Free of aromatics, low mutagenic emissions and engine smoke (neat renewable diesel)	Possible increase in fuel consumption	Availability of fuel	• Adjustments in the electronic control of the engine may be required • Additives to address the lubricity issues
	G. Hybridization (off-vehicle or on-vehicle charging)	40-50%	50k-100k marginal cost (one-off) (****) minus 5k-10k energy and maintenance cost benefits per year	• High fuel consumption benefits (especially buses) • Similar decreases in practically all pollutants • Low noise and PM resuspension, especially taking off from bus stops	n.a.	• Recharging necessary for off-vehicle charging vehicles • Driving range may decrease (better for urban applications)	Trucks not at mass production yet

* E.g. assuming 20,000 l of fuel per year, 3% fuel economy because of SCR use, and 1.38 €/l diesel price, fuel savings is 828 €; if AdBlue® is 4% of fuel consumption, and 0.6 €/l is AdBlue® price, the urea cost is 480 €.

** Marginal cost differences compared to conventional diesel may exist, but these do not affect the assessment made here.

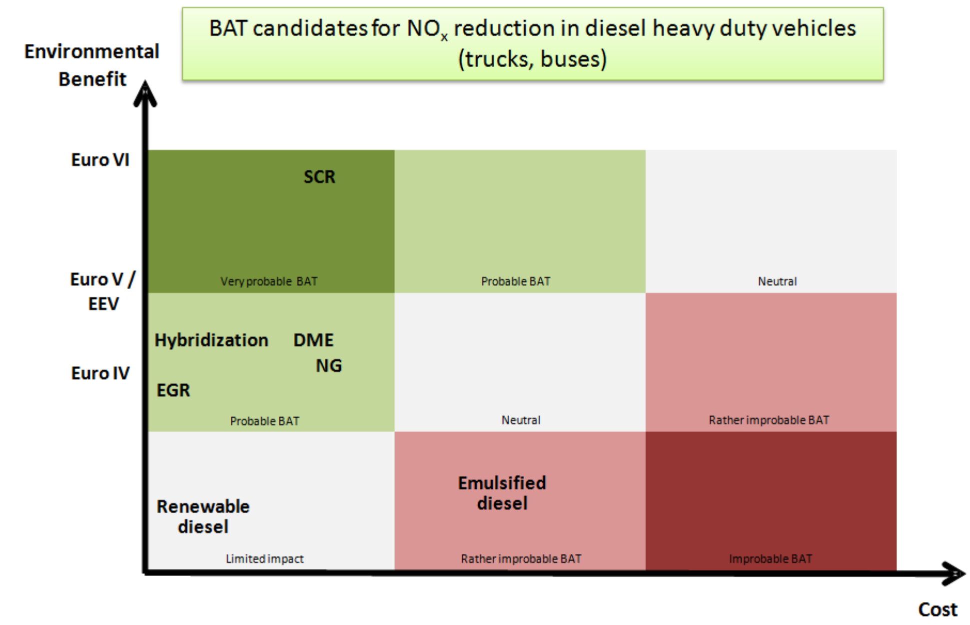
*** E.g. assuming 20,000 l of fuel per year, 20% increase in fuel consumption because of emulsified diesel use, and 0.06 €/l additional fuel cost, the cost of this option is 1,440 € per year.

**** Additional cost required to buy a new hybrid vehicle compared to buying a conventional diesel one in replacement of an older vehicle.

Table 4-6: BAT assessment for NO_x reduction in diesel heavy duty vehicles (trucks, buses)

Relative cost-effectiveness comparison of BAT candidates

Pollutant	NO_x
Application	Diesel HDVs (trucks, buses)
Reference Technology	Turbocharged compression-ignition engine with high-pressure fuel injection
Reference emission level	4-16 g/km
Techniques	SCR Hybridization CNG DME EGR Renewable diesel Emulsified diesel



Summary BAT assessment

SCR	• SCR is a cost-effective technology to reduce NO_x from diesel HDVs (trucks, buses), achieving high % reduction (70-95%). It also reduces PM, VOC, CO. • SCR is ideal for original equipment manufacturer (OEM) applications, providing possible fuel consumption benefits, but retrofit systems are also available and effective. • Urea additive has to be made widely available, since periodic refilling is required (on-board dosing unit). Risk for “ammonia slip” can be controlled with careful urea injection strategy (calibration optimization) or introduction of a clean-up catalyst downstream of the SCR catalyst. • In general, SCR is a BAT having some limitations that need to be taken into account (urea infrastructural needs, lower efficiency in low-load city driving where exhaust gas temperatures are low).
Hybridization	• Hybridization (replacement of old vehicle with a new hybrid one) can reduce NO_x (40-50%) and practically offer similar decrease in most pollutants with additional high fuel consumption benefits. • However, initial capital costs are high, although fuel efficiency improvements may lead to cost benefits in the long run. Recharging for off-vehicle charging (OVC) vehicles is a limiting factor, while the driving range may decrease. • In general, hybridization can be considered as BAT especially for buses. Hybrid trucks are not at mass production yet.
NG[43]	• Conversion of captive fleets to natural gas can lead to some NO_x reduction (20-50%) with additional PM, BC, NMVOC, CO benefits. CO_2 emissions are lower due to lower carbon content. • However, technical complications for conversion to NG, fuel availability, and high initial costs are limiting factors. Moreover, gas tank may limit storage space and increase vehicle weight, while the driving range of the vehicle may decrease. • An environmental side-effect is the increase of CH_4 emissions. • Based on the above, CNG is considered as BAT especially for OEM applications in captive fleets (e.g. buses), providing an alternative energy pathway to oil, that promotes energy security, and offering fuel cost savings because of lower fuel price. NG for truck applications is still at experimental scale and the experience in retrofit long term performance is limited.

[43] The two forms of natural gas, LNG and CNG, differ only in the way that the fuels are stored on board the vehicle. LNG is first vaporized and then injected, in a similar manner to CNG. Therefore, the combustion of the two forms of natural gas is identical and, hence, also results to identical emission profiles.

DME	• DME is a natural gas derivative, offering a similar emission reduction profile to NG. Easier handling for refueling and storage on board the vehicle because of much higher volumetric energy content than CNG. • Its general use is difficult and there is limited experience in DME-fuelled vehicles. It may be more appropriate for dedicated fleets (e.g. buses), where the fuel distribution is easier, or for use in fuel cells. • In general, DME can be considered for diesel replacement in the future, but the issues of production and distribution must be addressed first.
EGR	• EGR exhibits NO_x reduction efficiency of 25-45% which is modest compared to the above options. • It slightly reduces engine power, while exhaust cooling may result in engine wear due to excess water vapor. Major engine integration effort is required when retrofitted. • In general, EGR has limited potential due to technical difficulties integrating this on existing engines.
Renewable diesel	• Renewable diesel offers low NO_x emission reduction (5-10%) with some additional PM, BC, VOC, and CO benefits. The reduction is even lower when used as an additive. Neat renewable diesel is free of aromatics and it produces low mutagenic emissions and engine smoke. • The main issues concerning its use are fuel availability, adjustments in the electronic control of the engine, and additives to address the lubricity issues. • It is evaluated as technique with 'limited impact' because there are better options for significantly higher NO_x reduction.
Emulsified diesel	• Emulsified diesel exhibits low NO_x reduction efficiency (10-20%) with some additional PM benefits; it can be used in any new or existing diesel engine. • However, there is a decrease in power and fuel economy due to the fact that addition of water reduces fuel energy content; this increases the cost of this option in the long run. Fuel availability is also an issue. • It is evaluated as 'rather improbable BAT' technique because the long-term cost is high and there are better options for significantly higher NO_x reduction.

4.1.3.4 PM reduction in diesel heavy duty vehicles (trucks, buses)

Table 4-7 summarizes the different options for PM control in diesel HDVs. The techniques are placed according to their environmental effect and the cost per vehicle in the evaluation grid of Table 4-8. Based on this relative cost-effectiveness comparison and the limitations of each technique, the final evaluation and BAT assessment are performed.

Reference technology

Regarding particulate matter (PM) control in diesel HDVs, we have selected a typical base diesel engine without aftertreatment as a reference technology (turbocharged compression-ignition engine with high-pressure fuel injection). This technology is still met often around the world and is the prominent technology for heavy duty vehicles in least developed countries. Different versions of this reference technology may exist, for example with direct or indirect injection, intercooled or not, etc. Moreover, some of the engines may be equipped with exhaust gas recirculation. However, all these technology variants are relevant for the order of magnitude of PM produced and can all be considered to typically emit in the order of 0.1-0.5 g/km, depending on the size and age of vehicle, driving conditions, speed, etc.

Current usage conditions / popularity of reference technology

The above reference PM emission level corresponds to Euro III and older vehicles (official type-approval) and this seems to be in accordance with emissions in practice (European Environment Agency, 2013a). Hence, the reference technology considered here for BAT assessment is a popular one. A rough estimate of vehicles that may in practice emit PM in the range of the reference technology is ~45% of total heavy duty trucks fleet and ~52% of total buses fleet in EU28[44].

[44] EMISIA COPERT data 2013. Available at: http://www.emisia.com/content/copert-data

Table 4-7: Comparison of techniques for PM reduction in diesel heavy duty vehicles (trucks, buses)

BAT candidates for PM reduction in diesel heavy duty vehicles (trucks, buses)							
	Technique	"Expected effect"	Cost per vehicle (Euro)	Environmental side effects and synergies (positive / negative)		Limitations in applicability	Implementation and other issues
Engine measures	A. Closed Crankcase Ventilation (CCV)	5-15%	250-3,000 retrofit (one-off)	• Reduction of VOC (15-25%) and of engine oil consumption • 80-95% reduction of crankcase emissions • Eliminates odor and toxins from vehicle interior	n.a.	No limitations in applicability	Easy to implement (only filter elements that must be periodically replaced)
Aftertreatment	B. Diesel Particle Filter (DPF)	80-95%	3,000-5,000 retrofit installation (one-off) plus 200-700 additional fuel and maintenance costs per year	Reduction of VOC (85-95%), CO (50-90%), BC	• Fuel economy penalty (1-2%) • NO_2 formation, in particular for catalyzed DPFs	• Ultra Low Sulfur Diesel (ULSD) required <50ppm • High temperatures required for regeneration	• Regeneration and cleaning system needed • Periodic maintenance to clean out non-combustible materials
Aftertreatment	C. Diesel Oxidation Catalyst (DOC)	20-40%	1,500-1,700 retrofit installation (one-off)	Reduction of VOC (40-70%), CO (40-60%)	NO_2 formation	Ultra Low Sulfur Diesel (ULSD) required <50ppm	Easy to install, little or no maintenance required
Alternative fuels and powertrain	D. Conversion to natural gas (CNG)	85-95%	12k-15k (one-off for conversion) minus 500-1,000 fuel cost benefits per year	• Reduction of NO_x (20-50%), NMVOC (75-85%), CO (70-95%), BC • Lower CO_2 emissions due to lower carbon content	• Low volumetric energy content • Not so effective in PN as DPF • Increase of CH_4 emissions	• Availability of fuel • Gas tank limits storage space and increases vehicle weight • Driving range may decrease (better for urban applications)	• Changes to fueling infrastructure and maintenance facilities maybe required • Limited experience in retrofit long term performance • Truck applications still at experimental scale
Alternative fuels and powertrain	E. Dimethyl ether (DME)	85-95%	Comparable to conventional diesel (*)	• Reduction of NO_x (40-60%), BC • Higher volumetric energy content than NG (easier handling for refueling and storage on board the vehicle)	• Increase in fuel consumption (compared to diesel) • Possible higher CH_2O emissions	• Availability of fuel • Production and distribution issues	• General use is difficult and experience is limited • More appropriate for dedicated fleets (e.g. buses) or for use in fuel cells • Leakage problems and poor lubricity due to low viscosity
Alternative fuels and powertrain	F. Emulsified diesel	50-60%	1,200-1,600 per year (**)	Reduction of NO_x (10-20%)	Decrease in power and fuel economy	Availability of fuel	Over time the water can settle out of the emulsified fuel and may cause performance problems
Alternative fuels and powertrain	G. Renewable diesel	15-25%	Comparable to conventional diesel (*)	• Reduction of NO_x (5-10%), VOC (20-40%), CO (15-30%), BC • Free of aromatics, low mutagenic emissions and engine smoke (neat renewable diesel)	Possible increase in fuel consumption	Availability of fuel	• Adjustments in the electronic control of the engine may be required • Additives to address the lubricity issues
Alternative fuels and powertrain	H. Low biodiesel blends (up to B20)	10-15%	Comparable to conventional diesel (*)	• B20: Reduction of VOC (10%), CO (10%) • Proportional reduction of GHGs	• Possible increase in NO_x (2-3%) • Increase in fuel consumption, proportionally to the blend considered	• Current regulations in Europe limit blends to B7 • Higher blends are allowed in controlled captive fleets (e.g. buses)	• More often maintenance necessary • Incompatibility with some older engines

I. Hybridization (off-vehicle or on-vehicle charging)	40-50%	50k-100k marginal cost (one-off) (***) minus 5k-10k energy and maintenance cost benefits per year	• High fuel consumption benefits (especially buses) • Similar decreases in practically all pollutants • Low noise and PM resuspension, especially taking off from bus stops	n.a.	• Recharging necessary for off-vehicle charging vehicles • Driving range may decrease (better for urban applications)	Trucks not at mass production yet

* Marginal cost differences compared to conventional diesel may exist, but these do not affect the assessment made here.

