Best Available Techniques (BAT)

Technical review and assessment of emission control techniques on mobile sources

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Candidate techniques for BAT

A European Commission (DG Environment) project
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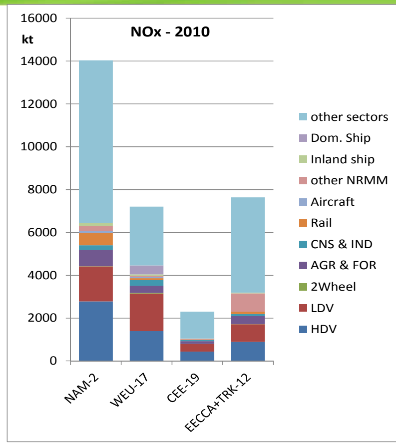
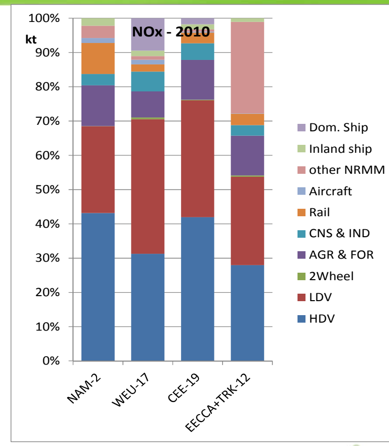
Present emission levels - NO_x





- Mobile sources contribute about **40% to 60% of all NO_x** emissions in the different UNECE regions in the year 2010
- The biggest single sources are **diesel cars and trucks**, followed by agricultural tractors

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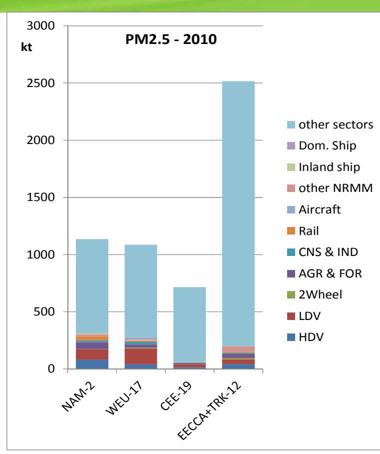
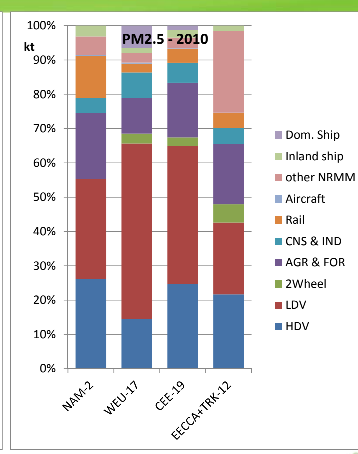
Present emission levels - PM





- Mobile sources contribute about **10% to 30% of all $PM_{2.5}$** emissions in the different UNECE regions in the year 2010
- The biggest single sources are **diesel cars and trucks**, followed by agricultural tractors and construction machinery

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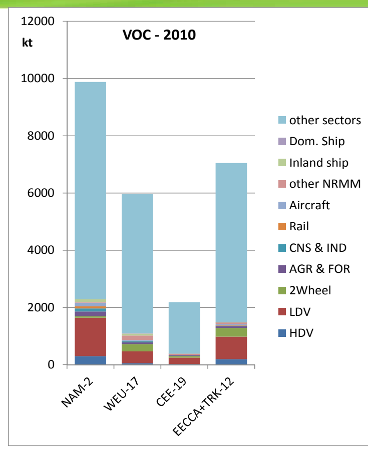
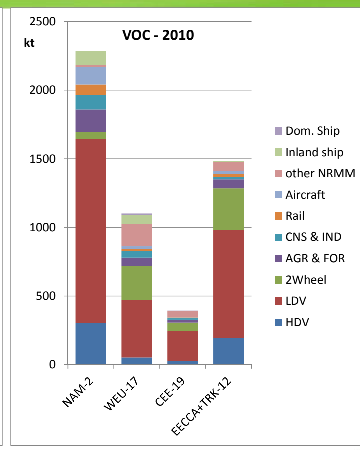
Present emission levels - VOC





- Mobile sources contribute about **20% of all VOC** emissions in the different UNECE regions in the year 2010
- The biggest single sources are **gasoline cars, mopeds, and motorcycles**, followed by smaller machinery and agriculture machines

According to revised GP

Each Party should apply best available techniques to mobile sources covered by Annex VIII…

- So, what are the best available techniques (BAT) available?
- What are achievable emission levels (BAT AELs) by these techniques?

