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Impact of Emerging Engine and After-Treatment Technologies for Improved Fuel Efficiency and Emission Reduction for the Future Rail Diesel Engines

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Abstract The future stringent emission limits and fuel-saving requirements for non-road engines, in particular for the rail sector, require further research investments both on engine and after-treatment technologies. Therefore, the aim of this study is to identify, mainly on a literature data base, the most promising emerging engine technologies (waste heat recovery, turbocharging, etc.) and exhaust after-treatment systems (de-NO_x catalyst systems, particulate filters, etc.) for improved fuel efficiency and emissions reduction of rail diesel engines. The considered technologies are currently from production series or under development mostly in the on-road research domain. The approach taken has been to gather available information and data from research and industry sources for the most promising emerging technologies of on-road heavy-duty (HD) engines. The collected data have been properly analyzed and elaborated in order to identify the most transferable data from road to the rail sector. The study is one of the results of a project carried out within the 7th European Framework program in which several academic and industrial partners have participated. Engine side and exhaust after-treatment system side technologies are discussed separately. The former takes into account quantitative data from the literature survey, mainly in terms of fuel efficiency benefits, and summarizes the evaluation in a return on investment calculation on the base of a reference rail engine cost. In the latter, essentially qualitative information has been collected. The analysis has been carried out by means of spider diagrams that are used to show the potential of the grouped after-treatment technologies in terms of pollutant emission reduction, size/weight reduction, technology maturity, and cost reduction. The results indicate that the emerging engine technologies are mostly about engine efficiency improvements, of which waste heat recovery shows the greatest potential in terms of fuel efficiency improvement. On the after-treatment system side, the integration of multiple after-treatment functionalities into a single device is particularly attractive for rail applications because it could significantly decrease space and weight requirements, as could the use of alternative to urea media for ammonia storage in the case of selective catalytic reduction (SCR) system functionalities.

Keywords Rail diesel engine technologies · After-treatment technologies · Rail diesel engine emissions · Engine technology costs

1 Introduction

Tier 4 (US)/Stage IV (EU) is the current step of the emission reduction program launched in 1996 for all non-road equipment. For rail engines with a class power range below 560 kW, the current regulation requires engine manufacturers to reduce the level of nitrogen oxides (NO_x) emissions to a level that is about 80 % lower than the previous standards Tier 3/Stage IIIB, while particulate matter (PM) emissions have to be reduced by an order of magnitude for US regulation only. The other gaseous pollutant limits remain the same. Table 1 shows the comparison (www.dieselnet.org).

An overview of the implementation timetable of the EU emission limits for all non-road mobile machinery (NRMM) engines is reported in Fig. 1 [1].

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Table 1 US Tier 3 and 4 regulations versus EU stage IIIB and IV

Emission standards for rail engine with power ≤560 kW [g/kWh]

	Year	CO	HC	NMHC + NO_x	NO_x	PM
US						
Stage Tier 3	2006	3.5	–	4	–	0.2
Stage Tier 4	2014	3.5	0.19	–	0.4	0.02
EU						
Stage IIIB	2012	3.5	0.19	–	2	0.025
Stage IV	2014	3.5	0.19	–	0.4	0.025

To achieve the new targets, the use of diesel particulate filters (DPFs) and higher levels of exhaust gas recirculation (EGR), and/or SCR systems are required, as indicated in Fig. 2.

However, new stringent regulations are under consideration. As an example, according to European Commission—Joint Research Center (JRC), a study concluded that even the most ambitious levels defined with Stage IV did not guarantee adequate protection from negative health effects of PM emissions [2]. Therefore, in line with the developments in the on-road sector, the introduction of a new emission stage (Stage V) targeting particle number (PN) limits rather than particle mass limits needs to be considered. This should focus on the engines in the power range between 56 and 560 kW, which provide by far the largest contribution to NRMM emissions.

In parallel, the continuous increase of diesel fuel cost in last decades has meant the strong interest for the fuel saving. On the other hand, as the diesel cost rises continuously, it can be only compensated with the adoption of new technologies able to increase the energy efficiency.

To find short and mid-term technological solutions for thermal powertrains of the rail sector is particularly important in order to avoid a partial modal shift from rail sector to the less-sustainable road sector on regional passenger lines and freight transportation specialized routes. In this respect, an European Union co-founded project, entitled "Clean European Rail-Diesel" (Cleaner-D), has been carried out between the years 2010 and 2013 in order to give a response to the issues reported above and also to find the best balance between environmental and economical requirements (http://www.cleaner-d.eu/).

Referring to the work program of the Cleaner-D project concerning the engine technology, in which authors have been collaborating, one of the target was to have a quantitative evaluation of the current state-of-the-art engine and exhaust after-treatment (EAT) technologies to meet Tier 4/Stage IV standards. In this respect, a quantitative basis analysis of the capacity of the current state-of-the-art engine and EAT technologies (EGR, DPF, and SCR) to meet Stage IIIB and lower emissions limits in diesel railcar applications was performed [3]. In that study, engine simulation tools were applied in order to estimate the emission reduction capabilities and the impact on fuel consumption (FC),

