DEVELOPMENT OF DIESEL RAIL VEHICLES IN THE FIELD OF REDUCING HARMFUL EMISSIONS

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ABSTRACT

The transport of goods and passengers by rail contributes to more efficient use of energy and reduced harmful emissions compared to other transport modes. This results from technical and technological specific characteristics of rail transport and the fact that about 80 % of rail traffic in Europe operates using electric traction. In the remaining part of Diesel traction, the specific fuel consumption and harmful emissions have to be additionally reduced, which is especially emphasised by introducing new regulations.

The paper presents the current and future regulations that refer to the permitted harmful emissions from exhaust gases generated by Diesel traction vehicles. It points to the drastic reduction of the permitted emission of nitrogen oxides and particulates according to the standards that will come into force as of January 2012. To meet these regulations, the researchers and the manufacturers have at their disposal measures that are undertaken in the engine and outside the engine, i.e. by means of subsequent processing of the exhaust gases. Due to very low permitted emissions both measures should be combined in an optimal ratio.

For the undertaken measures, the influence on the emission of individual harmful elements as well as on the specific fuel consumption is presented, and examples are provided for possible solutions. The paper also deals with the issue of inverse dependence between the NO_x emission and the specific fuel consumption, i.e. emissions of particulates, which significantly makes it difficult to achieve the overall good results. Finally, examples of developed systems for Diesel traction vehicles are provided. This refers to the solutions offered by well-known world manufacturers of Diesel engines and Diesel traction vehicles which will meet the future regulations regarding permitted harmful emissions.

Keywords: diesel rail vehicles, exhaust gases, harmful emissions

1 INTRODUCTION

Railway has a significant role in the energy efficiency in transporting goods and passengers and in the environmental protection in relation to other modes of transport. Special emphasis lies on the low specific harmful emissions (per kilometre and per ton, i.e. per kilometre and carried passenger). It is low because of the specific characteristic of Diesel traction in railway traffic and due to relatively low share of Diesel traction in the entire train traction. About 80 % of rail traffic in Europe operates with electric traction which does not pollute the environment locally. However, considering the entire power chain, the pollution in general can be higher or lower, depending on the starting energy source for obtaining electricity for train traction. The remaining 20 % of Diesel traction generates about 1-2 % particulates emission (PM10) and 1-3 % of nitrogen oxide (NO_x)

out of the entire transport emissions, and in this system 6 % of all passengers and 10.3 % of entire freight are transported by rail [1].

In spite of relatively low harmful emissions, there is need and possibility to undertake measures for additional reduction of these emissions. At the same time the work is being done regarding further increase of energy efficiency. This is the result of a general tendency of reducing the specific energy consumption and harmful emissions as well as of the valid regulations brought in this sense.

2 VALID REGULATIONS

In EU the regulations for vehicles that are not meant for driving on highways (EU Off Highway regulations) are classified into categories of engines that use Diesel fuel (CI - Compression Ignition) and petrol (SI - Spark Ignition). As part of CI category the classification is into Non-road Mobile Machinery (NRMM) (including agricultural and forestry tractors), inland water vessels and rail traction engines.

The standards for the emission of new Diesel engines of such vehicles have been adequately structured into stages from I to IV (Stage I…IV). They have been brought in the following steps:

Stage I/II is the first European regulation for the off-road mobile machinery with Diesel engines published on 16 December 1997 (Directive 97/68/EC). Stage I was introduced in 1999 and Stage II from 2001 to 2004 depending on the engine power. However, the locomotive engines were not included in Stage I/II standards.

Stage III/IV standards on Diesel engine emissions on non-road vehicles were adopted by the European Parliament on 21 April 2004 (Directive 2004/26/EC). In 2010 additional directives were accepted: Directive 2010/26/EU ensures additional technical details of engine testing and complies with Stage III B and Stage IV and Directive 2010/22/EU which amends the previous regulations regarding agricultural and forestry tractors.

Stage III standards are divided into Stage III A and Stage III B that are being gradually introduced from 2006 to 2013. Stage IV comes into force in 2014. In relation to engines included in Stage I/II, Stage III/IV standards include locomotive engines and inland water vessel engines. Stage III/IV standards refer only to new vehicles and equipment.