Key options per mobile source and pollutant

- Techniques with BAT potential for different vehicles/vessels
  - Engine measures
  - Exhaust aftertreatment
  - Fuel switching and/or alternative powertrain
  - Other (fuel evaporation, component wear and abrasion)
  - Non-technical measures
- Application on gasoline or diesel engines for road and non-road (NRMM, trains, vessels, aircrafts)
- *Treatment of marine vessels, aircraft, non-exhaust emissions is supplementary to the GP Annex VIII*

Required feedback to presentation

- Review technical information, to the degree possible
- Propose additional measures, if needed

Justification of selecting key measures

- Main environmental problems related to mobile sources (*aka solutions sought for*):
  - 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)

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Definitions (for technical descriptions and assessment)

- Reference technology
  - Defined for each mobile source category and used as a baseline for the assessment and comparison of different techniques and establishment of BAT AELs
  - Does **not** coincide with latest emission control technology
  - A technology still met often in many countries, with known environmental impacts that should be addressed
- Environmental benefit
  - Emission reduction potential (%) relative to the reference technology (indicative of BAT AEL)
  - A range of values is given, variations depending on application
- Cost
  - Additional cost relative to reference technology, required for implementation and operation
  - Order of magnitude estimate on a per vehicle basis

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Technical description of BAT candidates

- A common template has been used for all techniques. Focus on:
  - Pollutants addressed, type of application, short description
  - Environmental benefit (% reduction), costs (implementation, operation)
  - Side-effects (fuel consumption, non-regulated pollutants, trade-offs)
  - Limitations in applicability
  - Implementation issues
  - Maintenance requirements
  - Others, durability, safety, etc.
  - Successful examples, references
- Questionnaire sent out to ~30 industrial associations and individual industries
  - 14 provided feedback

General Description	
Name of technique	
Pollutants addressed	
Engine/vehicle/vessel types	
Short description of technique	
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	
Costs for implementation and operation (order-of magnitude estimations)	
Environmental Side Effects	
Impact on fuel consumption (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.)	
Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioural changes, etc.)	
Ease of implementation (technology or expertise required, infrastructural needs, etc.)	
Maintenance and operation requirements, monitoring, etc.	
Durability/lifetime of equipment	
Impacts on safety (users, citizens, …)	
References and Other Points	
Other comments or remarks	
Successful examples of implementation	
References for further details	

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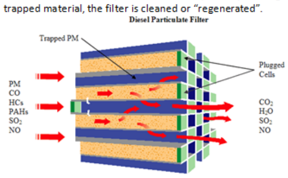
DPF example (screenshot from report)

General Description	
Name of technique	**Diesel Particulate Filter (DPF)**
Pollutants addressed	Mainly: PM, PN, BC, Synergies: HC, CO
Engine/vehicle/vessel types considered	Diesel engines and vehicles (new or retrofit applications): light- and heavy-duty vehicles, non-road machinery, trains.
Short description of technique	• DPF 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 particulate matter 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". 
Environmental Benefit and Costs	
Specific claims (% reduction range of pollutants addressed)	Reference technology: Turbocharged compression-ignition engine with high-pressure fuel injection • Wall-flow DPF: PM (80-95%), HC (85-95%), CO (50-90%) • Partial DPF: PM (30-60%), HC (40-75%), CO (10-60%)
Costs for implementation and operation	_ For heavy duty and non-road vehicles (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	• Slight fuel economy penalty (1-2%).
Non-regulated pollutants and trade-offs	Catalyzed DPFs may increase the NO_2 fraction of total NO_x emissions, as a means to help filter regeneration at lower temperatures