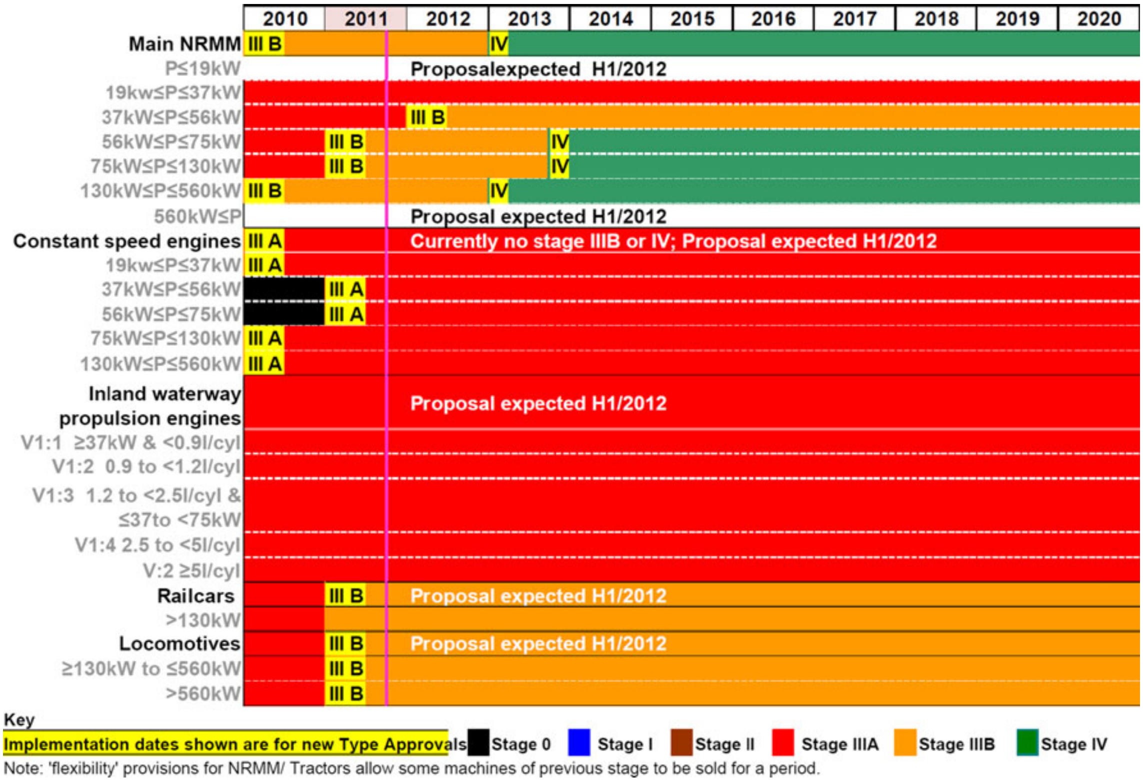
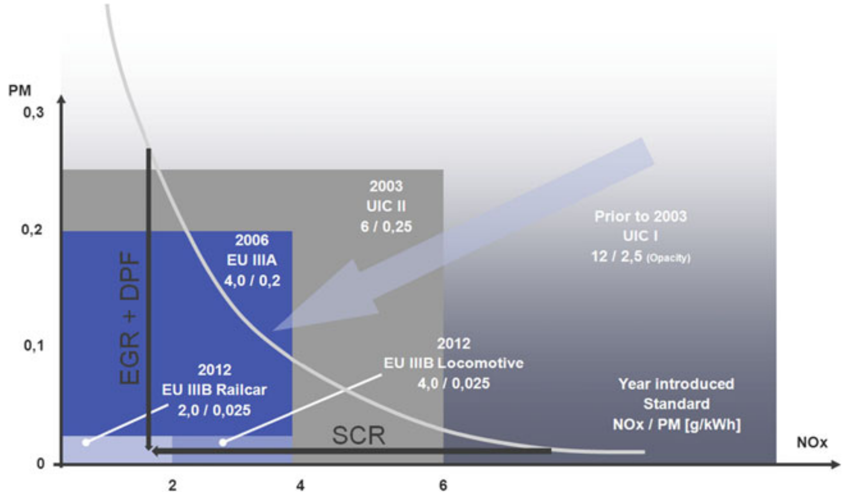


Fig. 1 Railway specific emission regulation

Fig. 2 EU legislation related to emission standards



urea consumption (in the case of SCR) and cooling requirements of these technologies on the whole railcar.

Another target of the work program was to identify the most promising solutions under development in the road sector for fuel efficiency improvement and emission reduction beyond the current Tier 4/Stage IV standards and evaluate their impact on rail engines. Such a second goal is important to support the choice of the guidelines for the development of the future rail diesel engines. However, such information is missing in the context of diesel engines for rail applications.

As often happens, a transfer of technologies from the road sector drives the development of NRMM engines. Therefore, the study was based on the gathering of available information from literature survey, research, and industry sources of the most promising technologies currently under development and mostly in the automotive research domain. The methodological approach consisted of: the identification and averaging of data from the most comparable on-road powertrains, with respect to the rail one in terms of engine characteristics and engine and vehicle duty cycle. Then, the gathered data were used for a cost-benefit analysis of the selected technologies applied to the rail engines. For clarity, engine side, and exhaust after-treatment system side technologies are discussed separately.

Fuel quality variation or alternative fuels and multi-fuel systems (e.g., dual-fuel configuration) were not considered in the study voluntarily owing to the fact that most of the alternative fuels under study for HD road transport could be potentially employed in the rail sector. However, taking into the complexity of the topic, it has been considered out of scope of the present work requiring a specific study.

In the case of engine side technologies, quantitative estimations in terms of fuel saving and relative costs of the most efficient solutions were collected from the database, permitting the evaluation of the return on investment for a reference railcar engine.

When considering EAT technologies, it was difficult or not yet possible to make any quantitative predictions regarding their impact in areas such as fuel efficiency, emissions reduction performance, space, and weight requirements, cost, etc. Therefore, the collected data have been used to make a qualitative assessment of their likely impact in their performance areas.

Approach used in the study, methodology of the analysis and results are discussed in the following section.

2 Approach of the Study and Database

In this study, the approach is to gather information and data from research and industry sources.

The emerging engine technologies concern mostly those under development/research for on-road HD powertrains, and which are potentially transferable to the rail sector.