Standards for non-road vehicles in EU typically use two dates for implementation:

- *Date of approval*, after which all the newly approved models have to comply with the standards;
- *Date of launching on the market (or first registration)*, after which all the new engines placed on the market have to comply with the standards.

In the majority of cases the dates of approval are one year before the date of marketing. Stage III A and III B standards have been adopted for engine powers greater than 130kW that are used for locomotives (categories R, RL, RH) and railcars (RC). For the dates of marketing for rail vehicle engines the permitted emission for Stage III A standards are given in Table 1, and in Table 2 for Stage III B standards. The symbols in these tables stand for the following: RC – Railcars, RL – Locomotives low power, RH – Locomotives high power, R – Railway application, A – Stage A, B – Stage B.

Table 1: Stage III A standards for rail vehicle engines

Category	Net Power	Date	CO	HC	HC+NO$_x$	NO$_x$	PM
	kW		g/kWh				
RC A	P > 130	01. 2006.	3.5	-	4.0	-	0.2
RL A	130 ≤ P ≤ 560	01. 2007.	3.5	-	4.0	-	0.2
RH A	P > 560	01. 2009.	3.5	0.5*	-	6.0*	0.2
* HC = 0.4 g/kWh and NO$_x$ = 7.4 g/kWh for engines of P > 2000 kW and D > 5 litres/cylinder							

Table 2: Stage III B standards for rail vehicle engines

Category	Net Power	Date	CO	HC	HC+NO_x	NO_x	PM
	kW		g/kWh				
RC B	P > 130	01. 2012.	3.5	0.19	-	2.0	0.025
R B	P > 130	01. 2012.	3.5	-	4.0	-	0.025

Compared to the currently valid standards, the 2012 standards plan drastic reduction of particulates emission (PM) from 0.2 g/kWh to as little as 0.025 g/kWh. The nitrogen oxide (NO_x) emission for railcar engines should not exceed 2 g/kWh. In order to comply with these regulations the manufacturers have to invest great efforts and implement all the latest achievements and knowledge in this field.

3 MEASURES TO COMPLY WITH STAGE III B STANDARDS

Measures that are undertaken in order to reduce harmful emissions are usually divided into measures within the engine and the measures of subsequent processing of exhaust gases, and they have to be supported by adequate control.

The undertaking of the mentioned measures should not disturb the requirements which are usually set for Diesel engines of rail vehicles, and these are:

- minimal dimensions and weight per power unit and suitability for adequate installation,
- compliance with regulations on harmful emissions,
- low price,
- low fuel consumption,
- low noise level,
- long maintenance intervals (minimum 18,000 engine running hours between overhauls),
- long service life (minimum 30,000 engine running hours, based on a typical running cycle),
- minimal requirements for cooling up to 45 ºC of ambient temperature,
- good engine diagnostics and communication with control system.

For undertaking the measures on the engine, in order to achieve the stipulated limits of harmful emissions, two basic approaches are topical. In the first approach the engine is optimised to the minimal particulates emission (PM), and by subsequent processing of exhaust gases the nitrogen oxide (NO_x) emission is reduced to the required level. This is at the same time the optimal variant for minimal fuel consumption. The other approach tends to use measures inside the engine to reduce the nitrogen oxide emissions to the lowest level, and subsequent processing of exhaust gases reduces the particulates emission by means of a filter. However, in the future these measures will not be sufficient for further reduction of harmful emissions.

In order to reduce the particulate emission to 0.025 g/kWh according to Stage III B in relation to 0.2 g/kWh according to Stage III A (reduction by almost 90 %), a particulate filter has to be implemented. In order to achieve the permitted nitrogen oxide emissions on railcars of 2 g/kWh according to Stage III B, apart from the particulate filter, a device for reduction of nitrogen oxides will also be necessary.

On Diesel engines for rail vehicles up to now mainly fuel consumption had been the object of optimisation. The reason for this is the need to reduce the costs of propulsion energy by using cheaper fuels and lower pressure from legal regulations to reduce harmful emissions.

Unlike road vehicle engines, rail engines had not seen until now the implementation of complex engine control optimisation which includes fuel consumption, harmful emissions and noise.