Limitations and Implementation Issues	
Limitations in its applicability (e.g. environmental conditions, fuel specifications, technological barriers, behavioral changes, etc.)	• The system should be properly designed for the particular application to be used. Ideally suited for new vehicles. Exhaust gas temperature data logging must be performed to determine if exhaust temperature meets specific requirements. • Ultra-low-sulphur diesel (ULSD) fuel required (<50ppm). • Minimum oxygen requirement in exhaust gas: 15% O_2. • 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	Trained personnel required for the modification, approved components need to be used.
Maintenance and operation requirements, monitoring, etc.	• 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 addressed above	• DPF can be combined with Selective Catalytic Reduction (SCR) system or Lean-NOx Catalyst (LNC) technologies 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 recirculated to the engine.

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1. Gasoline road vehicles

Mopeds, motorcycles, cars, light commercial vehicles

- Volatile Organic Compounds (VOC)
  - Two-way oxidation catalyst
  - Secondary air injection (SAI) (for mopeds and motorcycles)
  - Three-way catalyst (TWC) with oxygen sensor control
- Nitrogen Oxides (NO_x) from direct injection vehicles
  - Stoichiometric combustion for GDI vehicles
  - Lean NO_x Trap (LNT) for GDI vehicles
- Particulate Matter (PM) from direct injection vehicles
  - Engine measures for GDI vehicles
  - Gasoline Particle Filter (GPF)

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

Road: cars, light commercial vehicles, heavy duty trucks, buses
NRMM (industrial, construction, agricultural, forestry machinery), trains

- Nitrogen Oxides (NO_x)
  - Exhaust Gas Recirculation (EGR)
  - Selective Catalytic Reduction (SCR)
  - Lean NO_x Trap (LNT)
- Particulate Matter (PM)
  - Diesel Oxidation Catalyst (DOC)
  - Diesel Particle Filter (DPF)
- Volatile Organic Compounds (VOC)
  - Closed Crankcase Ventilation (CCV)

3. Gasoline engines non-road (incl. vessels)

Handheld and non-handheld equipment (household, gardening, agricultural and forestry machinery), boats and recreational crafts

- Particulate Matter (PM) and Volatile Organic Compounds (VOC)
  - Oxidation catalyst
  - Secondary air injection (SAI)
- All pollutants
  - Engine measures (e.g. no 2S or DI 2S)
  - Three-way catalyst (TWC) with temperature and oxygen sensor control

Not addressed in Sept. version of the report

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4. Diesel vessels

- Nitrogen Oxides (NOx)
  - Exhaust Gas Recirculation (EGR)
  - Selective Catalytic Reduction (SCR)
- Sulfur
  - Scrubbers
- Particulate Matter (PM)
  - Engine measures
  - Scrubbers
  - Diesel Particle Filter (DPF)

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5. Aircrafts

- Nitrogen Oxides (NO_x)
  - Low NO_x combustion
  - Aircraft design improvements
- Particulate Matter (PM)
  - Engine measures (not covered by GP - not addressed in report)

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Horizontal measures – Non exhaust

Applicable to more than one mobile sources

- Particulate Matter (PM) from component wear
  - Tyre measures
  - Brake measures
  - Road surface measures
- Volatile Organic Compounds (VOC) from fuel evaporation
  - Activated carbon canister
  - Low permeability tank

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Horizontal measures – Fuels / Fuel switching

- Gasoline related fuels
  - Liquefied Petroleum Gas (LPG)
  - Ethanol
  - Methanol
  - Gasoline components
- Diesel related fuels
  - Dimethyl Ether (DME)
  - Biodiesel
  - Renewable diesel
  - Emulsified diesel
  - Low-sulfur fuel for ships
- Gasoline-Diesel related fuels
  - Natural Gas (CNG/LNG)

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Horizontal measures - Powertrains

- Alternative powertrain
  - H2
  - Electrification
  - Hybridization

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Non-technical measures

Positive effect on all pollutants

- Environmental zones (EZs)
- Accelerated scrappage schemes
- Intelligent transport and communication systems (ITS)
- Enhanced inspection and maintenance programs (I/M)