The analysis carried out was based on a survey of available previous studies as well as technical information from manufacturers. In the last 5 years, six US and two EU studies were carried out in order to identify possible Scenarios. In a chronological order the analyzed public reports are listed in Table 2 [4–11]. The listed reports do not provide a comprehensive review of the technologies for HD engines, but concern technical and cost-benefits analysis of the future technologies for fuel saving and emission reduction of on-road HD engines.

The reports consider a wide range of powertrains, for medium and HD vehicles and for different applications. Therefore, in order to select the transferable data to the rail sector, a cross-checking analysis among the report data and the rail engine features in terms of engine size, power range, application, and duty cycle was done.

This kind of analysis provided the transferable data from road to rail sector of HD engines. It was assessed that the most correlated data are relative to the long haul trucks and the regional diesel multiple unit (DMU) railcars for road and rail sectors respectively. Table 3 displays the average values of the main features for a baseline long haul truck and two representative European DMU railcars.

Table 2 List and description of the public reports on heavy-duty powertrain efficiency improvement

Reference	Author	Title	Date	Description
[3]	TNO	Euro VI technologies and costs for heavy-duty vehicles. The expert panel's summary of stakeholders responses	2006	Report carried out to support Commission DG environment on the development of EU5 standards for LD vehicles and EU6 standards for HD vehicles. Study based on panel and stakeholder communications. Available online.
[4]	FURORE	R&D technology roadmap	2007	Report carried out to consolidate the automotive R&D technology roadmap for 2020 and beyond among the EU stakeholders. Available online.
[5]	NESCCAF/ICCT	Reducing heavy-duty long haul combination truck fuel consumption and CO_2 emissions	2009	Study to provide an assessment of available and emerging technologies for fuel consumption and CO_2 emission reduction from heavy-duty long haul trucks in US in the timeframe 2012–2017. Study based on information from the steering committee and model simulation. Available online.
[6]	NAS	Technologies and approaches to reducing the fuel consumption of medium- and heavy-duty vehicles	2010	Study commissioned to National Academy of Sciences to assess fuel economy technologies for medium- and heavy-duty vehicles (including how such technologies may be practically implemented in vehicles and identifying the potential costs). Information gathered from vehicle manufacturers, component suppliers, research labs, and major fleets during site visits by the committee. Available online.
[7]	NHTSA	Factors and considerations for establishing a fuel efficiency regulatory program for commercial medium- and heavy-duty vehicles	2010	Study of National Highway Safety Administration of USA to assess factors and measures for fuel economy for Medium- and Heavy-Duty vehicles. Information gathered from vehicle manufacturers, component suppliers, etc. Available online.
[8]	AEA/Ricardo	Reduction and testing of greenhouse gas (GHG) emissions from heavy-duty vehicles—Lot 1: strategy	2011	Project aimed to produce an initial step in the process of informing possible policy actions for energy saving of EU HD vehicle market and CO_2 emission reduction. Information gathered from OEM, public agencies, literature etc. Available online.
[9]	TIAX	European Union greenhouse gas reduction potential for heavy-duty vehicles	2011	Report based on the comparison of NAS (US) and AEA (EU) studies in order to determine whether conclusions for the US HDV sector may apply to the EU and to quantify the potential GHG reductions that may be achievable. Available online.
[10]	TRL/Ricardo	GB rail powertrain efficiency improvements	2012	Study aimed to identify technology from non-rail sector able to improve energy efficiency of diesel powered rolling stocks. Available online.

From Table 3 it can be noted that the 360 kW class of rail engines shows very similar features to the 360 kW truck engines, while the cylinder displacement of the 560 kW class engine is only slightly higher than that of the truck engine one. The average FC (in grams of fuel per 100 km) of truck and 360 kW rail engine on their respective reference transient cycles also have the same order of magnitude, while the 560 kW engine has the highest average FC. However, the vehicle transient cycle affects greatly the average FC. As an example, in the case of DMUs, the reference transient cycle includes several starts and stops at the stations, while the truck transient cycle consider less stop and start times. For details, see pages 31 and 32 in [7] and report CLD–D-UIC–013.02 in (http://www.cleaner-d.eu/).

Moreover, certain aspects, to be taken into account for the evaluation of the technologies, need to be clarified:

- Each study is based on a specific data collection methodology and application Scenario. Indeed, as discussed above, evaluation of a different vehicle duty cycle and relative fuel economy is an example. This context changes among the different studies.
- There are several citations of the oldest reports in the new ones, indicating that some information in the most recent reports is based directly on the previous reports.
- It is clearly indicated that there is a tendency among researchers to evaluate technologies under conditions which are best suited to that specific technology. This can be an

Table 3 Specification comparison for engines employed for 370 kW HD on-road truck, 360 kW railcar, and 560 kW railcar, respectively

Features	Vehicle		
	Long-haul truck	Regional 3-coach DMU railcar	Regional 3-coach DMU railcar*
Displacement (l)	≈13	≈13	≈20
Cylinder displacement (l)	≈2.1	≈2.1	≈2.5
Popular architecture	6 in-line cylinders	6 in-line cylinders	8V cylinders
Rated power (kW @ rpm)	370 @ 2100	360 @ 1800	560 @ 2100
Vehicle gross weight range (kg)	16000–40000	30000–40000	50000–60000
Minimum specific fuel consumption (g/kWh)	180–190**	195–200***	195–200***
Average fuel consumption on transient cycle (l/100 km)[a]	≈72**	≈108****	≈126***
Emission control system	EGR + DPF + SCR	EGR + DPF	EGR + DPF
Emission limits	EU VI	IIIB	IIIB

DMU diesel multiple unit, *EGR*, exhaust gas recirculation, *DPF*, diesel particulate filter, SCR, **s**elective **c**atalytic **r**eduction

[a] Transient cycle is referred to the duty cycle of the respective vehicle

*Each coach has one engine and values are referred to a single coach

**[7]

***(http://www.cleaner-d.eu/)

issue in situations where performance becomes strongly dependent on duty cycle.
- In some reports, the fuel type and fuel technology was also evaluated. In the present study, this aspect is not considered.