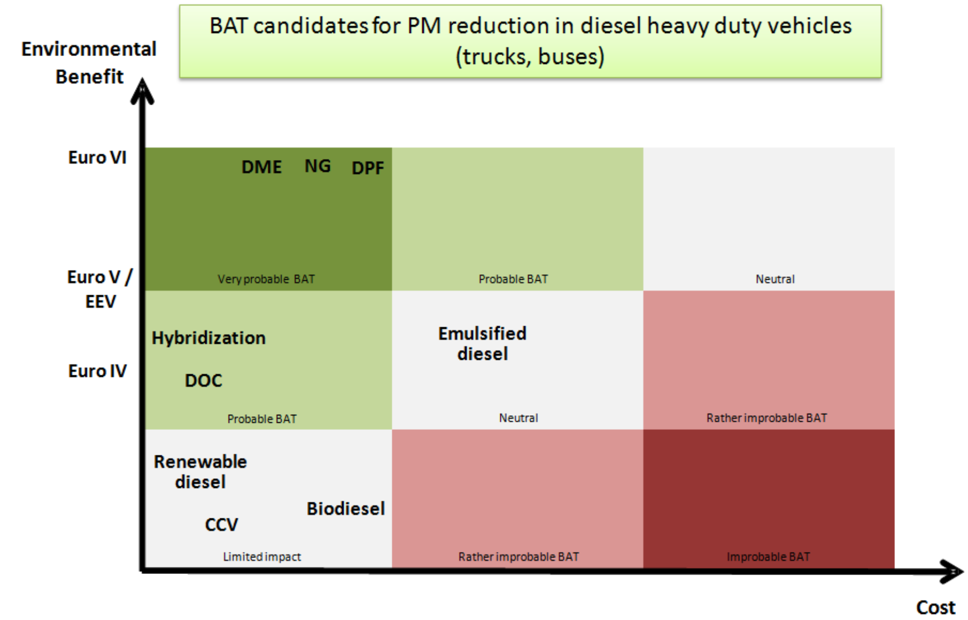
** E.g. assuming 20,000 l of fuel per year, 20% increase in fuel consumption because of emulsified diesel use, and 0.06 €/l additional fuel cost, the cost of this option is 1,440 € per year.

*** Additional cost required to buy a new hybrid vehicle compared to buying a conventional diesel one in replacement of an older vehicle.

Table 4-8: BAT assessment for PM reduction in diesel heavy duty vehicles (trucks, buses)

Relative cost-effectiveness comparison of BAT candidates

Pollutant	PM
Application	Diesel HDVs (trucks, buses)
Reference Technology	Turbocharged compression-ignition engine with high-pressure fuel injection
Reference emission level	0.1-0.5 g/km
Techniques	DPF CNG DME Hybridization DOC Emulsified diesel Renewable diesel Biodiesel CCV



Summary BAT assessment

DPF	• DPF is a cost-effective technology to reduce PM from diesel HDVs (trucks, buses), achieving high % reduction (80-95%). It also reduces BC, VOC, CO. • DPFs are ideal for original equipment manufacturer (OEM) applications, but retrofit systems are also available and effective. • Attention should be given to increase of NO_2 from some DPF implementations (catalyzed DPFs), while there is also a fuel economy penalty (1-2%). • DPF is a BAT when low sulfur fuel (<50ppm) is available. Other operational issues (regeneration at high temperatures and periodic maintenance with cleaning system) are not considered as severe limitations that may prevent its wide applicability.
NG[45]	• Conversion of captive fleets to natural gas can lead to high PM (and BC) reductions (85-95%) with additional NO_x, NMVOC, CO benefits. CO_2 emissions are lower due to lower carbon content. • However, technical complications for conversion to NG, fuel availability, and high initial costs are limiting factors. Moreover, gas tank may limit storage space and increase vehicle weight, while the driving range of the vehicle may decrease. • An environmental side-effect is the increase of CH_4 emissions, while CNG is not so effective in PN as DPF. • Based on the above, CNG is considered as BAT especially for OEM applications in captive fleets (e.g. buses), providing an alternative energy pathway to oil, that promotes energy security, and offering fuel cost savings because of lower fuel price. NG for truck applications is still at experimental scale and the experience in retrofit long term performance is limited.
DME	• DME is a natural gas derivative, offering a similar emission reduction profile to natural gas. Easier handling for refueling and storage on board the vehicle because of much higher volumetric energy content than CNG. • Its general use is difficult and there is limited experience in DME-fuelled vehicles. It may be more appropriate for dedicated fleets (e.g. buses), where the fuel distribution is easier, or for use in fuel cells. • In general, DME can be considered for diesel replacement in the future, but the issues of production and distribution must be addressed first.

[45] The two forms of natural gas, LNG and CNG, differ only in the way that the fuels are stored on board the vehicle. LNG is first vaporized and then injected, in a similar manner to CNG. Therefore, the combustion of the two forms of natural gas is identical and, hence, also results to identical emission profiles.

Hybridization	• Hybridization (replacement of old vehicle with a new hybrid one) can reduce PM (40-50%) and practically offer similar decrease in most pollutants with additional high fuel consumption benefits. Diesel hybrid buses with DPFs or alternative-fuel hybrid buses may lead to additional reductions. • However, initial capital costs are high, although fuel efficiency improvements may lead to cost benefits in the long run. Recharging for off-vehicle charging (OVC) vehicles is a limiting factor, while the driving range may decrease. • In general, hybridization can be considered as BAT especially for buses. Hybrid trucks are not at mass production yet.
DOC	• DOC exhibits PM reduction efficiency of 20-40% which is modest compared to the above options. It also reduces VOC, CO, but there are concerns that it may increase the NO_2 fraction of total NO_x emissions. • It has low installation cost and there are no particular installation limitations or maintenance requirements. • Hence, DOC retrofits may be considered as BAT (especially in large-scale applications), being more tolerant to fuel sulfur than DPF and when other technical factors exclude the applicability of DPFs.
Emulsified diesel	• Emulsified diesel can achieve satisfactory PM reduction (50-60%) with some additional NO_x benefits; it can be used in any new or existing diesel engine. • However, there is a decrease in power and fuel economy due to the fact that addition of water reduces fuel energy content; this increases the cost of this option in the long run. Fuel availability is also an issue. • It is evaluated as 'neutral' technique because there are other more cost-effective options for PM reduction in heavy duty diesel vehicles.
Renewable diesel	• Renewable diesel offers low PM emission reduction (15-25%) with some additional BC, NO_x, VOC, and CO benefits. The reduction is even lower when used as an additive. Neat renewable diesel is free of aromatics and it produces low mutagenic emissions and engine smoke. • The main issues concerning its use are fuel availability, adjustments in the electronic control of the engine, and additives to address the lubricity issues. • It is evaluated as technique with 'limited impact' because there are better options for significantly higher PM reduction.
Biodiesel	• Use of low biodiesel blends reduces PM (10-15%), VOC, CO, and GHGs; it may increase NO_x (2-3%) and fuel consumption, proportionally to the blend considered. • Current regulations in Europe limit blends to B7 and only gradually move towards higher blending ratios. Higher blends are allowed in controlled captive fleets where maintenance intervals and practices, as well as engine materials, can be adjusted to the fuel properties. • It is evaluated as technique with 'limited impact' because there are better options for significantly higher PM reduction.
CCV	• Closed crankcase ventilation is the best option to reduce VOC (and PM) from crankcase emissions of heavy duty diesel road vehicles. If left open, the crankcase from a pre-2007 diesel engine can contribute up to 25% of total VOC (and PM) emissions. CCV eliminates odor and toxins from vehicle interior. • It can be implemented in new vehicles or as retrofit, in combination with a DOC or DPF.

4.1.4 PM from component wear and abrasion

Even if PM exhaust emissions were totally eliminated, transport would still be an issue for air quality and public health due to the emission of non-exhaust PM from component wear and abrasion. Wear particles from brake linings, tyres, road surfaces, and to a lesser extent from other traffic related components, may contribute significantly to total PM emissions. Of particular importance is 'road dust' which is created by the tyre/road contact and makes up most of this non-exhaust PM.

The contribution of non-exhaust sources to PM_{10} and $PM_{2.5}$ ambient concentrations is not easy to quantify; large uncertainties exist in total non-exhaust PM estimates (primary emissions or resuspension). In any case, projections in the future show that wear emissions (PM_{10}) from road traffic will by far exceed exhaust emissions[46].

It should be clarified that inventories include only the primary emissions produced by wear of material. This includes new dust material produced and does not include resuspension of dust, already accumulated on the road, as vehicles pass by. This is of particular importance in identifying measures that are required to reduce emissions. For example, street sweeping has produced mixed results in reducing resuspension; it does, however, not at all address primary emissions. A summary of mitigation measures for wear emissions can be found in Denier van der Gon et al. (2013).

Measures for abatement of wear PM

Wear dust from pavement/tyre interaction is a significant source for PM_{10}. The contribution depends on pavement qualities and use of different tyre types. A generalized road dust emissions model can be found in Berger (2011). There are two directions to follow in order to minimize the negative effects:

i) minimize the sources,

- improvement of pavements and gritting material,
- usage of coarser, wear resistant rock aggregates,
- alternative pavements (porous, rubber mixed, concrete),
- adjustment of tyres,
- avoid using studded tyres,

ii) minimize dispersion to air,

- wet roads reduce resuspension,
- dust binding materials.

Practical trials of dust binding can be found in Gustafsson (2009) for Sweden. Effects of various dust binders ($MgCl_2$, $CaCl_2$, CMA, sugar, CMA/salt) varied between ~20-40% reductions of PM_{10} the day after application. However, a side effect observed was that of reduced friction.

In addition to the above, 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. For example, vehicle speed is a significant controlling factor of road dust emissions; a reduction of speed by 5-10km/h could decrease PM concentrations to a measurable degree. Gentle braking (and accelerations) also produce less wear. In any case, optimal combinations of the above abatement measures are expected to have better emission reduction potential.

---

[46] International Workshop Road Transport Wear Emissions, Amsterdam, June 22, 2011. Workshop report available at: http://slb.nu/slb/rapporter/pdf8/ovr2012_005.pdf

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 recently developed[47] that recuperates particulates generated by brake shoes. The system is purely mechanical and in effect 'vacuums' the particulates produced by the friction of braking. The particulates collected are stored in a casing, which is emptied when the vehicle is serviced. The first vehicles to be fitted with this system may be available from 2016.

Regenerative braking that is increasingly used in both hybrid and conventional cars also results into reduced braking emissions. With regenerative braking, an electrical generator rather than the brake pads is first applied during mild or moderate braking. The generator produces electric energy that is stored in the battery. This improves efficiency by reducing the frequency of operation of the normal alternator of the vehicle. Although this technology explicitly targets the improvement of fuel efficiency, it also has the positive side effect of leading to reduced normal brake use and, as a result, decrease of brake wear related emissions.

[47] http://www.fleeteurope.com/news/brake-particulate-collection-system-developed

4.2 Non-road mobile machinery (NRMM)

4.2.1 Gasoline engines

Gasoline engines for non-road applications 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. The main pollutants of concern emitted by engines of this category are VOC and CO. VOC are the result of incomplete combustion and scavenging losses, mostly due to the widespread utilization of two-stroke engines in this category. Lube oil blending in the fuel is an additional source of hydrocarbons in such engines. CO emissions originate from the rich combustion, which is required to retain low exhaust temperature (safety concerns).

There are also concerns with regard to PM emissions from such engine types. These are mostly a concern for those immediately exposed to their exhaust, such as the operator. The PM contribution of such engines to annual national inventories is limited due to their small numbers and low annual duration of operation. Unlike diesel engines, small spark-ignition engine PM is primarily the result of excess hydrocarbons. Hence, measures aiming at the control of HC are expected to have a direct (and rather proportional) effect to PM as well.

For the purpose of assessing emission reduction techniques, the following two subcategories are considered (Lochmann, 2012; 2014).

- Small handheld engines

  Chainsaws, trimmers, hedge trimmers, blowers, drills, pole pruners, brooms, cork harvesters, olive harvesters, cut off machines, brush cutters (saws), compactors. For this kind of applications, the engine is usually an integral part of the product.

  Reference technology: 2S high speed (11,000-13,000 rpm) gasoline engine without aftertreatment (≤50cm^3), typically emitting up to 400 g/kWh HC+NO_x.

- Ground-supported engines

  Lawn mowers, generators, water pumps, shredders, snow throwers, tillers, vibration plate compactors, concrete cutters. Here, the majority are 4S-engines and the engine is not an integral part of the product.

  Reference technology: 4S low speed (3,200-3,500 rpm) gasoline engine (≥225cm^3), typically emitting up to 70 g/kWh HC+NO_x.

Current usage conditions / popularity of reference technologies: Detailed stock data for non-road gasoline engines in each country do not exist, hence, it is difficult to quantify the contribution of the above reference technologies. An order of magnitude indication is that some tenths of millions of handheld and ground-supported engines in Europe fall within the emission ranges of the reference technologies. This is based on an estimation of the market population in EU15 provided in European Commission JRC (2008) (~44 million units – chainsaws, trimmers, lawn mowers, riding mowers, others). In addition, due to lack of proper market surveillance, many non-compliant products are sold on the EU market, often with no emission certification at all. Non-compliant engines may emit 5-6 times above the legal limits. These high emitters are the biggest threat among engines of this category and with a high emission reduction potential.

The boundary conditions and technical barriers for engines of this category are:

- *Temperature (emission reduction vs. safety):* Retaining a low operating temperature is essential for these applications due to the proximity of operator with the engine but also fire concerns when such engines operate close to dry vegetation. Exhaust catalysts usually increase exhaust and surface temperatures (e.g. in chainsaws, lawn mowers) and may increase the risk of skin burns, melting of materials, and lighting up dry grass. This boundary condition poses a significant limitation on the use of catalysts in these engines (for example, an indicative limit of temperature <246^{o}C is given as a safety threshold). In order to achieve low temperatures, the engine has to operate rich in fuel (λ=0.8), so that excess fuel evaporation decreases the temperature; this solution unavoidably deteriorates fuel economy and increases VOC and CO emissions.

- *Lifetime of equipment:* The useful lifetime of the complete equipment is short compared to other engine categories and NRMM applications. Typical total lifetime values are 30-50h for small handheld engines (expressed as EDP – emission durability period) or typical EDP of 125h for ground-supported engines. The short lifetime means that measures which are applicable to other engine types (such as part replacement or advanced maintenance) may not be applicable to such machinery types.
- *Noise:* The ground-supported engines usually operate in low speeds in order to reduce noise of the application/product. The compliance with the respective noise levels introduces one more technical limitation within engine design.

BAT for in-use engines

The best available techniques to reduce emissions from existing (in-use) gasoline engines used in non-road applications are the following:

a) *Replacement*

The small size of the engines and the boundary conditions described above (short lifetime of equipment, temperature increase with catalyst) make unfavorable the investment in aftertreatment emission control replacement. Hence, complete replacement of the old higher polluting equipment with newer machinery, complying with more stringent emission limits, maybe a ‘best available technique’ in this case.

b) *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 2S-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.

c) *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. Moreover, alkylate gasoline improves the startability and the long term operation of such engines.