Summary of techniques

Gasoline road vehicles

VOC

Two-way oxidation catalyst

Back

Main application (engine, vehicle)	•All gasoline vehicles: PCs, LCVs, mopeds/motorcycles •Mainly used in the past, now superseded by TWC
Pollutants addressed	•Ref. tech: SI gasoline engine without aftertreatment •VOC (60-95%), CO (70-95%), NMVOC (40-90%)
Cost	€150-300 (as a replacement part) for PCs, even lower for smaller vehicles
Environmental side effects and synergies	CH_2O (60-95%), HAPs (60-95%)
	No significant impact on fuel consumption
Limitations in applicability, implementation and other issues	No positive effect on NO_x (superseded by TWC)
	Pre-warming necessary to reach optimum temperature (SAI improves light-off performance during cold start)
	Effectiveness degradation over time, vibration, shock, heat, lack of vehicle maintenance can cause failures

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Secondary air injection (SAI)

Back

Main application (engine, vehicle)	•Mainly for power two wheelers: mopeds/motorcycles •Improves effectiveness of two-way oxidation catalyst
Pollutants addressed	•Ref. tech: P2W with 2-way oxidation catalyst •VOC, CO (75-85% from 50% without SAI)
Cost	€80-150 (as a replacement part)
Environmental side effects and synergies	Reduction of white smoke
	No significant impact on fuel consumption
Limitations in applicability, implementation and other issues	No specific limitations in applicability
	Easy to install
	No specific maintenance requirements

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Three-way catalyst (TWC)

Back

Main application (engine, vehicle)	•All gasoline vehicles: PCs, LCVs, mopeds/motorcycles •Primary emission control technology since early 1980s
Pollutants addressed	•Ref. tech: SI gasoline engine without aftertreatment •NO_x (90-95%), VOC (60-95%), CO (90-95%)
Cost	€600-1,200 (as a replacement part), for PCs/LCVs
Environmental side effects and synergies	•Reduction of CH_2O (80-95%), HAPs (80-95%) •Formation of H_2S, NH_3 may occur
	No significant impact on fuel consumption
Limitations in applicability, implementation and other issues	•Efficiency falls rapidly when engine not operated within a narrow band of air-fuel ratios near stoichiometry •Pre-warming necessary to reach optimum temperature (electrically heated, close-coupled catalysts) •Effectiveness degradation over time, vibration, shock, heat, lack of vehicle maintenance can cause failures, Pb and other metals poison the catalyst

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Summary of techniques

Gasoline road vehicles

NO_x from direct injection vehicles

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Stoich. combustion for GDI vehicles

Back

Main application (engine, vehicle)	•GDI (gasoline direct injection) vehicles: PCs, LCVs •Combined with TWC
Pollutants addressed	•Ref. tech: GDI lean-burn engine •NO_x (70-85%)
Cost	€85-290 (manufacturer cost)
Environmental side effects and synergies	Positive impact on non-regulated pollutants imposed by use of TWC
	Fuel consumption increase by ~5% (compared to lean)
Limitations in applicability, implementation and other issues	•Can basically be implemented only by the manufacturer •Limitations in applicability and implementation issues imposed by use of TWC

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LNT for GDI vehicles

Back

Main application (engine, vehicle)	•GDI (gasoline direct injection) vehicles: PCs, LCVs •Lean-burn engines
Pollutants addressed	•Ref. tech: GDI lean-burn engine •NO_x (70-85%)
Cost	€800-1,000 (as a replacement part)
Environmental side effects and synergies	Small fuel economy penalty (~2%) because of required brief periods of rich operation to regenerate
	NH_3 is generated during the rich regeneration phase (give up trapped NO_x)
Limitations in applicability, implementation and other issues	Low-sulfur fuel required because LNT also adsorbs SO_x resulting from the fuel sulfur content
	Periodic 'desulfation' cycle required to remove any adsorbed sulfur compounds
	High temperatures required for 'DeSO_x' regeneration (~700ºC) and 15-20' to be completed