Apart the aspects above that have to be taken into account when the information reported, even if differences in some features exist, the comparison in Table 3 legitimates the transfer of cost-benefits data from the on-road HD engines to rail sector, in particular for DMU applications. In principle, the data could be also considered valid for engines with power output up to 560 kW for railcar applications but cannot be extended to larger engines for heavy haul locomotives.

3 Analysis of the Engine Emerging Technologies

From the engine side, several technologies are almost ready for production or in an advanced development step. A brief list of the key points of each technology that can contribute to FC and emission reduction is given below. It is important to point out that the description in the following does not represent a technical review of the technologies, but a mere list of the main features of the technologies taken into account in the cost-benefit analysis. Therefore, the references listed below in addition to the reports have been considered as bibliography examples of how each feature affects the FC and the pollutant emissions.

(a) *Fuel injection systems* (*FIS*)

The following features of the FIS have been considered for fuel efficiency improvement of rail engines [6, 7, 10, 12–16]:

- Very high-pressure fuel injection;
- Advanced nozzle design;
- Finely shaped and controlled spray;
- Multiple injection;
- Improved control with more accurate timing and metering of injection.

(b) *Advanced EGR systems*

Regarding the EGR loop the following options has been considered [6, 7, 9, 10, 12, 17–20]:

- Low temperature EGR and as a result advanced injection timing (Because of lower exhaust temperature this technology is not compatible with exhaust energy recovery systems.)

(c) *Advanced turbochargers*

Turbocharging represents one of the most important component affecting engine efficiency and emissions. The main features under study are [6, 7, 9, 10, 12, 21–23]:

- Higher pressure ratio compressors;
- Producing adequate EGR flow without reducing turbo efficiency;
- Two turbochargers in series with intercooling for higher turbocharger efficiency;
- Modulated two-stage systems;
- Mechanical or electrical turbo-compound.

(d) *Combustion system design and advanced combustion control*

Combustion system design features like piston geometry, compression ratio, intake, and exhaust port design, greatly affect combustion process evolution, pollutant formation, and fuel efficiency. Moreover, higher power density is desired in order to apply the engine downsizing concept for fuel saving, while innovative premixed/homogeneous based combustion processes are under study for the sake of improving the pollutant emissions without sacrificing the high efficiency of the diesel cycle. The main features under investigation are [6–8, 12, 14, 18, 24–28]:

- Improved combustion chamber to improve air management and mixing;
- Improved materials and structural design for higher cylinder pressures;
- Alternatives to the standard diesel combustion such as low-temperature combustion (LTC), homogeneous charge compression ignition (HCCI), and premixed charge compression ignition (PCCI) to lower engine-out emissions in certain operating conditions;
- Engine efficiency improvements due to closed-loop control;
- Adding 200 lb/ft of torque in the top two transmission gears so that there is no need to reduce the downshifting on modest grades;
- Electronic controller with model-based controls;
- More sophisticated control (e.g., upgraded fuel system capabilities, sophisticated control algorithms, additional sensor inputs for feedback control).

(e) *Variable valve actuation* (*VVA*)

VVA is one of the most effective solution to control in-cylinder thermodynamic conditions and in consequence fuel ignition, combustion process evolution, and depending on the system flexibility, to permit advanced engine cycle emulation (e.g., miller cycle). Therefore, two features of the VVA system are considered effective for engine efficiency improvement [6, 7, 29]:

- Valve actuation (timing, duration, and lift) independently from the crankshaft angle;
- Cylinder deactivation.

f. *Waste heat recovery* (*WHR*)

From the point of view of the fuel saving technology roadmap, WHR represents the most attractive sector. Two key technologies are mainly under development [6–8, 21, 24, 30–33]:

- Secondary engine that uses exhaust energy or other heat sources from the primary engine to develop additional power without using additional fuel;
- Sources of energy to power a bottoming cycle can include the EGR stream, exhaust stream, charge air stream, and engine coolant circuit.

(g) *Electrification of engine-driven accessories*

The substitution of mechanical driveline of several accessories like water-pump etc. has also a good potential for fuel saving. More features under study are, [7, 9, 10]:

- Accessories can be electrically powered, which has the advantage to operate only when needed;
- Accessories can run at speeds independent of engine speed, which can reduce power consumption;
- Electrification of accessories will have more effect in short-haul/urban applications and less benefit in line-haul applications.

On the base of the fuel consumption improvement estimation versus technology, listed above, and on the capital cost of each one (development costs are not considered) reported in [8], the average fuel efficiency benefits versus engine cost increment has been assembled for road HD 370 kW class engines for long haul truck applications.

In order to transfer the cost-benefit data on the rail sector, a survey was carried out within the Cleaner-D consortium to define the capital cost of a reference rail engine and additional parameters for the return on investment calculation. An engine base cost of €70,000 for a 560 kW class engine has been considered (http://www.cleaner-d.eu/). Table 4 shows the results. A further criteria which is shown in Table 4 is the own weight with respect to the engine weight.

It is important to note that there may be some redundancy in the percentages quoted. It should also be considered that some technologies influence each other in a negative way. So the fuel improvements cannot be summed linearly. For further details, see [6, 7].