BAT for new engines

There are three techniques which can be considered as best available ones to control and reduce emissions from new gasoline engines used in non-road applications. These are engine measures (for manufacturers of the engines) and evaporation control (both for manufacturers and the users).

a) *Improved combustion in 2S engines (with or w/o catalyst)*

Engine measures for 2S engines include stratified scavenging, compression wave injection (CWI), direct injection (DI). These are measures for small handheld engines, e.g. chainsaws and cut off machines (medium-to-high speed multiposition tools and applications). A limitation to consider for these measures is possible increase of cost.

b) *Replacement of 2S engines with 4S or 4S hybrid engines*

Scavenging losses are a significant source of emissions in 2S engines. Therefore, enforcing the replacement of 2S engines with 4S or 4S 'hybrid' ones can be considered BAT for new machinery types, especially in medium-to-low speed applications (e.g. lawn mowers, but also trimmers and cutters). 'Hybrid' engines in this case do not refer to the combination of an internal combustion to an electric engine but to a combination of a four stroke combustion with a two stroke lubrication system. Possible limitations are the increase of cost and weight of the engines.

c) *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 (both for the manufacturers and the users of such engines).

4.2.2 Diesel engines (incl. rail)

4.2.2.1 NO_x reduction in diesel non-road mobile machinery (NRMM) and rail

Table 4-9 summarizes the different options for NO_x control in diesel NRMM and rail. The techniques are placed according to their environmental effect and the cost per vehicle in the evaluation grid of Table 4-10. Based on this relative cost-effectiveness comparison and the limitations of each technique, the final evaluation and BAT assessment are performed.

Reference technology

Regarding nitrogen oxides (NO_x) control in diesel NRMM and rail, we have selected a typical base diesel engine without aftertreatment as a reference technology (conventional compression ignition diesel engine). Different versions of this reference technology may exist, for example with mechanical or electronic injection, turbocharged or not, intercooled or not, etc. Moreover, some of the engines may be equipped with exhaust gas recirculation. However, all these technology variants are relevant for the order of magnitude of NO_x produced and can all be considered to typically emit in the order of 5-15 g/kWh, depending on the size and age of vehicle, driving and operating conditions, speed, etc.

Current usage conditions / popularity of reference technology

The above reference NO_x emission level corresponds to Stage II and older machinery (official type-approval) or even to Stage IIIA for machinery with power range (kW) 19≤P<37. Similar values (with possible slight differences) are also given as baseline emission factors in European Environment Agency (2013c). Due to lack of reliable stock data, it is difficult to quantify the popularity of reference technology considered here for BAT assessment. A rough estimate[48] is that, currently, up to 53% of the global NRMM stock (~22 million – or perhaps even more – units worldwide, ~23% share for Europe) would be suitable for SCR (>56kW). This estimate can be used as an order of magnitude indication of the popularity of the reference technology.

[48] https://www.integer-research.com/market-analysis/emissions-control-in-non-road-mobile-machinery/

Table 4-9: Comparison of techniques for NO_x reduction in diesel non-road mobile machinery (NRMM) and rail

BAT candidates for NO_x reduction in diesel non-road mobile machinery (NRMM) and rail							
	Technique	"Expected effect"	Cost per vehicle (Euro)	Environmental side effects and synergies (positive	/ negative)	Limitations in applicability	Implementation and other issues
Engine measures	A. Exhaust Gas Recirculation (EGR)	25-45%	500-800 (indicative manufacturer cost)	n.a.	• Slightly reduces engine power • PM recirculation if not combined with a DPF	Electronic control strategy required to ensure operation	• Major engine integration when retrofitted • Exhaust cooling may result in engine wear due to excess water vapour
Aftertreatment	B. Selective Catalytic Reduction (SCR)	70-95%	6k-11k retrofit installation (one-off) +500 urea +200 maintenance -800 possible fuel savings (OEM) per year (*)	• Reduction of PM (20-40%), VOC and CO (50-90%) • 3-5% possible fuel consumption benefits (OEM applications) • Reduction of the characteristic odor produced by a diesel engine and smoke	Risk for "ammonia slip" (careful urea injection strategy and clean-up catalyst required)	• Urea additive must be available (infrastructure required) • Certain temperature criteria for NO_x reduction to occur (data logging) • Lower efficiency in low exhaust gas temperatures	• Periodic refilling with urea required • SCR units are large, heavy, complex and bulky systems • NRMM environment: wider angles of operation, tougher vibrations, dust and dirt, fast stop and go movements
Alternative fuels and powertrain	C. Conversion to natural gas (CNG/LNG)	20-50%	13k-16k (one-off for conversion) minus 500-1,000 fuel cost benefits per year	• Reduction of PM and BC (85-95%), NMVOC (75-85%), CO (70-95%) • Lower CO_2 emissions due to lower carbon content	• Low volumetric energy content (especially CNG) • Not so effective in PN as DPF • Increase of CH_4 emissions	• Availability of fuel • Unsuitable for many off-highway applications (increase of weight because of tank size) • Driving range may decrease	• May require significant changes to fueling infrastructure and maintenance facilities • Limited experience as a retrofit and in train applications
	D. Dimethyl ether (DME)	40-60%	Comparable to conventional diesel (**)	• Reduction of PM and BC (85-95%) • Higher volumetric energy content than NG (easier handling for refueling and storage on board the vehicle)	• Increase in fuel consumption (compared to diesel) • Possible higher CH_2O emissions	• Availability of fuel • Production and distribution issues	• General use is difficult and experience is limited • More appropriate for dedicated fleets • Leakage problems and poor lubricity due to low viscosity
	E. Emulsified diesel	10-20%	1,200-1,600 per year (***)	Reduction of PM (50-60%)	Decrease in power and fuel economy	Availability of fuel	Over time the water can settle out of the emulsified fuel and may cause performance problems
	F. Renewable diesel	5-10%	Comparable to conventional diesel (**)	• Reduction of PM and BC (15-25%), VOC (20-40%), CO (15-30%) • Free of aromatics, low mutagenic emissions and engine smoke (neat renewable diesel)	Possible increase in fuel consumption	Availability of fuel	• Adjustments in the electronic control of the engine may be required • Additives to address the lubricity issues
	G. Hybridization (off-vehicle or on-vehicle charging)	40-50%	50k-100k marginal cost (one-off) (****) minus 5k-10k energy and maintenance cost benefits per year	• High fuel consumption benefits • Similar decreases in practically all pollutants • Low noise and PM resuspension	n.a.	• Recharging necessary for off-vehicle charging machinery • Driving range may decrease	Limited experience

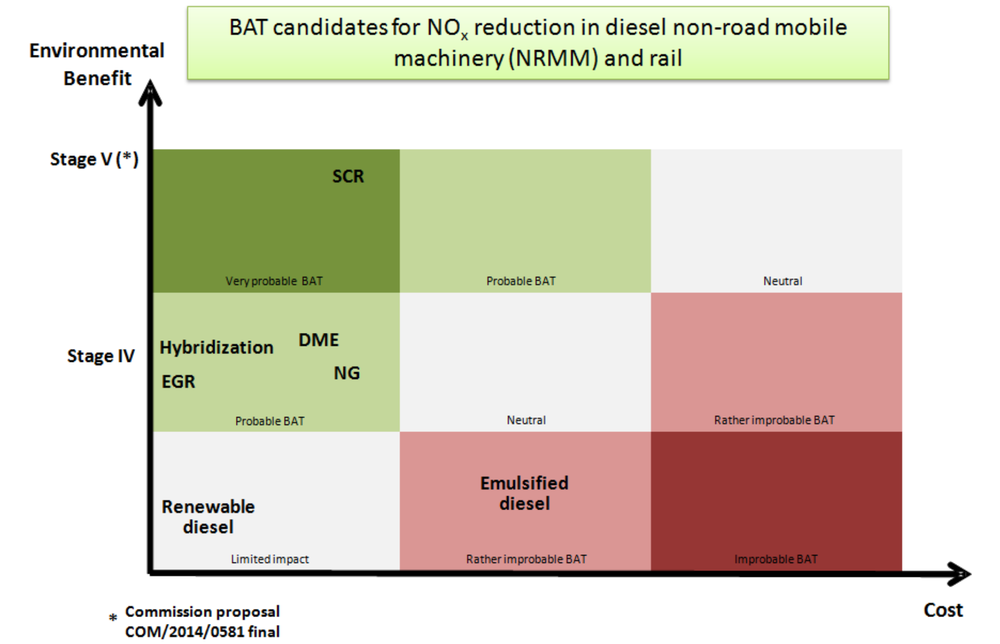
* E.g. assuming 20,000 l of fuel per year, 3% fuel economy because of SCR use, and 1.38 €/l diesel price, fuel savings is 828 €; if AdBlue® is 4% of fuel consumption, and 0.6 €/l is AdBlue® price, the urea cost is 480 €.

** Marginal cost differences compared to conventional diesel may exist, but these do not affect the assessment made here.

*** E.g. assuming 20,000 l of fuel per year, 20% increase in fuel consumption because of emulsified diesel use, and 0.06 €/l additional fuel cost, the cost of this option is 1,440 € per year.

**** Additional cost required to buy new hybrid machinery compared to buying conventional diesel one in replacement of older machinery.

Table 4-10: BAT assessment for NO_x reduction in diesel non-road mobile machinery (NRMM) and rail

<table>
<tr><th colspan="3">Relative cost-effectiveness comparison of BAT candidates</th></tr>
<tr><td>Pollutant</td><td>NO_x</td><td rowspan="5">
</td></tr>
<tr><td>Application</td><td>Diesel NRMM and rail</td></tr>
<tr><td>Reference Technology</td><td>Conventional compression ignition diesel engine</td></tr>
<tr><td>Reference emission level</td><td>5-15 g/kWh</td></tr>
<tr><td>Techniques</td><td>SCR
Hybridization
NG
DME
EGR
Renewable diesel
Emulsified diesel</td></tr>
<tr><th colspan="3">Summary BAT assessment</th></tr>
<tr><td>SCR</td><td colspan="2">• SCR is a cost-effective technology to reduce NO_x from diesel NRMM and rail, achieving high % reduction (70-95%). It also reduces PM, VOC, CO.
• SCR is ideal for original equipment manufacturer (OEM) applications, providing possible fuel consumption benefits, but retrofit systems are also available and effective.
• Urea additive has to be made widely available, since periodic refilling is required (on-board dosing unit). Risk for “ammonia slip” can be controlled with careful urea injection strategy (calibration optimization) or introduction of a clean-up catalyst downstream of the SCR catalyst.
• In general, SCR is a BAT having some limitations that need to be taken into account (urea infrastructural needs, lower efficiency in low-loads where exhaust gas temperatures are low).</td></tr>
<tr><td>Hybridization</td><td colspan="2">• Hybridization (replacement of old machinery with new hybrid ones) can reduce NO_x (40-50%) and practically offer similar decrease in most pollutants with additional high fuel consumption benefits.
• However, initial capital costs are high, although fuel efficiency improvements may lead to cost benefits in the long run. Recharging for off-vehicle charging (OVC) machinery is a limiting factor, while the driving range may decrease.
• In general, hybridization can be considered as BAT with potential to be further established in the future. Currently, the technology is not at mass production yet and the experience is limited.</td></tr>
<tr><td>NG[49]</td><td colspan="2">• Conversion to natural gas can lead to some NO_x reduction (20-50%) with additional PM, BC, NMVOC, CO benefits. CO_2 emissions are lower due to lower carbon content.
• However, technical complications for conversion to NG, fuel availability, and high initial costs are limiting factors. Moreover, gas tanks may prohibitively increase vehicle weight.
• An environmental side-effect is the increase of CH_4 emissions.
• Based on the above, NG can be considered as BAT especially for OEM applications, providing an alternative energy pathway to oil, that promotes energy security, and offering fuel cost savings because of lower fuel price. However, the experience is limited as a retrofit and in train applications.</td></tr>
</table>

[49] The two forms of natural gas, LNG and CNG, differ only in the way that the fuels are stored on board the vehicle. LNG is first vaporized and then injected, in a similar manner to CNG. Therefore, the combustion of the two forms of natural gas is identical and, hence, also results to identical emission profiles.

DME	• DME is a natural gas derivative, offering a similar emission reduction profile to NG. Easier handling for refueling and storage on board the vehicle because of much higher volumetric energy content than natural gas (especially CNG). • Its general use is difficult and there is limited experience in DME-fuelled vehicles. It may be more appropriate for dedicated fleets, where the fuel distribution is easier. • In general, DME can be considered for diesel replacement in the future, but the issues of production and distribution must be addressed first.
EGR	• EGR exhibits NO_x reduction efficiency of 25-45% which is modest compared to the above options. • It slightly reduces engine power, while exhaust cooling may result in engine wear due to excess water vapor. Major engine integration effort is required when retrofitted. • In general, EGR has limited potential due to technical difficulties integrating this on existing engines.
Renewable diesel	• Renewable diesel offers low NO_x emission reduction (5-10%) with some additional PM, BC, VOC, and CO benefits. The reduction is even lower when used as an additive. Neat renewable diesel is free of aromatics and it produces low mutagenic emissions and engine smoke. • The main issues concerning its use are fuel availability, adjustments in the electronic control of the engine, and additives to address the lubricity issues. • It is evaluated as technique with 'limited impact' because there are better options for significantly higher NO_x reduction.
Emulsified diesel	• Emulsified diesel exhibits low NO_x reduction efficiency (10-20%) with some additional PM benefits; it can be used in any new or existing diesel engine. • However, there is a decrease in power and fuel economy due to the fact that addition of water reduces fuel energy content; this increases the cost of this option in the long run. Fuel availability is also an issue. • It is evaluated as 'rather improbable BAT' technique because the long-term cost is high and there are better options for significantly higher NO_x reduction.

4.2.2.2 PM reduction in diesel non-road mobile machinery (NRMM) and rail

Table 4-11 summarizes the different options for PM control in diesel NRMM and rail. The techniques are placed according to their environmental effect and the cost per vehicle in the evaluation grid of Table 4-12. Based on this relative cost-effectiveness comparison and the limitations of each technique, the final evaluation and BAT assessment are performed.