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Summary of techniques

Gasoline road vehicles

PM from direct injection vehicles

Engine measures for GDI vehicles

Back

Main application (engine, vehicle)	•GDI (gasoline direct injection) vehicles: PCs, LCVs •Lean combustion mode or stoichiometric mode	
Pollutants addressed	High pressure spray-guided multi-injection: less PM, PN, BC emissions (two orders of magnitude) than wall-guided	
Cost	•Spray-guided injection more expensive than wall-guided •Fuel savings 2-5%	
Environmental side effects and synergies	No significant impact on non-regulated pollutants	
	Fuel consumption may improve 2-5% (with corresponding reduction in CO_2 emissions)	
Limitations in applicability, implementation and other issues	Spray-guided injection more difficult to implement than wall-guided (which, although not optimal, is commonly used)	
	More stringent standards (e.g. Euro 6c GDI PN limits) are likely to compel manufactures move to spray-guided	
	Low-sulfur fuel required, no specific maintenance requirements, only implemented by OEM	

Gasoline Particle Filter (GPF)

Back

Main application (engine, vehicle)	•GDI (gasoline direct injection) vehicles: PCs, LCVs •GPFs maybe required by Euro 6c GDI PN limits
Pollutants addressed	•Ref. tech: GDI engine •PM (75-95%), PN, BC
Cost	€800-1,600 (indicative cost)
Environmental side effects and synergies	No significant impact on non-regulated pollutants (any effects should rather be on the positive side)
	Small increase in fuel consumption and CO_2 emissions 1-3% due to increased back pressure and regeneration
Limitations in applicability, implementation and other issues	As in DPFs, regeneration and cleaning system needed to prevent blocking (periodic maintenance to clean out non-combustible materials and accumulated soot)
	Problem not as intense as in DPFs (lower soot mass and higher exhaust temperatures than diesel counterparts)

Summary of techniques

Diesel vehicles road / non-road

excluding vessels

NO_x

Exhaust Gas Recirculation (EGR)

Back

Main application (engine, vehicle)	Diesel engines/vehicles (new/retrofit): PCs, LCVs, HDTs, buses, NRMM (construction/agriculture), trains
Pollutants addressed	•Ref. tech: T/C CI engine, high-pressure fuel injection •NO_x (25-45%)
Cost	Indicative manufacturer cost: €450-600 (LDVs), €1,400-1,800 (HDVs), even higher for non-road machinery
Environmental side effects and synergies	Risks by PM recirculation if not combined with a DPF
	Slightly reduces engine power
Limitations in applicability, implementation and other issues	ULSD (<50ppm) and electronic control strategy required to ensure efficient operation
	Limited use as retrofit (major engine integration)
	Exhaust cooling may result in engine wear due to excess water vapor

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Selective Catalytic Reduction (1/2)

Main application (engine, vehicle)	Diesel engines/vehicles (new/retrofit): PCs, LCVs, HDTs, buses, NRMM (construction/agriculture), trains
Pollutants addressed	•Ref. tech: T/C CI engine, high-pressure fuel injection •NO_x (70-95%), VOC and CO (50-90%)
Cost	HDV: €7,500 installation (one-off) +€500 urea +€200 maintenance -€800 possible fuel savings (OEM) (p.a.)
Environmental side effects and synergies	•Reduction of PM (20-40%), also reduction of smoke and the characteristic odor produced by a diesel engine •3-5% possible fuel consumption and CO_2 benefits (OEM) •Risk for NH_3 slip
Limitations in applicability, implementation and other issues	•Infrastructure for urea additive must be available •Periodic refilling with urea (on-board dosing unit)
	•Certain temperature criteria for NO_x reduction to occur •Lower efficiency in low-load city driving (low temperatures)
	•SCR units are large, heavy, complex and bulky systems •SCR application may not be appropriate for all vehicles

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Selective Catalytic Reduction (2/2)

Back

A more detailed cost analysis

_ **For light duty vehicles:**

•Installation: €1,200-1,800 (one-off)

•Possible fuel savings (OEM): €30-130 p.a. (e.g. assuming 2,000 l of fuel p.a., 3% fuel economy because of SCR, and 1.38 €/l diesel price, fuel savings is €83)

•Urea use: €30-70 p.a. (e.g. assuming AdBlue® consumption 4% of fuel consumption, and 0.6 €/l AdBlue® price, the cost is €48)

•Additional maintenance cost: €50 p.a.