The return on the investment calculation has been carried out by taking into account the engine cost increments, the fuel efficiency improvements, the fuel cost and its consumption for a reference working day. The corresponding values are listed in the following (http://www.cleaner-d.eu/):

- Operating hours: 14 h per day
- Diesel costs: €1.30/liter
- Fuel density: 850 g/dm^3
- Average fuel consumption: 25000 g/h

Table 4 List of engine emerging technologies versus costs, fuel consumptions, and weights

Technology	Engine cost increment (%) (engine baseline cost = €70,000)	Fuel efficiency improvement (%) (Euro V as baseline value)	Additional weight related to engine weight [%]
Fuel injection systems	From 0 to 1 %	From 1.5 to 3.2 %	From 0 to 1 %
Advanced EGR	From 0.5 to 1 %	From 1 to 1.5 %	From 0 to 2 %
Advanced turbochargers	From 0.3 to 1 %	From 1 to 2 %	From 0 to 2 %
Combustion system design	From 0.5 to 1.5 %	From 1 to 3 %	From 0 to 1 %
Advanced combustion	~10 %	From 1 to 2 %	0
Advanced combustion control	From 0.1 to 0.15 %	From 1 to 3 %	0
Variable valve actuation	~0.3 %	~1 %	From 0.5 to 3 %
Waste heat recovery	From 5 to 20 %	From 4 to 8 %	From 6 to 20 %
Electrification of engine-driven accessories and auxiliaries	From 0 to 2 %	From 0 to 3 %	From −1 to 2 %

The results of the calculations are summarized in Fig. 3.

The pessimistic estimation has been calculated in a way that the lowest fuel improvement and the highest cost increment are assumed. The optimistic way considers the highest fuel improvement estimation and the lowest cost increment.

Figure 3 shows that the return on investment is less than 1 year in most cases. Only “advanced combustion” and the pessimistic consideration of WHR run away. This is why both advanced combustion and WHR technologies are characterized by the highest costs of investment (Table 4). However, the WHR technologies show the highest potential in terms of FC reduction, and by taking into account the huge current efforts in research and development in this field, the topic appears as the most strategic of the long-term solution for fuel efficiency improvement. On the other side, the listed features of the “advanced combustion” technologies appear as strategic not only for FC improvements but also in terms of pollutant emission control, noise vibration and harshness (NVH) performance.

This section shows the capability of engine emerging technologies for fuel efficiency improvement for rail heavy-duty engine in a class power up to 560 kW. Except WHR, the influence on the design of the vehicle is only small, because it affects only the engine.

Matching lower emission levels generally influences the fuel consumption in a negative way (e.g., DPF or NOx removal technologies). Therefore, it is important to have technologies as described above which work against this trend.

4 Analysis of the Exhaust After-Treatment System Emerging Technologies

As already stated, exhaust after-treatment will be the key technology area for meeting future pollutant emissions regulations. The listed technologies below are based on the following sources:

- The strategic research agendas (SRA) of the European Road Transport Research Advisory Council (ERTRAC), September 2011 [34].
- Published material in the DieselNet (www.dieselnet.org) technology guide.
- Several scientific papers [35–50].
- Information exchanged during the participation of the authors from CERTH in several meetings of the advanced internal combustion engine (AICE) task force of the European Automotive Research Partner Association (EARPA) (www.earpa.org).

The emerging technologies that are in the research phase of development are presented in the following:

(a) *DPF related*:

- DPF with membrane coating;
- DPF with heat recovery;
- New DPF substrate materials;
- Catalyst synthesis and application;
- Electrified DPF;

(b) *SCR related*:

- Solid ammonia storage;
- Zonal coating of SCR;
- LNT + SCR;

(c) *System level technology themes*:

- On-board monitoring and diagnostics;
- Fuel-tailored emission control system;
- Precious metal substitution.

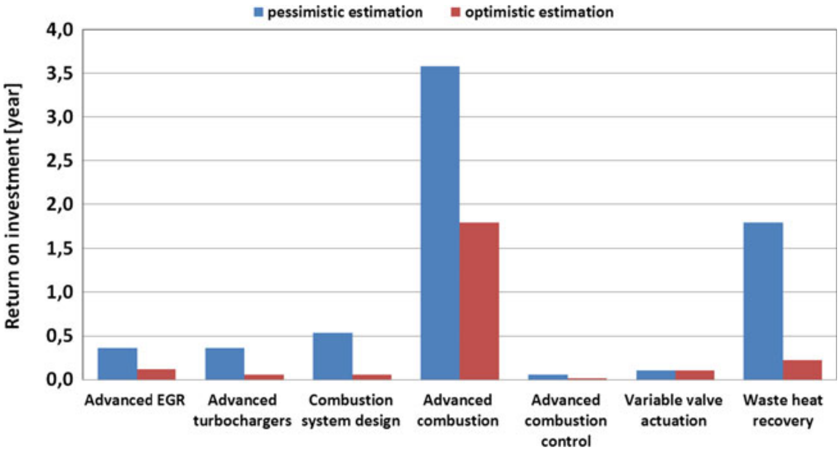


Fig. 3 Return on investment study of engine emerging technologies

The impact potential and maturity of these technologies can be assessed with respect to:

- Pollutant emissions reduction potential;
- Cost reduction potential (manufacturing cost + system operating cost);
- After-treatment system size and/or weight reduction potential;
- Technology maturity;

On a qualitative basis, the impact potential of the emerging technologies can therefore be visualized using the following spider diagrams (Figs. 4, 5, and 6) for the three technology areas. For the interpretation of these diagrams it is noted that the ranking is relative along each axis and applies only to the technologies depicted on the diagram; the ranking of different technologies on different diagrams should not be compared. The ranking of the technologies is the result of a review analysis within the partner consortium Cleaner-D based on the cited literature and internal communication within the consortium (http://www.cleaner-d.eu/).

Emerging exhaust after-treatment technologies focus mainly on increasing emissions reduction performance, reducing space requirements, reducing the fuel consumption penalty associated with their use, improving system monitoring and control, and reducing their production cost. It is worth noting that the first point among the others is the most important for railcar manufacturers.