Reference technology

Regarding particulate matter (PM) control in diesel NRMM and rail, we have selected a typical base diesel engine without aftertreatment as a reference technology (conventional compression ignition diesel engine). Different versions of this reference technology may exist, for example with mechanical or electronic injection, turbocharged or not, intercooled or not, etc. Moreover, some of the engines may be equipped with exhaust gas recirculation. However, all these technology variants are relevant for the order of magnitude of PM produced and can all be considered to typically emit in the order of 0.2-1.0 g/kWh, depending on the size and age of vehicle, driving and operating conditions, speed, etc.

Current usage conditions / popularity of reference technology

The above reference PM emission level corresponds to Stage IIIA and older machinery (official type-approval). Similar values (with possible slight differences) are also given as baseline emission factors in European Environment Agency (2013c). Due to lack of reliable stock data, it is difficult to quantify the popularity of reference technology considered here for BAT assessment. A rough estimate is that a large fraction of the global NRMM stock (estimated ~22 million – or perhaps even more – units worldwide, ~23% share for Europe)[50] would be suitable for DPF to meet the PM limit of 0.025 g/kWh (Stage IIIB); in reality, a significant proportion of engines were able to meet previous PM limit through in-cylinder technologies, without filters[51]. This estimate can be used as an order of magnitude indication of the popularity of reference technology.

[50] https://www.integer-research.com/market-analysis/emissions-control-in-non-road-mobile-machinery/

[51] http://dieselnet.com/standards/eu/nonroad.php

Table 4-11: Comparison of techniques for PM reduction in diesel non-road mobile machinery (NRMM) and rail

	BAT candidates for PM reduction in diesel non-road mobile machinery (NRMM) and rail								
		Technique	"Expected effect"	Cost per vehicle (Euro)	Environmental side effects and synergies (positive / negative)		Limitations in applicability	Implementation and other issues
Engine measures	A.	Closed Crankcase Ventilation (CCV)	5-15%	250-3,000 retrofit (one-off)	• Reduction of VOC (15-25%) and of engine oil consumption • 80-95% reduction of crankcase emissions • Eliminates odor and toxins from vehicle interior	n.a.	No limitations in applicability	Easy to implement (only filter elements that must be periodically replaced)
Aftertreatment	B.	Diesel Particle Filter (DPF)	80-95%	4,000-7,000 retrofit installation (one-off) plus 200-700 additional fuel and maintenance costs per year	Reduction of VOC (85-95%), CO (50-90%), BC	• Fuel economy penalty (1-2%) • NO_2 formation, in particular for catalyzed DPFs	• Ultra Low Sulfur Diesel (ULSD) required <50ppm • High temperatures required for regeneration	• Regeneration and cleaning system needed • Periodic maintenance to clean out non-combustible materials
Aftertreatment	C.	Diesel Oxidation Catalyst (DOC)	20-40%	1,500-2,500 retrofit installation (one-off)	Reduction of VOC (40-70%), CO (40-60%)	NO_2 formation	Ultra Low Sulfur Diesel (ULSD) required <50ppm	Easy to install, little or no maintenance required
Alternative fuels and powertrain	D.	Conversion to natural gas (CNG/LNG)	85-95%	13k-16k (one-off for conversion) minus 500-1,000 fuel cost benefits per year	• Reduction of NO_x (20-50%), NMVOC (75-85%), CO (70-95%), BC • Lower CO_2 emissions due to lower carbon content	• Low volumetric energy content (especially CNG) • Not so effective in PN as DPF • Increase of CH_4 emissions	• Availability of fuel • Unsuitable for many off-highway applications (increase of weight because of tank size) • Driving range may decrease	• May require significant changes to fueling infrastructure and maintenance facilities • Limited experience as a retrofit and in train applications
Alternative fuels and powertrain	E.	Dimethyl ether (DME)	85-95%	Comparable to conventional diesel (*)	• Reduction of NO_x (40-60%), BC • Higher volumetric energy content than NG (easier handling for refueling and storage on board the vehicle)	• Increase in fuel consumption (compared to diesel) • Possible higher CH_2O emissions	• Availability of fuel • Production and distribution issues	• General use is difficult and experience is limited • More appropriate for dedicated fleets • Leakage problems and poor lubricity due to low viscosity
Alternative fuels and powertrain	F.	Emulsified diesel	50-60%	1,200-1,600 per year (**)	Reduction of NO_x (10-20%)	Decrease in power and fuel economy	Availability of fuel	Over time the water can settle out of the emulsified fuel and may cause performance problems
Alternative fuels and powertrain	G.	Renewable diesel	15-25%	Comparable to conventional diesel (*)	• Reduction of NO_x (5-10%), VOC (20-40%), CO (15-30%), BC • Free of aromatics, low mutagenic emissions and engine smoke (neat renewable diesel)	Possible increase in fuel consumption	Availability of fuel	• Adjustments in the electronic control of the engine may be required • Additives to address the lubricity issues
Alternative fuels and powertrain	H.	Low biodiesel blends (up to B20)	10-15%	Comparable to conventional diesel (*)	• B20: Reduction of VOC (10%), CO (10%) • Proportional reduction of GHGs	• Possible increase in NO_x (2-3%) • Increase in fuel consumption, proportionally to the blend considered	• Current regulations in Europe limit blends to B7 • Higher blends are allowed in controlled captive fleets (e.g. buses)	• More often maintenance necessary • Incompatibility with some older engines

I. Hybridization (off-vehicle or on-vehicle charging)	40-50%	50k-100k marginal cost (one-off) (***) minus 5k-10k energy and maintenance cost benefits per year	• High fuel consumption benefits • Similar decreases in practically all pollutants • Low noise and PM resuspension	n.a.	• Recharging necessary for off-vehicle charging machinery • Driving range may decrease	Limited experience

* Marginal cost differences compared to conventional diesel may exist, but these do not affect the assessment made here.

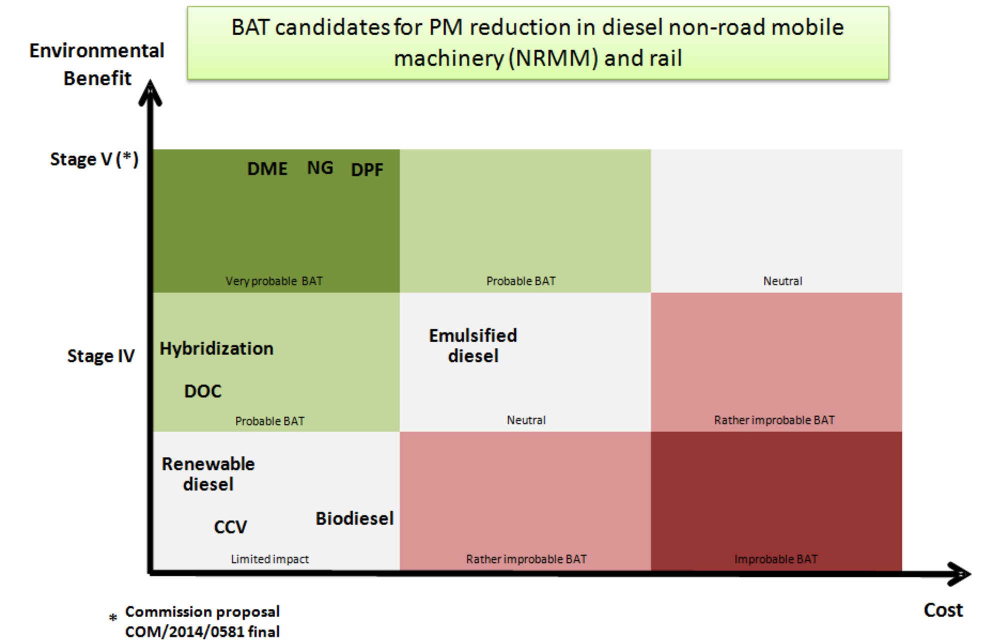
** E.g. assuming 20,000 l of fuel per year, 20% increase in fuel consumption because of emulsified diesel use, and 0.06 €/l additional fuel cost, the cost of this option is 1,440 € per year.

*** Additional cost required to buy new hybrid machinery compared to buying conventional diesel one in replacement of older machinery.

Table 4-12: BAT assessment for PM reduction in diesel non-road mobile machinery (NRMM) and rail

Relative cost-effectiveness comparison of BAT candidates

Pollutant	PM
Application	Diesel NRMM and rail
Reference Technology	Conventional compression ignition diesel engine
Reference emission level	0.2-1.0 g/kWh
Techniques	DPF NG DME Hybridization DOC Emulsified diesel Renewable diesel Biodiesel CCV



Summary BAT assessment

DPF	• DPF is a cost-effective technology to reduce PM from diesel NRMM and rail, achieving high % reduction (80-95%). It also reduces BC, VOC, CO. • There are many successful examples of implementation and, in general, it is ideal for original equipment manufacturer (OEM) applications, while retrofit systems are also available and effective. • Attention should be given to increase of NO_2 from some DPF implementations (catalyzed DPFs), while there is also a fuel economy penalty (1-2%). • DPF is a BAT when low sulfur fuel (<50ppm) is available. Other operational issues (regeneration at high temperatures and periodic maintenance with cleaning system) are not considered as severe limitations that may prevent its wide applicability.
NG[52]	• Conversion to natural gas can lead to high PM (and BC) reductions (85-95%) with additional NO_x, NMVOC, CO benefits. CO_2 emissions are lower due to lower carbon content. • However, technical complications for conversion to NG, fuel availability, and high initial costs are limiting factors. Moreover, gas tanks may prohibitively increase vehicle weight. • An environmental side-effect is the increase of CH_4 emissions, while NG is not so effective in PN as DPF. • Based on the above, NG can be considered as BAT especially for OEM applications, providing an alternative energy pathway to oil, that promotes energy security, and offering fuel cost savings because of lower fuel price. However, the experience is limited as a retrofit and in train applications.
DME	• DME is a natural gas derivative, offering a similar emission reduction profile to NG. Easier handling for refueling and storage on board the vehicle because of much higher volumetric energy content than natural gas (especially CNG). • Its general use is difficult and there is limited experience in DME-fuelled vehicles. It may be more appropriate for dedicated fleets, where the fuel distribution is easier. • In general, DME can be considered for diesel replacement in the future, but the issues of production and distribution must be addressed first.

52 The two forms of natural gas, LNG and CNG, differ only in the way that the fuels are stored on board the vehicle. LNG is first vaporized and then injected, in a similar manner to CNG. Therefore, the combustion of the two forms of natural gas is identical and, hence, also results to identical emission profiles.

Hybridization	• Hybridization (replacement of old machinery with new hybrid ones) can reduce PM (40-50%) and practically offer similar decrease in most pollutants with additional high fuel consumption benefits. Diesel hybrid machinery with DPFs may lead to additional reductions. • However, initial capital costs are high, although fuel efficiency improvements may lead to cost benefits in the long run. Recharging for off-vehicle charging (OVC) machinery is a limiting factor, while the driving range may decrease. • In general, hybridization can be considered as BAT with potential to be further established in the future. Currently, the technology is not at mass production yet and the experience is limited.
DOC	• DOC exhibits PM reduction efficiency of 20-40%, which is modest compared to the above options. It also reduces VOC, CO, but there are concerns that it may increase the NO_2 fraction of total NO_x emissions. • It has low installation cost and there are no particular installation limitations or maintenance requirements. • Hence, DOC retrofits may be considered as BAT (especially in large-scale applications), being more tolerant to fuel sulfur than DPF and when other technical factors exclude the applicability of DPFs.
Emulsified diesel	• Emulsified diesel can achieve satisfactory PM reduction (50-60%) with some additional NO_x benefits; it can be used in any new or existing diesel engine. • However, there is a decrease in power and fuel economy due to the fact that addition of water reduces fuel energy content; this increases the cost of this option in the long run. Fuel availability is also an issue. • It is evaluated as 'neutral' technique because there are other more cost-effective options for PM reduction in diesel NRMM and rail.
Renewable diesel	• Renewable diesel offers low PM emission reduction (15-25%) with some additional BC, NO_x, VOC, and CO benefits. The reduction is even lower when used as an additive. Neat renewable diesel is free of aromatics and it produces low mutagenic emissions and engine smoke. • The main issues concerning its use are fuel availability, adjustments in the electronic control of the engine, and additives to address the lubricity issues. • It is evaluated as technique with 'limited impact' because there are better options for significantly higher PM reduction.
Biodiesel	• Use of low biodiesel blends reduces PM (10-15%), VOC, CO, and GHGs; it may increase NO_x (2-3%) and fuel consumption, proportionally to the blend considered. • Current regulations in Europe limit blends to B7 and only gradually move towards higher blending ratios. Higher blends are allowed in controlled captive fleets where maintenance intervals and practices, as well as engine materials, can be adjusted to the fuel properties. • It is evaluated as technique with 'limited impact' because there are better options for significantly higher PM reduction.
CCV	• Closed crankcase ventilation is the best option to reduce VOC (and PM) from crankcase emissions of diesel non-road mobile machinery. If left open, the crankcase from a pre-2007 diesel engine can contribute up to 25% of total VOC (and PM) emissions. CCV eliminates odor and toxins from vehicle interior. • It can be implemented in new vehicles or as retrofit, in combination with a DOC or DPF.

4.3 Waterborne transport

4.3.1 Gasoline boats and recreational crafts

The majority of spark-ignition engines for boats and recreational crafts are outboard engines (~120,000 sales in the European region in 2013). Inboard engines correspond to a much smaller fraction of the total market (~2,000 sales in 2013). Legacy outboard engines have been of the two-stroke combustion concept, to benefit from the high power to weight ratio of the particular type. Current regulatory and market developments have shifted the technology mostly to four-stroke engines with the few two stroke models remaining being equipped with electronic fuel injection. The typical use of such engines is ~40-45 h/year with a total lifetime of approximately 10 years.

Emission standards require manufacturers to control exhaust emissions from these engines. In US, evaporative emissions from fuel tanks and fuel lines are also controlled[53]. Marine engines are limited in terms of their exhaust configuration, so that water injection is mandatory to reduce their exhaust temperature and for noise attenuation. Spark ignition marine engines are currently regulated by Directive 2003/44/EC and from January 2016 by Directive 2013/53/EU with applicable emission limits varying, depending on the size (power of the engine), currently the emission application (two stroke vs. four stroke), and from 2016 by engine type (outboard, personal watercraft, or inboard).