_ **For heavy duty and non-road vehicles:**

•Installation: €5,000-10,000 (one-off) (cost can be even higher for a large piece of NRMM)

•Possible fuel savings (OEM): €500-1,100 p.a. (e.g. assuming 20,000 l of fuel p.a., 3% fuel economy because of SCR, and 1.38 €/l diesel price, fuel savings is €828)

•Urea use: €400-600 p.a. (e.g. assuming AdBlue® consumption 4% of fuel consumption, and 0.6 €/l AdBlue® price, the cost is €480)

•Additional maintenance cost: €200 p.a.

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Lean NO_x Trap (LNT)

Back

Main application (engine, vehicle)	**•Diesel PCs and LCVs (new/retrofit) •For heavy duty and non-road vehicles, SCR dominates**
Pollutants addressed	**•Ref. tech: T/C CI engine, high-pressure fuel injection •NO_x (70-85%)**
Cost	**€800-1,000 (as a replacement part)**
Environmental side effects and synergies	**Fuel economy penalty (1-2%) because of required brief periods of rich operation to regenerate**
	NH_3 is generated during the rich regeneration phase (give up trapped NO_x)
Limitations in applicability, implementation and other issues	**ULSD (<10ppm) fuel required because LNT also adsorbs SO_x resulting from the fuel sulfur content**
	Periodic 'desulfation' cycle required to remove any adsorbed sulfur compounds
	High temperatures required for 'DeSO_x' regeneration (~700ºC) and 15-20' to be completed

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Summary of techniques

Diesel vehicles road / non-road

excluding vessels

PM

Diesel Oxidation Catalyst (DOC)

Back

Main application (engine, vehicle)	Diesel engines / vehicles (new / retrofit): PCs, LCVs, HDTs, buses, NRMM (construction / agriculture), trains
Pollutants addressed	•Ref. tech: T / C CI engine, high-pressure fuel injection •PM (20-40 %), VOC (40-70 %), CO (40-60 %)
Cost	•€500-600 (installation for LDVs) •€1,500-1,700 (installation for HDVs)
Environmental side effects and synergies	Concerns that DOCs may increase the nitrogen dioxide (NO_2) fraction of total NO_x emissions
	No significant impact on fuel consumption
Limitations in applicability, implementation and other issues	•ULSD (<50ppm) required, no positive effect on NO_x •Easy to install, little or no maintenance required
	•Can be coupled with CCV, SCR or lean NO_x catalysts •Can also be integrated with DPFs

Diesel Particle Filter (DPF)

Back

Main application (engine, vehicle)	Diesel engines/vehicles (new/retrofit): PCs, LCVs, HDTs, buses, NRMM (construction/agriculture), trains
Pollutants addressed	•Ref. tech: T/C CI engine, high-pressure fuel injection •PM (80-95%), VOC (85-95%), CO (50-90%) (wall-flow)
Cost	•€800-1,600 (LDVs) or €3,000-5,000 (HDVs) (one-off installation) •Plus €100-400 or €200-700 (fuel/maintenance cost p.a.)
Environmental side effects and synergies	NO_2 formation, in particular for catalyzed DPFs
	Fuel economy penalty (1-2%)
Limitations in applicability, implementation and other issues	•ULSD (<50ppm) required, no positive effect on NO_x
	•Regeneration and cleaning system needed (periodic maintenance to clean out non-combustible materials) •High temperatures required for regeneration (exhaust gas temperature data logging)

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Summary of techniques

Diesel vehicles road/non-road

excluding vessels

VOC

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Closed Crankcase Ventilation (CCV)