In the area of particle emissions control, emerging technologies concentrate mainly on improved regeneration performance and monitoring of the DPF due to its importance for fuel economy. In the area of NOx control, emerging alternative ammonia storage media and LNT + SCR strategies could significantly reduce space requirements. Others technologies with potentially high impact on rail applications are emerging catalyst synthesis that could enable the integration of multiple after-treatment functionalities into a single device (e.g., DPF

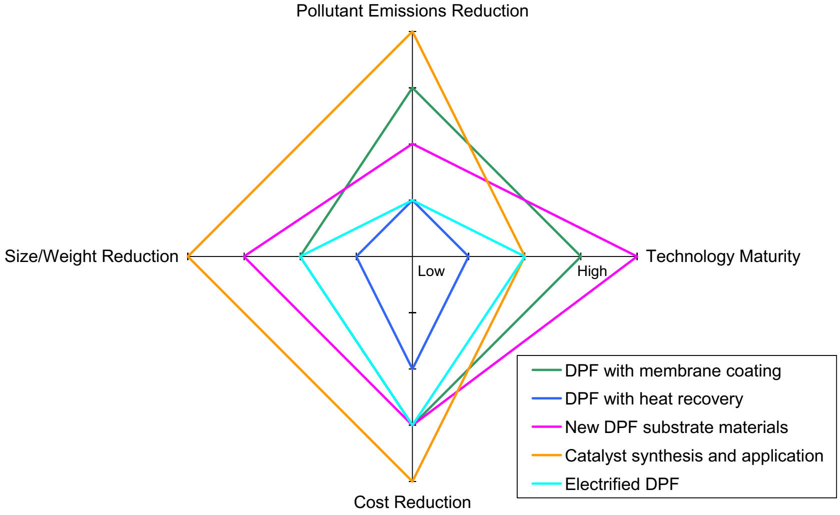
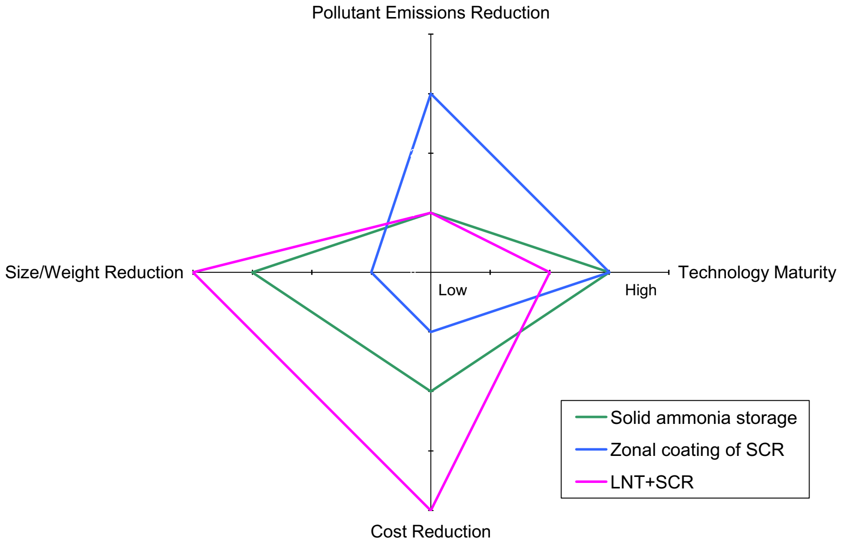


Fig. 4 Impact potential and maturity of DPF related emerging technologies

Fig. 5 Impact potential and maturity of SCR related emerging technologies



and SCR functionality in the same device). This could significantly reduce the space and weight requirements of the after-treatment system.

5 Overview of Emerging Technologies

Starting from the analysis of the reports listed in Table 2, with additional information from journals and conference proceedings, Tables 5 and 6 have been assembled. Table 5 shows the main technologies, their status of development/application, as well as their potential benefits and drawbacks.

Table 6 is a compiled list of the most promising technologies of after-treatment system. For each technology the development status, advantages and possible issues are pointed out.

While fuel consumption technologies refer to in-engine modifications that have almost no influence on the vehicle in terms of design and structure (apart that relative to the WHR), the after-treatment technologies will define the appearance of the railcars of the future. Therefore, the task is to develop highly efficient, compact and light after-treatment technologies.

However, there are many additional topics as regeneration, maintenance, long-term durability, safety, engine interaction (back pressure), complexity of the control, and reliability which have to be considered as well.

6 Conclusions

The evaluation of the emerging technologies for rail engine sector with class power up to 560 kW shows that there are

Fig. 6 Impact potential and maturity of emerging after-treatment system level technology themes