Emission control

Emission control is less advanced than in spark-ignition engines used in on-road applications because of various limiting factors, including low maximum operation temperature, noise control, and relatively short total lifetime. Rapid cooling of the engine exhaust with water injection in outboard engines for noise and temperature control makes catalytic aftertreatment technically challenging. The recent shift to four stroke engines and use of fuel injection in two stroke ones has led to significant reduction of VOC emissions.

Evaporation control

Evaporation losses are significant contributors to total VOC emissions. The rather simplistic fuel system and the use of carburettor (on engines less than 40hp) lead to relatively high fuel evaporation. Therefore, usage of low permeability tanks and fuel lines is recommended 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.

BAT options for gasoline marine engines

The simple emission control system and the limited total lifetime[54] of these engines offer little possibilities for substantial emission reductions. General rules that can be followed to retain the emission performance of these engines within their designed targets include:

a) *Use of lubrication oil of good quality*

Use of good quality (approved by the manufacturer) marine lubrication oil is important and enforcing the use of manufacturer recommended oils rather than cheap alternatives can be considered a good practice for these engines.

---

[53] http://www.epa.gov/otaq/marinesi.htm

[54] Inboards: 480h or 10yrs, PWC: 350h or 5yrs, outboards: 350h or 10yrs (Dir 2003/44/EC Annex1.B.3)

b) *Keeping the maintenance schedule*

Maintenance of the engines by professionals and respecting the measurement schedule of the manufacturer improves performance, including pollutants production.

In general, boats and watercrafts are mostly on the sea or larger lakes, hence, specific local VOC air quality issues are not expected. For example, even on a busy summer day most marinas may have ~80% of the boats on their mooring. In any case, controlling the accessibility of marine spark ignition engines, in particular during the summer season (maximum sunlight), could alleviate part of any possibly existing VOC problem. However, such measures are difficult to enforce and to receive acceptance within local communities.

4.3.2 Diesel vessels

4.3.2.1 NO_x reduction in diesel vessels

Table 4-13 summarizes the different options for NO_x control in diesel vessels. The techniques are placed according to their environmental effect and the cost per vessel in the evaluation grid of Table 4-14. Based on this relative cost-effectiveness comparison and the limitations of each technique, the final evaluation and BAT assessment are performed.

Reference technology

Regarding nitrogen oxides (NO_x) control in diesel vessels, we have selected a typical base diesel engine without aftertreatment as a reference technology (conventional compression ignition diesel engine). Different versions of this reference technology may exist, for example with mechanical or electronic injection, turbocharged or not, etc. However, all these technology variants are relevant for the order of magnitude of NO_x produced and can all be considered to typically emit in the order of 10-20 g/kWh, depending on the size and design of the ship, rated engine speed (crankshaft rpm), fuel used, etc.

Current usage conditions / popularity of reference technology

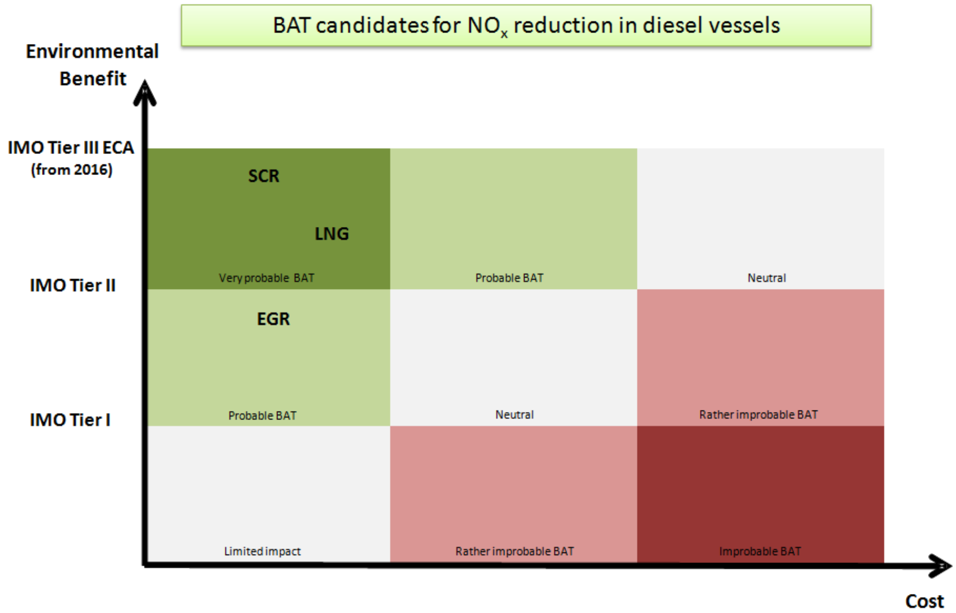
The above reference NO_x emission level corresponds to IMO Tier I, Global 2000 (or IMO Tier II, Global 2011, depending on rated engine speed) and older vessels. Similar values in this range for NO_x emission factors can also be found in European Environment Agency (2013d). Due to lack of reliable stock data, it is difficult to quantify the popularity of reference technology considered here for BAT assessment. A rough estimate is that the majority of diesel vessels can be considered as candidates for the emission reduction techniques presented below. Especially with the most stringent NO_x legislation, IMO Tier III for ECAs (Emission Control Areas), which will be enforced from 2016, it is claimed that demands for NO_x reduction may be difficult to reach without using “end of pipe” abatement technology (Brynolf, 2014).

Table 4-13: Comparison of techniques for NO_x reduction in diesel vessels

	BAT candidates for NO_x reduction in diesel vessels						
	Technique	"Expected effect"	Cost per vessel (Euro)	Environmental side effects and synergies (positive	/ negative)	Limitations in applicability	Implementation and other issues
Engine measures	A. Exhaust Gas Recirculation (EGR) for ships	25-80%	• 300k-2m capital cost (usually higher than SCR) depending on ship size • Operation cost lower than SCR	n.a.	• Slightly reduces engine power (possible fuel penalty 1-2%) • PM and SO_x recirculation if not combined with a DPF or SO_x scrubber	• Not a mature technology for ships • Many drawbacks and limited use as retrofit (major engine integration required)	• Risk of increased maintenance requirements • Electronic control strategy required to ensure operation • Unlike SCR, low-load operation is not a constraining factor
Aftertreatment	B. Selective Catalytic Reduction (SCR)	70-95%	600k capital cost (one-off) +80k urea +25k maintenance -20k possible fuel savings (OEM) per year (*)	• Reduction of PM (20-40%), VOC and CO (50-90%) • 2-4% possible fuel consumption benefits (OEM applications) • Reduction of the characteristic odor produced by a diesel engine and smoke	Risk for "ammonia slip" (careful urea injection strategy and clean-up catalyst required)	• Urea additive must be available • Certain temperature criteria for NO_x reduction to occur (data logging) • Efficiency issues in low-loads (<25%) and during slow steaming	• Requires infrastructure for urea additive • Periodic refilling with urea required (on-board dosing unit) • SCR units are large, heavy, complex and bulky systems
Cleaner fuels	C. Conversion to natural gas (LNG)	50-85%	• 500k-5.5m capital cost (one-off) • Possible fuel cost benefits (compared to HFO and MGO)	• Reduction of PM and BC (75-95%), SO_x (90-100%), NMVOC (75-85%) • Lower CO_2 emissions due to lower carbon content	Increase of CH_4 emissions	• Availability of fuel • Gas tanks may limit vessel storage space • Retrofitting requires substantial modifications	• Refueling infrastructure must be expanded • Heavy and highly insulated fuel tanks required to retain fuel at the desired temperature (liquid form)

* More info (detailed SCR cost calculation model) can be found at http://www.iaccsea.com/scr-cost-model/ by IACCSEA.

Table 4-14: BAT assessment for NO_x reduction in diesel vessels

Relative cost-effectiveness comparison of BAT candidates		
Pollutant	NO_x	
Application	Diesel vessels	
Reference Technology	Conventional compression ignition diesel engine	
Reference emission level	10-20 g/kWh	
Techniques	SCR LNG EGR	

Summary BAT assessment	
SCR	• SCR is a cost-effective technology to reduce NO_x from diesel vessels, achieving high % reduction (70-95%). It also reduces PM, VOC, CO. • SCR is ideal for original equipment manufacturer (OEM) applications, providing possible fuel consumption benefits, but retrofit systems are also available and effective. • Urea additive has to be made widely available, since periodic refilling is required (on-board dosing unit). Risk for “ammonia slip” can be controlled with careful urea injection strategy (calibration optimization) or introduction of a clean-up catalyst downstream of the SCR catalyst. • In general, SCR is a BAT having some limitations that need to be taken into account (urea infrastructural needs, lower efficiency in low-loads <25% and during slow steaming where exhaust gas temperatures are low).
LNG	• Conversion of a ship to run on natural gas (LNG) can lead to NO_x reduction (50-85%) with additional PM, BC, SO_x, NMVOC benefits. CO_2 emissions are lower due to lower carbon content. • However, technical complications for conversion to NG, fuel availability, and high initial capital costs for conversion are limiting factors. Moreover, gas tanks may limit vessel storage space and increase weight. • An environmental side-effect is the increase of CH_4 emissions. • Based on the above, LNG can be considered as BAT especially for OEM applications, providing an alternative energy pathway to oil, that promotes energy security, and offering possible fuel cost savings because of lower fuel price. As a retrofit, substantial modifications are required and the experience is limited.
EGR	• EGR in diesel vessels can achieve NO_x reduction efficiency of 25-80% which is generally higher than in road vehicles. The initial capital cost is usually higher than SCR, but the operation cost is lower. • It slightly reduces engine power (with possible fuel penalty), but it has the advantage over SCR that low-load operation is not a constraining factor. • In general, EGR for ships is not a mature technology yet and there are many drawbacks and limited use as retrofit (major engine integration effort required).

4.3.2.2 PM and SO_x reduction in diesel vessels

Table 4-15 summarizes the different options for PM and SO_x control in diesel vessels. The techniques are placed according to their environmental effect and the cost per vessel in the evaluation grid of Table 4-16. Based on this relative cost-effectiveness comparison and the limitations of each technique, the final evaluation and BAT assessment are performed.

Reference technology

Regarding particulate matter (PM) and sulfur oxides (SO_x) control in diesel vessels, we have selected a typical base diesel engine without aftertreatment as a reference technology (conventional compression ignition diesel engine), operating on heavy fuel oil. Different versions of this reference technology may exist, for example with mechanical or electronic injection, turbocharged or not, etc. However, all these technology variants are relevant for the order of magnitude of PM and SO_x produced and can all be considered to typically emit in the order of 0.5-2.0 g/kWh (PM) and 10-20 g/kWh (SO_x), depending on the size and design of the ship, rated engine speed (crankshaft rpm), fuel specifications and in particular sulfur content, etc.

Current usage conditions / popularity of reference technology

The above reference PM and SO_x emission levels correspond to vessels operating on HFO without specific measures to control SO_x emissions (e.g. with low sulfur fuel or scrubbers), hence, do not comply with latest SO_x requirements (ECA or Global). Due to lack of reliable stock data, it is difficult to precisely quantify the popularity of this reference technology and the percentage of stock operating on HFO, considered here for BAT assessment. Nevertheless, the large majority of deep-sea vessels can generally be considered as candidates for the emission reduction techniques presented to reduce PM and SO_x emission levels.

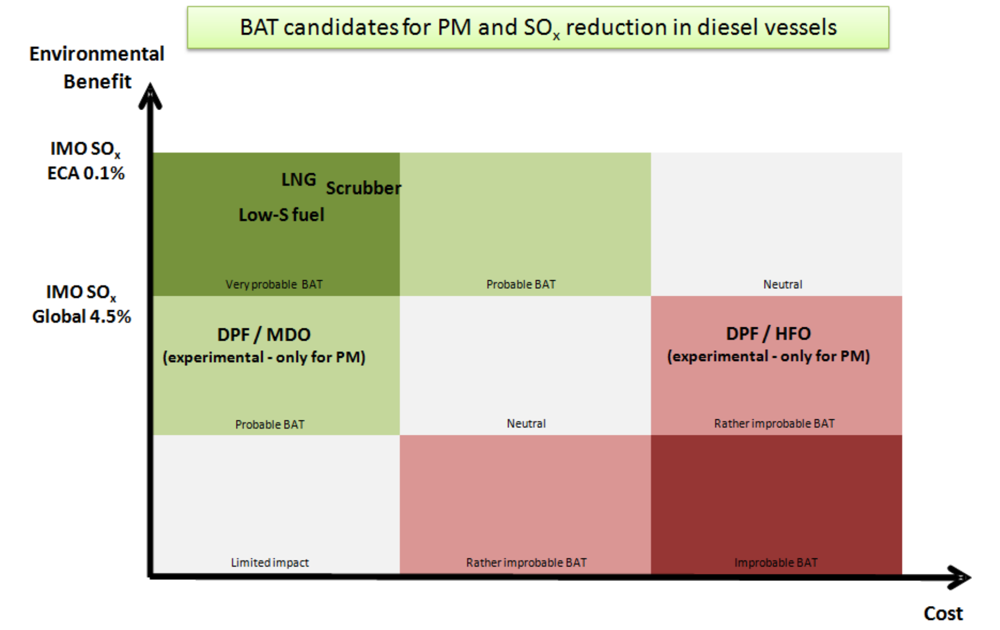
Table 4-15: Comparison of techniques for PM and SO_x reduction in diesel vessels