Back

Main application (engine, vehicle)	Diesel engines/vehicles (new/retrofit): HDTs, buses, NRMM (construction/agriculture), trains
Pollutants addressed	•Ref. tech: T/C CI engine without crankcase emission control •VOC: ~20% (80-95% reduction of crankcase emissions * 25% contribution to total VOC)
Cost	€250-3000 (retrofit)
Environmental side effects and synergies	CCV eliminates odor and toxins from vehicle interior
	CCV reduces engine oil consumption
Limitations in applicability, implementation and other issues	No limitations in applicability, easy to implement (only filter elements that must be periodically replaced)
	If left open, crankcase from a pre-2007 diesel engine can contribute 25% of total VOC, PM emissions from vehicle
	CCV can be paired with a DOC or DPF

Summary of techniques

Diesel vessels

NO_x

Exhaust Gas Recirculation (EGR)

Back

Main application (engine, vehicle)	Diesel ships (mainly new ones, many drawbacks for retrofitting)
Pollutants addressed	•Ref. tech: Conventional CI diesel engine •NO_x (25-80%) -> higher than EGR in HDVs!
Cost	•€0.3M-2M (initial cost for installation) •Operation: SFOC penalty, water treatment and sludge handle
Environmental side effects and synergies	PM and SO_x recirculation if not combined with a DPF or SO_x scrubber
	•Slightly reduces engine power •Possible fuel penalty 1-2%
Limitations in applicability, implementation and other issues	Not a mature technology for ships, limited use as retrofit (major engine integration required)
	•Electronic control strategy required to ensure operation •Risk of increased maintenance requirements
	Unlike SCR, fuel sulfur content and low load operation are not constraining factors for EGR systems

Selective Catalytic Reduction (SCR) (1/2)

Main application (engine, vehicle)	Diesel ships (new and retrofit)
Pollutants addressed	•Ref. tech: Conventional CI diesel engine •NO_x (70-95%), VOC and CO (50-90%)
Cost	€400k-800k capital cost (one-off) (ship size matters!) +€30k-140k urea +€15k-30k maintenance -€5k-40k possible fuel savings (OEM) p.a.
Environmental side effects and synergies	•Reduction of PM (20-40%), also reduction of smoke and the characteristic odor produced by a diesel engine •2-4% possible fuel consumption and CO_2 benefits (OEM) •Risk for NH_3 slip, as the catalyst degrades over time
Limitations in applicability, implementation and other issues	•Infrastructure for urea additive must be available •Periodic refilling with urea (on-board dosing unit)
	High temperatures for catalytic reaction, efficiency issues in low-loads (<25%) and during slow steaming
	•SCR units are large, heavy, complex and bulky systems •Can be combined with DPF or SO_x scrubber

Selective Catalytic Reduction (SCR) (2/2) Back

A more detailed cost analysis (cost model by IACCSEA)

_ **1st example:**

- 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., NO_x Neutralized (lifetime) = ~ 1,800 t

_ **2nd example:**

- 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., NO_x Neutralized (lifetime) = ~ 10,000 t

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Summary of techniques

Diesel vessels

Sulfur

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Scrubbers

Back

Main application (engine, vehicle)	•Diesel ships (new/retrofit) (main alternative to low sulfur fuel) •Open-loop, closed-loop, hybrid mode
Pollutants addressed	•Ref. tech: Conventional CI diesel engine •SO_x (65-95%), PM, BC (70-90%)
Cost	•€0.5M-9M (initial cost for installation) •Operation: ~1.5-2% of added fuel cost (NaOH 50%: 200€/t)
Environmental side effects and synergies	No significant impact on non-regulated pollutants
	Increase in fuel consumption (0.5-3%)
Limitations in applicability, implementation and other issues	Documented operational experience of closed-loop scrubbers remains very limited
	•Space, weight, ship stability constraints when retrofit •Can work with high sulfur HFO, in zero discharge mode (scheduled and periodical discharge) •Can be used in conjunction with EGR, SCR

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Summary of techniques

Diesel vessels

PM

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DPF for ships

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Main application (engine, vehicle)	Diesel ships (new / retrofit), technology under demonstration (cannot be simply transferred from automotive / NRMM)
Pollutants addressed	•Ref. tech: Conventional CI diesel engine •PM, PN, BC (45-90 %), VOC and CO (60-90 %) (wall-flow)
Cost	Still at experimental phase, cannot provide indicative cost ranges
Environmental side effects and synergies	NO_2 formation, in particular for catalyzed DPFs
	Slight fuel economy penalty (1-2 %)
Limitations in applicability, implementation and other issues	Technology not entirely ready for commercial operation (% emission reduction not as high as in automotive / NRMM)
	Severe problem with accumulated soot (ash)
	•Periodic regeneration and cleaning system needed •High temperatures required (temperature data logging)