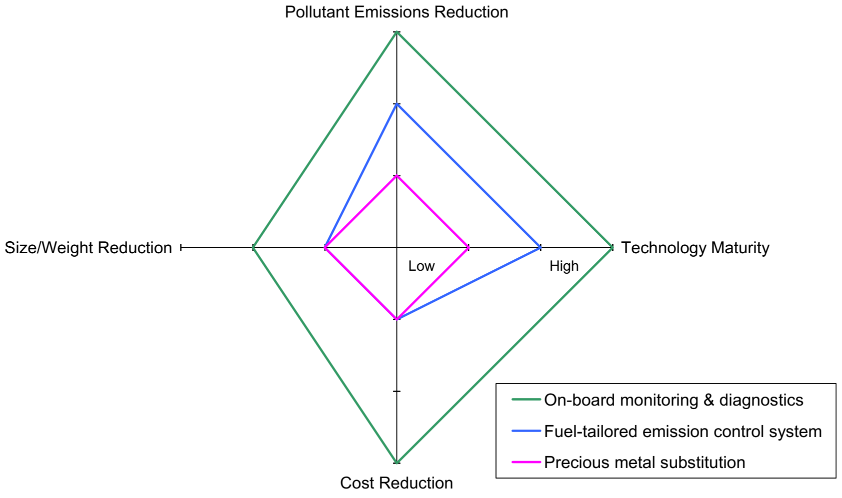


Table 5 Engine emerging technologies

Technology	Development status	Advantages	Possible issues
FIS [6, 12–15]	• CR systems (both solenoid and piezo) are the mainstream FIE technology and are continuously being improved to achieve higher injection pressures (IP); Max IP of 2500 bar is the current status for the best systems (developing both pump and injector); A target of ≈ 3000 bar under development	• Reduced soot formation • Adjusting the EGR level, at same exhaust NO_x/PM trade-off, less BSFC is obtainable • Improved fuel rate control	• Long-term durability of the fuel rate control • Cost • Increased cooling circuit volume due to high EGR level
EGR [6, 8, 11, 16–19, 23]	• HPEGR is a mature technology; current developing area is for super-cooling capability, gas flow rate increment and pressure loss reduction. • LPEGR is under developing for a large scale use.	• HPEGR: robust and low cost system for NO_x emission reduction. • LPEGR: higher cold EGR flow w.r.t HPEGR; at same PM/NO_x trade-off lower penalty on BSFC w.r.t. HPEGR	• HPEGR: additional cost for larger components and improved control tools; packaging. • LPEGR: fouling and corrosive phenomenon on intake pipe component (compressor, CAC etc.); high cost; packaging; additional costs for control development (special in transient maneuvers) • SCR required to achieve very low NO_x emission.
Advanced Turbocharging [5, 6, 8, 20–22]	• 2-stage turbochargers in production; 3-stage TC in development. • Turbo-compounding and E-turbo under development/research phase; their application in combination with bottoming cycle solutions.	• 2-stage turbochargers: higher boost pressure; reduced TC size; robust technology. • Turbo-compound and E-turbo: very good engine response and drivability; exhaust energy transferred from turbine to crankshaft; key to superior fuel economy; for E-turbo independent control of engine speed and turbine speed makes E-turbo slightly more efficient than Turbo-compound,	• 2-stage turbo: complex control, if intercooling is used between the two turbo and before the intake manifold; an EGR pump could be required to facilitate EGR flow management; possible acid water condensation in the downstream compressor; packaging of 2-stage TC is sometime complex and difficult with the intercooling. • Long-term durability of turbo-compound should to be verified; E-turbo is ideal application is for hybrid systems.
Combustion system design [5–7, 11, 13, 17, 24, 25].	• Conventional diesel: refinement is under development continuously.	• Conventional diesel: very robust application and very effective for combustion control; high torque/power density, durability, overall pollutant emissions control.	• Conventional diesel: after-treatment systems required for pollutant emission control; further improvement of the combustion process subordinated to the injection system, EGR, air charging etc.
Advanced combustion [5, 6, 11, 13, 17, 24, 26, 27].	• Advanced combustion design (for low NO_x/PM combustion as HCCI/PCCI/LTC): Partially applied in a limited engine operating range; they are still in research phase for a larger application	• Advanced combustion: very effective for engine out NO_x and PM reduction; potential for overall emission reduction in future at almost same BSFC in the low/partial load of the engine operating area	• Advanced combustion: same combustion efficiency of conventional Diesel one, but only in a limited operating range (20–40 % of load); little impact on the fuel economy for engine that operates most of the time at higher loads (long-haul truck application); complex combustion control; high unburned gaseous emissions; after-treatment system required.
Combustion control [6, 7, 25–27]	• In production for some top class passenger car engines; under development for large scale application. • Under development for HD application.	• Overall improvement of combustion control in real time; pollutant emission and fuel consumption reduction; fuel quality influence mitigation; easier application of advanced combustion system. • High potential for precise combustion evolution control; fuel quality detection; better after-treatment management	• Long-term durability; cost; complex control methodologies.
VVA [5–7, 13, 28].	• In production on SI passenger car engines.	• Huge impact on engine performance and fuel economy for SI engines, for HD	• Long-term durability; high cost; complex engine architecture;

Table 5 (continued)

Technology	Development status	Advantages	Possible issues
	• Under development for LD and HD Diesel engines	Diesel engines the potential benefits are limited; flexibility to operate a TC at a more efficient point on the compressor map (SCR temperature management could be an issue); improvement of the power output of a turbo-compound; high flexibility of the engine control during transient phases; quite mandatory for large application of advanced combustion system.	packaging; sophisticated control methodologies.
WHR [5, 6, 8–11, 13, 17, 20, 23, 24, 29–32].	• In development/research domain • Turbo-compound and E-turbo also considered bottoming cycle solutions	• Recovery of “free” energy; fuel consumption reduction.	• High cost; efficiency is limited by the amount (flow rate) and quality (temperature) of waste heat sources; disadvantaged by variability in heat sources linked to varied driving conditions; amount of energy available is strongly dependent on engine speed and load; packaging; others issues related to the freezing and surviving on-road vibration.
Electrification [6, 8, 9].	• Available for some modern vehicles • Other solutions in development	• Reduction of the amount of energy required to drive the accessories. • Lower fuel consumption and lower GHG emissions.	• Costs, durability, safety

technologies to meet lower emission levels in the future. The identified emerging engine and exhaust after-treatment system technologies have the potential to improve fuel efficiency and emissions reduction.

The discussed technologies are mature or under development in the on-road sector. Where possible, the quantitative evaluation of the potential of technologies has been carried out. In particular this is the case of technologies concern the fuel efficiency improvement. In the case of after-treatment technologies, most of them are under development; then, the relative analysis has a qualitative base. It is important point out that most of the emerging technologies are only tested in automotive applications. However, it is considered that the transfer of these technologies into railway applications has to be applicable in the future when considering upcoming more stringent emission legislations for all non-road equipment.