	BAT candidates for PM and SO_x reduction in diesel vessels						
	Technique	**"Expected effect"**	**Cost per vessel (Euro)**	**Environmental side effects and synergies (positive**	**/ negative)**	**Limitations in applicability**	**Implementation and other issues**
Aftertreatment	A. Scrubber (open-loop, closed-loop, hybrid)	PM 70-90% SO_x 90-95%	• 500k-9m initial capital cost (one-off) • Operation cost: ~1.5-2% of added fuel cost (NaOH 50%: 200€/t)	BC	~0.5-3% increase in fuel consumption	• Space, weight, ship stability constraints when retrofit • Limited documented operational experience of closed-loop scrubbers	• Can work with high sulfur HFO, in zero discharge mode (scheduled and periodical discharge) • Can be combined with EGR, SCR
Aftertreatment	B. Diesel Particle Filter (DPF)	PM 45-90%	n.a. (still at experimental phase)	Reduction of VOC and CO (60-90%), BC	• Fuel economy penalty (1-2%) • NO_2 formation, in particular for catalyzed DPFs	Technology under demonstration, not ready for commercial operation (% emission reduction not as high as in automotive/NRMM)	• Periodic maintenance, regeneration and cleaning system needed to clean out non-combustible materials • Severe problem with accumulated soot (ash)
Cleaner fuels	C. Conversion to natural gas (LNG)	PM 75-95% SO_x 90-100%	• 500k-5.5m capital cost (one-off) • Possible fuel cost benefits (compared to HFO and MGO)	• Reduction of NO_x (50-85%), NMVOC (75-85%), BC • Lower CO_2 emissions due to lower carbon content	Increase of CH_4 emissions	• Availability of fuel • Gas tanks may limit vessel storage space • Retrofitting requires substantial modifications	• Refueling infrastructure must be expanded • Heavy and highly insulated fuel tanks required to retain fuel at the desired temperature (liquid form)
Cleaner fuels	D. Use of low-sulfur (low-S) fuel	PM 20-60% SO_x 75-90%	• Negligible initial capital cost • High operating cost especially in ECAs (higher fuel price)	n.a.	n.a.	• Availability of fuel • Major operational challenges for fuel switch (machinery components must be capable of operating on low viscosity marine distillate fuel)	• No or little modifications required • Best alternative if retrofitting a SO_x scrubber or conversion to LNG are technically (or economically) not attractive options

Table 4-16: BAT assessment for PM and SO_x reduction in diesel vessels

Relative cost-effectiveness comparison of BAT candidates

Pollutant	PM and SO_x
Application	Diesel vessels
Reference Technology	Conventional compression ignition diesel engine
Reference emission level	• 0.5-2.0 g/kWh (PM) • 10-20 g/kWh (SO_x)
Techniques	LNG Scrubber Low-S fuel DPF



Summary BAT assessment

LNG	• Conversion of a ship to run on natural gas (LNG) can lead to high PM (75-95%) and SO_x (90-100%) reductions with additional BC, NO_x, NMVOC benefits. CO_2 emissions are lower due to lower carbon content. • However, technical complications for conversion to NG, fuel availability, and high initial capital costs for conversion are limiting factors. Moreover, gas tanks may limit vessel storage space and increase weight. • An environmental side-effect is the increase of CH_4 emissions. • Based on the above, LNG can be considered as BAT especially for OEM applications, providing an alternative energy pathway to oil, that promotes energy security, and offering possible fuel cost savings because of lower fuel price. As a retrofit, substantial modifications are required and the experience is limited.
Scrubber	• Retrofitting a scrubber to a ship can efficiently reduce PM (70-90%), SO_x (90-95%), and BC. • This option has high initial capital cost and additional operation cost due to increase in fuel consumption, use of NaOH, water treatment, etc. Compared with other options, e.g. low-S fuel, the return of investment (ROI) depends mainly on price difference between low-S fuel and high-S HFO, but also on other factors such as the size and design of the ship, ECA exposure, etc. • There are space, weight, and ship stability constraints when retrofitted, while the documented operational experience of closed-loop scrubbers is limited. However, it has the advantage of working with high-S HFO, while it can also operate in zero discharge mode (for scheduled and periodical discharge). • In general, scrubber can be considered as BAT especially for OEM applications (possibly combined with EGR or SCR for additional NO_x reduction); retrofit is possible, but with technical limitations for implementation.
Low-S fuel	• Use of low-S fuel achieves PM (20-60%) and SO_x (75-90%) reductions with negligible initial capital cost, since no or little modifications to the vessel are required. • However, this option has high operation cost (especially in ECAs) because of higher fuel price. • Other issues to be taken into account are fuel availability and the fact that machinery components must be capable of operating on low viscosity marine distillate fuel. • In general, use of low-S fuel can be considered as BAT and it is the best alternative if retrofitting a SO_x scrubber or conversion to LNG are technically (or economically) not attractive options.

DPF	• DPF for ships is a technology under demonstration (still at experimental phase). It is not ready for commercial operation and the % reduction of PM (and BC) is not guaranteed to be as high as in automotive/NRMM. • The well-known technical and other operational issues of automotive/NRMM also exist in diesel vessels (periodic maintenance and regeneration needed to clean out non-combustible materials, fuel economy penalty, NO_2 formation, etc). • Especially the problem with accumulated soot (ash) is very intense due to the high ash content of HFO. From some experiments performed, it has been pointed out that the engine must not be too polluting for application of DPF (maximum limit 350 mg PM per kWh); furthermore, the exhaust gas should not contain too much oil. This implies that the most 'dirty' engines would need to be replaced first or retuning to reduce the engine-out PM levels. Low-S and low ash fuel is also required. • Based on the above, DPF has limited potential for ships and there is a lot of space for more research, experimental testing, and performance improvements before this becomes a mainstream technology.

5 Summary and conclusions

This section summarizes the main conclusions of the study. It is based on the technical descriptions of section 3 and the assessment made in section 4. The conclusions and proposals presented here are complementary to the previous sections and the rationale is to provide a discussion on a multi-pollutant basis for each mobile source category (in contrast to the pollutant-by-pollutant assessment already made in section 4). The discussion contains specific recommendations for emission reduction clearly distinguished into measures for new vehicles produced by OEMs (current situation), in-use vehicles (existing stock), and future vehicles (prospective technologies).

5.1 Mopeds and motorcycles

BAT for new vehicles

Regulation

The latest emission standard in Europe for both mopeds and motorcycles is Euro 3, enforced already since 2006 for motorcycles and only in 2014 for mopeds. This standard was introduced with Directive 2002/51/EC[55] for motorcycles (emission limits adjusted to the new driving cycle WMTC with Directive 2006/72/EC[56]) and Directive 2013/60/EU[57] for mopeds. Latest emission limit values (Euro 3, two-wheelers)[58]: 0.15 g/km NO_x, 0.80 g/km HC (<150cc), 0.30 g/km HC (≥150cc), and 2 g/km CO.

Typical exhaust emission control considered as BAT

Current production mopeds and motorcycles have to comply with latest emission limits and the technology used to meet these limits is considered (assumed) as BAT for new vehicles. Due to the long anticipation of Euro 3 (more than 10 years), recent technology Euro 2 mopeds already complied with the Euro 3 standards. The technology used to meet the latest emission limits is 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.

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,

55 Directive 2002/51/EC of the European Parliament and of the Council of 19 July 2002 on the reduction of the level of pollutant emissions from two- and three-wheel motor vehicles and amending Directive 97/24/EC.

56 Commission Directive 2006/72/EC of 18 August 2006 amending for the purposes of adapting to technical progress Directive 97/24/EC of the European Parliament and of the Council on certain components and characteristics of two or three-wheel motor vehicles.

57 Commission Directive 2013/60/EU of 27 November 2013 amending for the purposes of adapting to technical progress, Directive 97/24/EC of the European Parliament and of the Council on certain components and characteristics of two or three-wheel motor vehicles, Directive 2002/24/EC of the European Parliament and of the Council relating to the type-approval of two or three-wheel motor vehicles and Directive 2009/67/EC of the European Parliament and of the Council on the installation of lighting and light-signalling devices on two- or three-wheel motor vehicles.

58 http://transportpolicy.net/index.php?title=EU:_Motorcycles:_Emissions

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.

Two-stroke engines: Although 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 of such engines is requested. This includes electronically controlled fuel injection directly in the cylinder for precise metering of the quantity and the timing of the fuel supplied, secondary air injection in the exhaust line and an oxidation catalyst to control hydrocarbon 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.

Fuel evaporation control

Evaporative emissions control on motorcycles consists of carbon canisters connected to the fuel system to capture and recycle HC vapors back to the intake of the engine to be combusted. Low permeability tanks are also used to control evaporative emissions, 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.

BAT for the existing stock (in-use vehicles)

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:

a) *Emission control system maintenance*

   To ensure compliance with applicable exhaust emission standards, a vehicle inspection and maintenance (I/M) program should be implemented. A program requiring annual inspections of all two-wheel vehicles subject to emissions regulations is recommended.

b) *Fuel and lubrication oil of good quality*

   Catalyst deactivation maybe caused by impurities in fuel and lubrication oil. For two-stroke, in cylinder addition of lube oil magnified the 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 vehicles.

Future vehicle types

a) *Gasoline vehicles*

   Regulation (EU) No 168/2013[59] introduces the next Euro 4 (2016/2017) and Euro 5 (2020) standards for mopeds and motorcycles. These next stages already set very

[59] Regulation (EU) No 168/2013 of the European Parliament and of the Council of 15 January 2013 on the approval and market surveillance of two- or three-wheel vehicles and quadricycles.

demanding targets with numerical emission limits which are at the same (or in some cases below the) level of passenger car ones. These limit values will require advanced emission control technology for compliance in future vehicles of this category.

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 requested. 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.

Regarding fuel evaporation control, the combination of carbon canisters and use of low permeability tanks will continue to be the most effective strategy to control evaporative emissions.

b) *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.

5.2 Spark-ignition (gasoline) on-road light duty vehicles

BAT for new vehicles

Regulation[60]

The latest emission standard in Europe for light duty vehicles is Euro 6 which became effective in September 2014 and was introduced by Regulation (EC) No 715/2007[61] and several follow up technical implementation regulations. An overview of the environmental regulations for light duty vehicles, ranging from the historic to recent years and the foreseeable future, can be found in Ntziachristos (2014). Latest emission limit values (Euro 6, gasoline): 0.06 g/km NO_x[62], 0.0045 g/km PM (GDI only), and 0.10 g/km HC[63].

Typical exhaust emission control considered as BAT

Current production light duty vehicles have to comply with latest emission limits and the technology used to meet these limits is considered (assumed) as BAT for new vehicles (state-of-the-art). Euro 6 emission limits did not differ numerically than earlier Euro 5 standards. Hence, the basic technology between Euro 5 and Euro 6 vehicles is the same. Because of the relatively good emission performance of gasoline vehicles already since Euro 4, and their overall compliance with emission limits, emissions from Euro 6 gasoline vehicles have not received much attention (with the exception of GDI, discussed below).

The main component for emission control in light duty gasoline vehicles is a closed-loop three-way catalyst (TWC), which oxidizes CO and HC and reduces NO_x in stoichiometric combustion mode. TWC became mandatory across Europe with Directive 91/441/EEC for passenger cars in 1992 and it is still used, only improved in its technical implementation, in all gasoline cars (and light duty vehicles in general) produced around the world today. Improvements in the TWC technology include continuous evolution and redesign of the catalytic coating, the substrate, and its thermal management, in order to improve the overall performance while maintaining a competitive cost effectiveness of the complete assembly.

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 conditions. A downstream oxygen sensor is also used to monitor the oxygen storage capacity of the catalyst and, by this, its real world performance.

This typical configuration of stoichiometric combustion with TWC and oxygen sensor(s) leads to the lowest emission levels of all conventional vehicle technologies today.

Exhaust emission control for gasoline direct injection (GDI) vehicles

GDI is a more recent technology of SI engines introduced to improve fuel efficiency and power output by directly injecting fuel into the cylinder rather than upstream of the intake valve. This allows the engine to operate in a diesel-like lean combustion mode at light

[60] Information for latest emission standard is provided. Corresponding UNECE regulation for light duty vehicles can be found in http://www.unece.org/trans/main/welcwp29.html. For example, in Regulation No. 83 there are uniform provisions concerning the approval of vehicles (M1 and N1) with regard to the emission of pollutants according to engine fuel requirements (Revision 4 of this regulation in 2011).

[61] Regulation (EC) No 715/2007 of the European Parliament and of the Council of 20 June 2007 on type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information.

[62] For gasoline light commercial vehicles of categories N1-II/III the Euro 6 NO_x emission limits are higher (0.075 g/km and 0.082 g/km, respectively).

[63] For gasoline light commercial vehicles of categories N1-II/III the Euro 6 HC emission limits are higher (0.13 g/km and 0.16 g/km, respectively).

engine loads (cruising situations where little acceleration is demanded) or in stoichiometric combustion mode similar to PFI (port fuel injection) engines in other situations.

Today, most of the GDI engines operate stoichiometrically but engines that combine both modes in different load regions are also available.

NO_x concern: Stoichiometric GDI NO_x emissions do not differ substantially from conventional PFI vehicles. However, lean burn GDI engines have difficulties in maintaining low NO_x emission levels during long periods of lean operation. A lean NO_x trap (LNT) can be used in these lean applications to reduce NO_x (instead of conventional TWC which is 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 concern: 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 due to the incomplete combustion caused by heterogeneous mixing and cold flame phenomena on the wall, respectively. PM (and PN) emissions 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. The upcoming Euro 6c PN limit may require the use of GPF in some or in all GDI vehicles.

Fuel evaporation control

Non-methane volatile organic compounds (NMVOC) originate from fuel escaping both the combustion process and the fuel system. NMVOC emissions from the vehicle's fuel system are called evaporative emissions and 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 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 tanks reduce 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.

BAT for the existing stock (in-use vehicles)

The majority of gasoline passenger cars on the road today are already equipped with three-way catalysts 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 urban air pollution. Experience shows that accelerated replacement schemes boosted by financial incentives are very effective in removing these older vehicles from the road.

The following techniques are proposed as BAT options for TWC equipped vehicles:

a) *Emission control system maintenance*

The emission reduction effectiveness of the catalyst may be severely degraded over time. Excessive vibration or shock, excessive heat, lack of proper vehicle maintenance, or improper vehicle operation or fuel usage each can cause catalyst failures. The catalyst can also be damaged if the engine is not properly tuned and excess fuel enters the catalyst. Moreover, fuel/air ratio adjustment may fail with time for a variety of reasons (lambda sensor failure, injectors plugging, etc).

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 are also adequate but can be further enhanced to be more effective (e.g. including measurement of NO_x levels). Finally, OBD related failure identification techniques can be plausible 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).