Summary of techniques

Horizontal measures

VOC from fuel evaporation

Activated Carbon Canister

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Main application (engine, vehicle)	Gasoline vehicles (PCs, LCVs, P2W) and small handheld machinery (lawn, garden) (retrofit or replace smaller canisters)
Pollutants addressed	•Ref. tech: Vehicle/engine with no evaporation control •VOC (up to 99% of breathing losses)
Cost	€40-50 (as a replacement part – carbon canister, hoses, purge valve)
Environmental side effects and synergies	No significant impact on fuel consumption and other non-regulated pollutants
Limitations in applicability, implementation and other issues	•Adsorption efficiency may decrease with ethanol content •Deterioration of canister performance with mileage
	More complicated retrofit installation, space concerns for small mopeds/machinery
	No effect on other evap. losses (permeation, leakages, refueling), combine with low-permeability tank / hoses

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Low permeability tank

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Main application (engine, vehicle)	Gasoline vehicles (PCs, LCVs, P2W), small handheld machinery (lawn, garden), boat engines
Pollutants addressed	•Ref. tech: Fluorinated tank with monolayer structure •VOC: ~14% (70% reduction of permeation losses * 20% contribution to total VOC)
Cost	€200-250 (typical installation cost)
Environmental side effects and synergies	No significant impact on fuel consumption and other non-regulated pollutants
Limitations in applicability, implementation and other issues	Metal tanks add weight and limit the shape necessary to meet stringent packaging requirements
	Permeation and compatibility issues with ethanol blends above 10% for older vehicles
	No effect on other evaporation (e.g. breathing) losses, combine with activated carbon canister

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Summary of techniques

Horizontal measures

Fuel switching

Natural gas (here CNG for diesel HDVs) *Back*

Main application (engine, vehicle)	•Diesel heavy duty road vehicles (trucks, buses) •New, retrofit, dual fuel engines (bi-fuel vehicles)
Pollutants addressed	•Ref. tech: T/C CI engine, high-pressure fuel injection •PM (85-95%), NO_x (20-50%), NMVOC (75-85%), CO (70-95%)
Cost	€12k-15k (one-off for conversion to NG) -€500-1,000 fuel cost benefits p.a. (because of lower fuel price)
Environmental side effects and synergies	•Increase of NO_x emissions in some retrofit applications •Not so effective in PN as DPF, increase of CH_4 emissions
	Less CO_2 emissions (10-20%) due to lower carbon content
Limitations in applicability, implementation and other issues	Fuel availability, significant changes to fueling infrastructure and maintenance facilities maybe required
	Volumetric energy content is ~4-5 times lower than diesel, hence requiring appropriate filling infrastructure
	•Gas tank limits storage space and increases weight •Limited experience in retrofit long term performance

Summary of techniques

Non-technical measures

Environmental zones (EZs)

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Main application (engine, vehicle)	Road vehicles in urban areas
Pollutants addressed	•Real impact not easy to quantify and generalize •Indicative ranges from specific examples: PM (5-35%), NO_x (5-20%)
Cost	•€10m-60m initial set up, €1m-10m to run p.a. •€50-250 penalty fine per day for non-compliant vehicles
Environmental side effects and synergies	EZs aim at having positive impact on practically all pollutants by accelerating natural fleet turnover, forcing owners of polluting vehicles to retrofit with upgraded aftertreatment equipment, or use hybrid vehicles, etc.
Limitations in applicability, implementation and other issues	Maybe required: fixed or mobile cameras, police enforcement, a lot of preparatory work
	Political and societal opposition may be faced (burdensome to economically disadvantaged operators of older vehicles)
	For greatest benefit, EZs should cover large geographical area (e.g. whole city) and affect the fleet