The evolution of heavy-duty powertrains toward future emission regulations will include both after-treatment system development as well as engine measure solutions. The common opinion of the stakeholders is that future emission targets (2020 and beyond) will be met by the integration of several technologies. The combination of the different technologies will depend on many factors, such as the application scenario, a working duty cycle, costs, reliability, packaging, etc.

The after-treatment systems (DPF, SCR, etc.) will play the main role in pollutant emissions control, and the applied solutions for each type of powertrain will be drawn from the best combinations of the previous mentioned factors. In this respect, pollutant emissions control by means of engine measures will play a secondary role, while engine R&D activities will focus on fuel consumption reduction. Therefore, the key factor for simultaneous pollutant emissions and fuel consumption reduction is—and will be—the correct integration of those emerging technologies that will be gradually available for production series application.

The study showed that cutting the emission levels has the tendency to yield to heavier and bigger propulsion units. In addition the fuel consumption rises which likely can be compensated with engine emerging technologies. Nevertheless, it is not so straightforward to achieve, because most of these technologies tend to lower the exhaust temperature, which has a negative influence on the after-treatment system's efficiency.

AICE, advanced internal combustion engine; DPF, diesel particulate filter; CO2, carbon dioxide; CR, common rail; CRT, continuously regenerating trap (trademark of Johnson Matthey); DI, direct injection; DMU, diesel multiple unit; DOC, diesel oxidation catalyst; DPF, diesel particulate filter; EEA, European environmental agency; EGR, exhaust gas recirculation; EARPA, European Automotive Research Partner Association; EAT, exhaust after treatment; ERTRAC, European Road Transport Research Advisory Council; FC, fuel consumption; FIS, fuel injection systems; HCCI, homogeneous charge

Table 6 Exhaust after-treatment system emerging technologies

Technology	Development status	Advantages	Possible issues
DPF with porous membrane coating on the inlet channels [38].	• Tests on plate and honeycomb filters have demonstrated higher clean filter filtration efficiency and lower pressure drop due to reduced deep bed filtration.	• Reduced back pressure can enable smaller DPF volumes and/or lower fuel economy penalty. • Linear variation of pressure drop with soot mass load can improve monitoring and regeneration control • More rational soot–catalyst contact due to membrane could enable lower catalyst loadings	• Long-term durability of membrane coating • Additional cost of coating the DPF
DPF with internal heat recovery for improved regeneration [45, 46]	• Experimental tests have shown faster thermal response and homogeneous in-filter temperatures during active regeneration, leading to lower regeneration fuel economy penalty	• Improved filter durability due to lower thermal stressing of substrate under active regeneration	• Additional cost due to more complicated manufacturing process
New DPF substrate materials [36]	• Development of new aluminum titanate compositions with lower porosity but improved pore design	• Can enable higher soot mass loads or lower substrate pressure drop without compromising thermal toughness	
Catalyst synthesis and application:			
• Gas oxidation/NO_x reduction and soot oxidation catalyst on a single DPF substrate [48]	• Prototypes developed and assessed with on-vehicle tests	• Low pressure drop • High gas oxidation activity • High catalytic soot activity	• Low NO_x reduction • Durability needs to be verified
• Integration of SCR catalysts in DPF [37, 44, 47]	• Experimental tests on wall-flow DPFs coated with SCR catalysts has shown similar NOx reduction performance to conventional flow-through SCR	• Smaller size and cost of after-treatment system (one less device)	• Potentially lower SCR performance due to coking of SCR catalysts from soot.
Electrically regenerated metal DPF [45, 49]	• Prototypes developed and assessed with engine bench tests	• Very low fuel penalty with respect to filter regeneration • Low-weight structure • Suitable for Diesel hybrid and range extender vehicles	• Low filtration efficiency • Possibly high cost
Solid ammonia storage methods, alternative to urea, e.g., carbamate [42] and metal ammines [39]	• Approximately 70 % lower system volume • Equal SCR performance compared to urea • Simpler delivery system compared to urea • Freezing not a problem • Currently undergoing precompetitive service trials	• Lower recharging frequency during service • Easier transportation, storage and handling compared to urea • Production supported by already existing infrastructures	
Zonal coating of SCR substrate with high temperature (Fe-zeolite) and low temperature (Cu-zeolite) catalysts for wider operating temperature range [43]	• Experimental tests have demonstrated an increase in SCR operating temperature range	• Increased SCR temperature range	
LNT + SCR technology [47]	• Prototypes have been developed	• Ammonia is generated by the LNT • Less LNT PGM content is needed compared to LNT-only solutions	• LNT durability • Precise control of ammonia production
Exhaust on-board monitoring and diagnostics [40]	• Prototype sensors and systems have been developed (still not massively produced)	• Enabling engine close-loop control • Enabling fuel economy and enforcing system durability • Increase system safety	• High cost • Reliability • Durability
Tailored emission control systems for Diesel mixtures with biofuels and/or fuel-flexible engines [35]	• In R&D phase	• Increased performance and fuel economy	
Development of emission control systems with low precious metal loadings [41]	• Feasibility has been proven with experimental tests	• Lower system cost	• Durability

compression ignition; HD, heavy duty; HPEGR, high-pressure loop EGR; JRC, European Commission Joint Research Center; LD, light duty; LNT, lean NO_x trap; LTC, low-temperature combustion; NOx, nitric oxides; NRMM, non-road mobile machinery; NVH, noise vibration harshness; PCCI, premixed charge compression ignition; PM, particulate matter; SRA, strategic research agendas; SCR, selective catalytic reduction; SOC, soot oxidation catalyst; TC, turbocharger; VVA, variable valve actuation; WG, waste gate; WHR, waste heat recovery

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