It should be mentioned that 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.

b) *Fuel evaporation control*

Despite some technical difficulties, retrofitting activated carbon canisters and low permeability tanks can be considered as BAT to reduce evaporative emissions. Compatibility issues with ethanol blends above 10% for older vehicles may exist. Moreover, 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. Moreover, replacing the canister can be considered a BAT for older vehicle types.

Future vehicle types

a) *Gasoline vehicles*

The TWC will continue to be the main component for emission control in gasoline LDVs in the future. In US, emission limits introduced at Tier 3 level are arithmetically 4-5 times lower than existing Euro 6 limits in Europe and are expected to be met by TWC vehicles. This shows that this emission control concept can achieve reductions which are even much lower than current stringent limits. 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 limits (2017-2018). This low limit is expected to require the use of GPFs for several models. Current research focuses on the combination of TWC and GPF with commercial systems already appearing. PM and PN GDI Euro 6c limits may also be possible to achieve with engine measures, 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 and TWC can be used.

b) *Fuel evaporation control for gasoline vehicles*

Further to the more stringent control of exhaust emissions, future gasoline vehicles will also be more stringently regulated in terms of their evaporation emissions. A revision of the relevant European legislation is currently underway (Haq et al., 2013) aiming at improving the control of evaporative emissions in real world driving conditions, especially given the rising ethanol fuel use. Such an update is already requested by EC Regulation No 715/2007 and EC Communication 2008/C 182/08[64]. It is expected that any new evaporation limits will continue to be addressed using activated carbon canisters (with high durability / low degradation carbon) and advanced low permeability tanks.

c) *Hybrid 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 compared to conventional powertrains, because of the smoother internal combustion engine operation, on average. Vehicle sales statistics show that more than 30 hybrid vehicle models were available in Europe in 2013, although they make only some 1.4% of total sales (ICCT, 2014). However, this percentage is more than twice as high as two years ago and, in any case, it is deemed to increase as more and more models are offered.

d) *Battery and fuel cell electric vehicles, H_2 combustion*

These advanced technology vehicle types have the potential to achieve significant GHG and air pollutant emission reductions in the future and may be considered for replacement candidates for both gasoline and diesel cars. A significant real world penetration of electric vehicles 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.

An alternative pathway for utilization of hydrogen is that of its combustion in an IC 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.

[64] EU 2008/C 182/08: Communication on the application and future development of Community legislation concerning vehicle emissions from light-duty vehicles and access to repair and maintenance information (Euro 5 and 6).

5.3 Diesel on-road light duty vehicles

BAT for new vehicles

Regulation

Similar to SI vehicles, latest emission limits for diesel LDVs correspond to Euro 6 level introduced by Regulation No 715/2007 and specified later by more technical regulations. The Euro 6 regulation mainly introduces a more stringent NO_x emission limit over Euro 5. Latest emission limit values (Euro 6, diesel): 0.08 g/km NO_x[65] and 0.0045 g/km PM.

Typical exhaust emission control considered as BAT

The regulation of diesel LDVs at a Euro 6 level has received more public attention than probably any other previous emission standard step because of the big discrepancy between limit values for NO_x emissions and the real-driving emissions of diesel cars (already since Euro 3). This discrepancy has introduced difficulties in meeting NO_2 air quality targets in Europe. In terms of engine measures to control emissions, a typical Euro 6 diesel engine 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 vehicle 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), iii) SCR with urea injection in the exhaust line.

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.

Euro 6 LDVs also utilize a DPF (of improved performance and better packaging compared to Euro 5) to control PM and PN levels within regulatory limits. DPFs constitute a total filter in the exhaust line and are considered to effectively reduce emissions under any operation condition. The only possible departure from this rule is the emission levels during DPF regeneration, i.e. during the periodical burn out of soot that accumulates in the DPF, so that a new loading cycle begins. Such regeneration events occur every few hundreds of kilometers, last for a few minutes and increase the particle concentrations as soot is combusted in the filter. As the regeneration operation lasts for only a fraction of normal operation (~0.5% to 1.5% of total time), the contribution of regeneration to total emissions is moderate and is not expected to correspond to an actual environmental issue.

BAT for the existing stock (in-use vehicles)

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. This is the result of the

---

[65] For diesel light commercial vehicles of categories N1-II/III the Euro 6 NO_x emission limits are higher (0.105 g/km and 0.125 g/km, respectively).

tuning of the emission control systems to deliver emission reductions only within the operation boundaries of the type approval driving pattern.

However, there are not many options to control emissions from such vehicles, in particular the older stock, since emission control systems retrofits (e.g. DPF, SCR, LNT) are generally not recommended because of the technical difficulties and the limited space available. For LDVs 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 emission reductions, they cannot be recommended for widespread use on existing diesel light duty vehicles due to excessive modifications required and various limitations (technical, economical, etc.), or low emission reduction effectiveness (biodiesel).

Therefore, the range of emission reduction measures for such vehicle types are restricted to non-technical ones:

a) *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.

b) *Inspection and maintenance*

I/M schemes can be used to identify high emitters or possible failures and malfunctions of the emission control system. Similar to gasoline vehicles, techniques involving remote sensing of emissions coupled to number plate recognition can be very effective in identifying high emitters. Traditional periodical simplified tests are also adequate but can be further enhanced to be more effective (e.g. including measurement of NO_x levels or using more sensitive soot instead of smoke sensors). Finally, OBD enabled identification techniques can be plausible, in particular for more recent vehicle types with enhanced OBD systems.

Future vehicle types

a) *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 SCR catalyst) is necessary to avoid ammonia slip when SCR is used. This may require further uptake in regulations.

b) *Hybrid vehicles*

Hybrid vehicles have the potential to achieve emission reductions in practically most of pollutants, compared to their conventional counterparts, with additional fuel consumption benefits. Currently, the experience in diesel-hybrids is limited, commercial applications only appeared in mass production in 2013. Whether diesel hybrids will perform better than conventional Euro 6 diesel cars remains to be seen (Ntziachristos, 2014). In any case, combination of hybrid powertrain with alternative fuels may lead to additional reductions.

c) *Alternative and future fuels*

CNG (compressed natural gas) 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. Currently, natural gas is still a niche fuel (~1.5% share worldwide), but it has great potential for considerable growth in the future, especially as the infrastructure is being developed and the relevant technology improves.

Second generation biofuels are currently under focus. Different pathways for diesel replacement fuels are foreseen. There is not much information on emission benefits that these fuels can offer in addition to their greenhouse gas savings.

d) *Battery and fuel cell electric vehicles, H_2 combustion*

These technologies have the potential to achieve significant emission reductions in the future and may be considered for replacement of both gasoline and diesel vehicle types. Therefore, the reader is referred to the relevant spark-ignition (gasoline) section 5.1 in this report.

5.4 Diesel on-road heavy duty vehicles (trucks, buses)

BAT for new vehicles

Regulation[66]

The latest emission standard for heavy duty vehicles in Europe is Euro VI, introduced by Regulation (EC) No 595/2009[67] with technical details specified in Regulation (EU) No 582/2011[68]. The emission limits at Euro VI level are comparable in stringency to the US 2010 standards and became effective in January 2013. Further to strict control of PM and NO_x emissions, the Euro VI standard also introduced particle number (PN) emission limits, stricter OBD requirements, and a number of new testing requirements, including in-use testing implementing Portable Emission Measurement Systems (PEMS). Latest emission limit values (Euro VI): 0.40 g/kWh NO_x and 0.01 g/kWh PM.

Typical exhaust emission control considered as BAT

Euro VI engines benefit from high combustion efficiency owed to improved turbocharging compared to previous generations, increased fuel injection pressure and matched injection strategy, optimization in the combustion chamber geometry, compression ratio adjusted for best compromises between optimum efficiency and low soot production rate, and others.

A typical exhaust line of a Euro VI truck consists of a series of aftertreatment components. The first component is a DOC that increases the production of NO_2 and the temperature of the exhaust gas before this enters in a catalyzed DPF which collects soot. Urea injection takes place downstream of the DPF and is decomposed before it enters the main SCR catalyst where NO_x levels are reduced. The final component is an ammonia slip catalyst that oxidizes any excess ammonia to avoid ammonia slipping above the regulatory limit of 10 ppm. According to the regulations, this complex system needs to deliver sufficient reductions over 700,000 km of operation for trucks of more than 16 t gross vehicle weight.

Variations of this basic configuration are available. One path is to significantly increase combustion efficiency and NO_x emissions and then install a very efficient SCR to remove the high engine-out NO_x emissions (i.e. without the use of EGR). Other implementations follow a more conservative approach that sacrifices some of the engine efficiency to control engine-out NO_x emissions by EGR (cooled or not cooled) and precise turbocharging adjustment (often with variable geometry) to come up with lower engine-out NO_x emissions.

Upcoming developments in the area include improved efficiency by means of excess heat recuperation. This will significantly change the engine/aftertreatment configuration and calibration. In aftertreatment, combined DPF+SCR may offer synergies for NO_x/soot suppression, decrease the overall volume required, and offer better packaging options.

---

[66] Information for latest emission standard is provided. Corresponding UNECE regulation for heavy duty vehicles can be found in http://www.unece.org/trans/main/welcwp29.html. For example, in Regulation No. 49 the first gaseous pollutant limits were developed in 1982 and techniques to control NO_x, HC, and CO were set (latest Revision 6 of this regulation in 2013). The operation cycle ECE-R49, consisting of 13 operation points and appropriate weighing factors, was also introduced in this regulation.

[67] Regulation (EC) No 595/2009 of the European Parliament and of the Council of 18 June 2009 on type-approval of motor vehicles and engines with respect to emissions from heavy duty vehicles (Euro VI) and on access to vehicle repair and maintenance information and amending Regulation (EC) No 715/2007 and Directive 2007/46/EC and repealing Directives 80/1269/EEC, 2005/55/EC and 2005/78/EC.

[68] Commission Regulation (EU) No 582/2011 of 25 May 2011 implementing and amending Regulation (EC) No 595/2009 of the European Parliament and of the Council with respect to emissions from heavy duty vehicles (Euro VI) and amending Annexes I and III to Directive 2007/46/EC of the European Parliament and of the Council.

BAT for the existing stock (in-use vehicles)

Existing heavy duty vehicles is a good candidate for emission reduction measures. Several of them are state-owned or belong to captive fleets (e.g. urban buses, refuse trucks, etc.), hence, implementation of measures such as retrofits and fuel changes can be materialized. Criteria and guidance for retrofits can be provided by UN Regulation 132[69]. Based on the assessment conducted, the following techniques can be considered as BAT for HDVs.

a) *SCR and DPF retrofits*

Retrofitting exhaust after-treatment devices is a cost-effective technique that can achieve high environmental benefit. 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.

b) *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 exclude the applicability of DPFs.

Closed crankcase ventilation (CCV) retrofits can be considered as BAT to control crankcase emissions of heavy duty vehicles. If left open, 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. It can be combined with a DOC or DPF.

c) *Fuel switching*

NG (natural gas in compressed or liquid form) retrofits 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 fuels, only renewable diesel is suggested. Alternatives such as DME and emulsified diesel are not recommended due to various technical, economical, or other limitations, as described earlier. DME in particular seems to have a promising future, once economical issues with its production are solved. Biodiesel has low emission reduction effectiveness.

Future vehicle types

a) *Typical diesel emission control*

A combination of EGR, DOC, SCR, and DPF is expected to constitute the default emission control system for future diesel heavy duty vehicles. 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 system.

b) *Hybrid vehicles*

Hybrid vehicles have the potential to achieve emission reductions in practically most of pollutants, compared to their conventional counterparts, with additional fuel consumption benefits. Currently, the technology is limited to urban buses and developments for

[69] Regulation (UN) No. 132. Uniform provisions concerning the approval of Retrofit Emission Control devices (REC) for heavy duty vehicles, agricultural and forestry tractors and non-road mobile machinery equipped with compression ignition engines.

delivery trucks are ongoing. Long-distance applications are unlikely to significantly benefit from hybrid powertrain concepts. Combination of a hybrid powertrain and alternative fuels may lead to additional reductions.

c) *Alternative and future fuels*

NG (natural gas in compressed or liquid form) 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. Because of space concerns to store NG, urban buses rather than long-haul trucks are best candidates for this fuel.

DME, a natural gas derivative, is more energy dense than natural gas, enabling easier refueling and storage on board the vehicle, hence solving some of the NG issues. Because of its highly oxygenated character, DME combustion results to soot levels that can meet Euro VI limits without the need of a DPF, while SCR is required to reduce NO_x. In general, DME can be an excellent diesel fuel replacement in the future, but the issues of production and distribution must be first addressed.

Second generation biofuels are currently under focus. Different pathways for diesel replacement fuels are foreseen. There is not much information on emission benefits that these fuels can offer in addition to their greenhouse gas savings. From an engineering perspective, second generation biofuels are not expected to bring significant additional emission benefits over conventional diesel, once a vehicle is equipped with Euro VI type of emission control.

Use of *hydrogen* – H_2 (or other suitable fuels) in fuel cells may also offer significant benefits in terms of both air pollutants and GHGs. Prototype fuel cell buses have been manufactured as demonstrators of the technology and several small fuel cell bus fleets already operate in different parts of the world (Eudy, 2007). Similar to other vehicle types, the proliferation of hydrogen technologies will only be achieved when (if) the hydrogen production and distribution becomes economically competitive.

5.5 PM from component wear and abrasion from road vehicles

PM from component wear and abrasion may contribute significantly to total PM emissions. 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. 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 report responds to only addresses primary emissions. Hence, specific measures to reduce resuspension (such as road sweeping) are not included in our recommendations.

Regulation

From 1999, European Directive 98/12/EC enforced asbestos-free brake pads for all road vehicles. This does not necessarily affect the total PM emission factor for brake wear, but it certainly has an impact on the chemical composition of the associated particles. There is no other legislation which deals specifically with PM emissions from tyres and brakes. Currently, efforts are focusing on the development of low-friction tyres for fuel consumption and CO_2 benefits. Such tyres might also result in lower emissions of particles (European Environment Agency, 2013b). Work within the Particle Measurement Program (PMP) currently aims at better understanding non exhaust PM emissions and how to control these.

Measures for abatement

There are two directions to follow in order to minimize the negative effects of wear dust:

i) minimize the sources,

- improvement of pavements and gritting material, usage of coarser, wear resistant rock aggregates, alternative pavements (porous, rubber mixed, concrete),
- adjustment of tyres and avoiding using studded tyres,

ii) minimize dispersion to air,

- wet roads, dust binding materials.

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.

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. The first vehicles to be fitted with this system may be available from 2016.

Regenerative braking also becomes increasingly widespread in recent 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. There are no exact studies to quantify the improvement achieved.

5.6 Spark-ignition engines in non-road applications (incl. marine engines)

BAT for new engines

The latest emission standard for small gasoline engines used in non-road applications is Stage II (European Environment Agency, 2013c), introduced by EU Directive 2002/88/EC[70]. The next step of emission control (Stage III) for such engines is being discussed (European Commission, 2014). In this new context, related sub-categories include '*NRSh*' comprising hand-held SI engines having a reference power less than 19kW exclusively for use in hand-held machinery, and the '*NRS*' comprising SI engines having a reference power that is less than 56kW and not included in the *NRSh* category. Latest emission limit values for small handheld engines (Stage II): 50 g/kWh HC+NO_x, 805 g/kWh CO; for ground supported engines (Stage II): 12.1 g/kWh HC+NO_x, 610 g/kWh CO.

Spark ignition marine engines are regulated by Directive 2013/53/EU with applicable emission limits varying depending on the size (power of the engine) and the emission concept (two stroke vs. four stroke).

Boundary conditions / technical barriers: Non road SI engines are limited by low operating temperature requirements (due to the proximity of operator with the engine but also due to fire concerns when operating close to dry vegetation), short useful lifetime of the complete equipment, and low speed operation of ground supported engines for noise reduction. In addition, marine engines are limited in terms of their exhaust configuration, so that water injection is mandatory to reduce their exhaust temperature and for noise attenuation.

Typical emission control considered as BAT

Emission control in such engine categories is less advanced than in spark-ignition 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.

Emission control mostly focuses in 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 (DI), compression wave injection (CWI), 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.

Emission control by catalytic aftertreatment is less frequent than in larger 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. In marine, engines rapid cooling of the engine exhaust with water injection in outboard engines limits catalytic aftertreatment to the rather infrequent type of inboard spark ignition engines. Therefore, catalytic control is used on special machinery only.

[70] Directive 2002/88/EC of the European Parliament and of the Council of 9 December 2002 amending Directive 97/68/EC on the approximation of the laws of the Member States relating to measures against the emission of gaseous and particulate pollutants from internal combustion engines to be installed in non-road mobile machinery.

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

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

a) *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.

b) *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 2S-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.

c) *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. Moreover, alkylate gasoline improves the startability and the long term operation of such engines.

Future engines

New engine types which are designed to fulfill Stage III standards may benefit from more advanced technological solutions:

a) *Combustion improvements*

Four stroke will continue to proliferate and is expected to appear for smaller engines as well, including marine applications. 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.

b) *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.

5.7 Diesel non-road mobile machinery (NRMM) and rail

BAT for new engines

Stage IV of emission control for NRMM engines entered into force in 2014. NRMM emission standards were initially specified by Directive 97/68/EC[71], followed by subsequent technical content Directives from 2002 to 2012[72]. Also, a proposal by the European Commission has already proposed Stage V emission regulations (European Commission, 2014), adopting particle number (PN) emission limits for several categories of CI engines, to be applicable from 2019 on. Furthermore, it extends the scope of emission controls to machines smaller than 19 kW and larger than 560 kW engine power. Latest emission limit values (Stage IV, NRMM): 0.40 g/kWh NO_x and 0.025 g/kWh PM.

Typical exhaust emission control considered as BAT

A typical configuration of a Stage IV emission control system comprises a direct injection diesel engine with turbocharging and intercooler. EGR may be present in some applications but SCR is usually sufficient to achieve the emission reductions required. An ammonia slip catalyst may also be used to oxidize any excess ammonia to avoid ammonia slipping above the regulatory limit of 25 ppm. For PM control, diesel oxidation catalysts or particle oxidation catalysts (POC) are usually used. Wall-flow DPFs are generally not necessary to achieve Stage IV limits.

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

NRMM have a long lifetime, e.g. engines still used in some construction machines or agricultural tractors may be more than 30 years old. Because of this long lifetime, several technical measures can be considered as BAT candidates for the existing stock. The assessment conducted in this report came up with the following recommendations:

a) *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. UN Regulation No 132 provides guidance on retrofit practices. SCR (for NO_x control), DPFs (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).

b) *Other retrofits*

DOC can be implemented in combination with DPF and SCR. As a standalone 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 exclude the applicability of DPFs.

Closed crankcase ventilation (CCV) retrofits can be considered as BAT to control crankcase emissions of non-road diesel engines. If left open, 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. It can be combined with a DOC or DPF.

[71] Directive 97/68/EC of the European Parliament and of the Council of 16 December 1997 on the approximation of the laws of the Member States relating to measures against the emission of gaseous and particulate pollutants from internal combustion engines to be installed in non-road mobile machinery.

[72] http://ec.europa.eu/enterprise/sectors/mechanical/documents/legislation/emissions-non-road/index_en.htm

c) Repowering

Repowering involves replacing the existing engine with a new one and can be an effective strategy because of the long useful lifetime of the NRMM equipment. It provides 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).

d) Fuel switching

Among the alternative fuels that can be used, only renewable diesel is suggested for existing engines. However, reductions that can be achieved by renewable diesel are only moderate. All other fuels (natural gas, DME, emulsified diesel) although can offer some reductions and/or GHG benefits, cannot be recommended for widespread implementation solely on air quality reasons, due to various limitations (technical, economical, etc.) or low emission reduction effectiveness (biodiesel), as earlier described.

Future engines/machinery

a) Emission control for diesel concepts

The major update expected in Stage V 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, possible combination of SCR and DPF in the same component and general system optimization.

b) Alternative and future fuels

Diesel combustion is by far preferable to such engine types owed to its high efficiency, durability and torque characteristics. Alternative fuels to fossil diesel can be used in this concept. Developments in this area will be guided by developments regarding on-road diesel replacement, because of the much higher total quantities of fuel consumed in the latter. Therefore, the reader is referred to the relevant on-road diesel section 5.4 in this report.

c) Hybrid engines/machinery

Hybridization is a technology not yet at mass production for NRMM and the experience is very limited. However, 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. In any case, the growth of hybrid powertrains is expected to be significantly greater than other powertrain types in the future.

5.8 Diesel vessels

Diesel vessels and engines are amongst the longest lived transport equipment with lifetimes that often exceed 30 years of age. Moreover, only a few decades or hundreds (maximum) of ships are scrapped and replaced every year, out of a total ocean-going ship stock of approximately 60 thousand units. Therefore technology 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.

Shipping emission control regulations are internationally agreed at International Maritime Organization (IMO). The regulations generally fall into two categories, either addressing the fuel specifications and here notably the maximum allowed sulfur content, or the maximum allowed pollutant emission levels from the propulsion and auxiliary engines. The fuel specifications usually affect all vessels, while the emission levels will apply to newly built (or major re-engined) vessels. These standards are set globally, but in specifically designed coastal areas, where air quality problems are acute, more stringent emission requirements can be mandated for the ships operating in these waters, so-called emission control areas (ECA). So far this has been implemented as a sulfur emission control area requiring much lower sulfur contents in the fuels, and as nitrogen emission control area requiring much lower NO_x emissions from newly built ocean-going ships.

The latest and most advanced emission control measures (e.g. as required in emission control areas) can be considered as BAT. Specifically, the most widespread control techniques include:

a) *Emission control areas*

Emission control areas (ECA) can specify maximum allowed sulfur levels for all and maximal nitrogen emission levels for new ocean-going vessels operating in these areas. 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. Particular fuels and/or on-board emission control technologies are required for ships operating in these areas. Extension of such ECAs can lead to significant air pollution benefits for the affected areas, but have to be first agreed within IMO.

b) *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.

c) *On-board aftertreatment devices*

Two aftertreatment devices lately become popular for NO_x and SO_x control. SCR systems, conceptually similar to the ones used on road diesel vehicles, can be retrofitted on existing ships or can be used on new vessels to effectively control NO_x emissions down to IMO Tier III level. Also, scrubbers have been successfully implemented to enable HFO operating vessels to enter ECAs.

d) *Shift to alternative fuels*

One option to meet both SO_x and NO_x emission control requirements 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 only for newly built vessels. However, port availability is currently considered the largest obstacle against its more widespread use.

e) *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.

6 References

Aparicio A. et al. (2012), "*Scientific Assessment of Strategic Transport Technologies*", JRC Scientific and Policy Reports, Luxembourg: Publications Office of the European Union, doi:10.2788/94181.

Berger J. and Denby B. (2011), "*A generalized model for traffic induced road dust emissions. Model description and evaluation*", Atmospheric Environment 45 (2011) 3692–3703.

Brynolf S., Magnusson M., Fridell E., and Andersson K. (2014), "*Compliance possibilities for the future ECA regulations through the use of abatement technologies or change of fuels*", Elsevier Transportation Research Part D 28 (2014) 6–18.

Carslaw et al. (2011), "*Recent evidence concerning higher* NO_x *emissions from passenger cars and light duty vehicles*", Journal of Atmospheric Environment 45 (2011) 7053-7063.

Denier van der Gon H.A.C. et al. (2013), "*The Policy Relevance of Wear Emissions from Road Transport, Now and in the Future – An International Workshop Report and Consensus Statement*", Journal of the Air & Waste Management Association, 63:2, 136-149.

Eudy L., Chandler K., and Gikakis C. (2007), "*Fuel Cell Buses in U.S. Transit Fleets: Summary of Experiences and Current Status*", NREL/TP-560-41967, National Renewable Energy Laboratory. Available at: http://www.nrel.gov/hydrogen/pdfs/41967.pdf

European Commission JRC (2008), "2007 *Technical Review of the NRMM Directive 1997/68/EC as amended by Directives 2002/88/EC and2004/26/EC*", Joint Research Centre – Institute for Environment and Sustainability (IES), September 2008 – final, Part II.

European Commission (2014), "*Proposal for a Regulation of the European Parliament and of the Council on requirements relating to emission limits and type-approval for internal combustion engines for non-road mobile machinery*", COM(2014) 581 final, Brussels, 25.9.2014. Available at: http://ec.europa.eu/transparency/regdoc/rep/1/2014/EN/1-2014-581-EN-F1-1.Pdf

European Environment Agency (2013a), "*EMEP/EEA air pollutant emission inventory guidebook 2013*", EEA Technical report No 12/2013, Technical chapter 1.A.3.b Exhaust emissions from road transport. Available at: http://www.eea.europa.eu/publications/emep-eea-guidebook-2013

European Environment Agency (2013b), "*EMEP/EEA air pollutant emission inventory guidebook 2013*", EEA Technical report No 12/2013, Technical chapter 1.A.3.b.vi Road vehicle tyre and break wear, 1.A.3.b.vii Road surface wear. Available at: http://www.eea.europa.eu/publications/emep-eea-guidebook-2013

European Environment Agency (2013c), "*EMEP/EEA air pollutant emission inventory guidebook 2013*", EEA Technical report No 12/2013, Technical chapter 1.A.4 Non-road mobile sources and machinery. Available at: http://www.eea.europa.eu/publications/emep-eea-guidebook-2013

European Environment Agency (2013d), "*EMEP/EEA air pollutant emission inventory guidebook 2013*", EEA Technical report No 12/2013, Technical chapter 1.A.3.d Navigation (shipping). Available at: http://www.eea.europa.eu/publications/emep-eea-guidebook-2013

Franco V., Sánchez F.P., German J, and Mock P. (2014), "*Real world exhaust emissions from modern diesel cars*", International Council on Clean Transportation (ICCT). Available at: http://www.theicct.org/real-world-exhaust-emissions-modern-diesel-cars

Gary Haq A., Martini G., and Mellios G. (2013), "*Estimating the Costs and Benefits of Introducing a New European Evaporative Emissions Test Procedure*", JRC Scientific and Policy Reports, EUR 26057 EN, 2013.

Gustafsson M. (2009), "*Dust binding: practical trials in Sweden*", Air Quality alongside motorways, November 25 – 26, 2009, Rotterdam.

ICCT (2014), European vehicle market statistics pocketbook 2014.

Lochmann H. (2012), "*Small Handheld Nonroad SI Engines*", Euromot AECC Workshop, Nov. 2012.

Lochmann H. (2014), "*Exhaust emissions of small spark ignited engines*", ANDREAS STIHL AG & Co., WG-SSIE-Euromot, Aug. 2014.

MECA (2008), Emission Control of Two- and Three-Wheel Vehicles, August 2008.

Ntziachristos L., Geivanidis S., Samaras Z., Xanthopoulos A., Steven H., and Bugsel B. (2009), "*Study on possible new measures concerning motorcycle emissions*", Final report - revised version, Thessaloniki, Greece, p. 167.

Ntziachristos L. and Dilara P. (2012), "*Sustainability Assessment of Road Transport Technologies*", JRC Scientific and Policy Reports, EUR 25341 EN, Joint Research Centre – Institute for Energy and Transport, doi:10.2788/28167.

Ntziachristos L. (2014), "*Emission Factors for new and upcoming technologies in road transport*", JRC Report, Dilara P. (Ed.), July 2014.

Verbeek R.et al. (2013), "*Natural gas in transport – An assessment of different routes*", TNO-ECN-CE Delft Report, May 2013.

Wallner, T., Lohse-Busch, H., Gurski, S., Duoba, M., Thiel, W., Martin, D., Korn, T. (2008), "*Fuel economy and emissions evaluation of BMW Hydrogen 7 Mono-Fuel demonstration vehicles*", International Journal of Hydrogen Energy 33, 7607-7618.

IIASA GAINS (2014):

- Emissions calculated for the Revision of the European Union's Thematic Strategy of Air Pollution (TSAP reports -> http://ec.europa.eu/environment/air/review_air_policy.htm)
- Emissions calculated for IEA's World Energy Outlook 2012/Energy Technology Perspectives 2050 (http://www.worldenergyoutlook.org/media/weowebsite/energymodel/documentation/IIASA_WEO2012_air_pollution.pdf)