3.1 Measures within the engine

Measures within the engine affect directly the combustion process, and thus also the fuel consumption and harmful emissions. The measures can be divided into conventional and non-conventional. The conventional measures include optimisation of the processes of combustion, injection and turbo charging, and non-conventional measures include return of exhaust gases, injection of water with Diesel fuel or Miller's procedure. The implementation of these measures requires significant interventions on the engine so that they can be carried out only on new engines that are fitted into new vehicles or vehicles whose engine is being replaced in overhaul (re-motorisation).

In undertaking measures within the engine the known inverse dependence between the NO_x emission and specific fuel consumption occurs. Basically, the undertaken measures are used to achieve lower specific fuel consumption and particulate emission or lower NO_x emission. Since fuel consumption is very important because it affects directly and significantly the running cost, its reduction has to be present in all the undertaken measures on the engine. Table 3 shows the effects of the undertaken measures for the reduction of NO_x emission by about 30 % on the fuel consumption, dimensions and weight [2].

Table 3: Influence of the undertaken measures on the engine for reduction of NO_x emissions on fuel consumption, dimensions and weight

Measure undertaken	Fuel consumption	Dimensions	Weight
Common rail 2nd generation	increases	neutral	neutral
Common rail with EGR	increases slightly	neutral	neutral
Diesel fuel and water emulsion	neutral	+ 40% tank volume	+ 50 % weight of fuel
Miller's procedure	increases slightly	neutral	neutral

To achieve the maximal effect of the mentioned measures their optimal combination is planned in the future. The implementation of the Common rail device for fuel injection allows good injection process control. It refers to the beginning of injection and the possibility of multiple injections with different volumes. Injection is realized with very high pressures (over 1,800 bar) which ensure fine fuel spraying and improved combustion. To reduce NO_x emissions the fuel injection should be slightly delayed. This results in lower maximal temperatures during combustion and deterioration of the conditions for the formation of NO_x. The drawback of this measure is the increase in fuel consumption and particulate emission. The particulate emission can be reduced by additional injection of fuel whose combustion increases the temperature and subsequent oxidation of particulates.

The contrary effects between specific fuel consumption and NO_x emission can be alleviated by the combination of returning a greater quantity of exhaust gases (EGR), higher injection pressure and turbo-charging (higher air factor). Turbo-charging requires application of air cooler in order to increase the mass of intake air and reduce the average temperature in the cylinder, including the NO_x emissions.

The application of the Diesel fuel emulsion and water leads to the reduction of NO_x emission in order to reduce the maximal temperature of combustion caused by injected water which uses for its evaporation and heating a part of released heat in fuel combustion. However, this system requires a water tank with adequate device for emulsion preparation which complicates the entire system, increases its dimensions and weight and represents the basic drawback.

Miller's procedure means delayed closing of the intake valve which seemingly reduces the level of compression, highest pressure and temperature. This leads to the reduction of NO_x

emission. However, this measure reduces the volume of air taken into the cylinder. The solution of this problem is achieved by the implementation of turbo-charging. In order to prevent increase in air temperature along with pressure increase in turbo-charging, it is necessary to implement its cooling. It is realized with an air cooler which is installed between the compressor and the engine cylinders.

3.2 Subsequent processing of exhaust gases

Although the measures within the engine significantly reduce harmful emissions, they cannot achieve the necessary reduction in emission regulated by Stage III B standards. Therefore, subsequent processing of exhaust gases is required. Considered should be the specific characteristics of railway vehicle exploitation and the requirements that are set, such as:

- significant reduction of harmful emissions in specific driving conditions with high share of idling;
- wide range of operating temperatures with exhaust gas temperatures from 80 ºC to 600 ºC;
- necessary stability in dynamic loads specific for rail vehicles and sudden changes of exhaust gas temperatures;
- low exhaust gases counter-pressure;
- not to increase the fuel consumption;
- long service life;
- low maintenance requirements.

Various principles of subsequent exhaust gases processing are known, according to the method of operation, complexity, dimensions, weight, fuel and the level of reducing harmful emission components. The overview of the mentioned elements is given in Table 4 [2]. The symbols of individual systems in the table denote the following: SCR - Selective Catalytic Reduction, CRT - Continuously Regenerating Trap, SCRT - combination of SCR and CRT. The symbols of components denote the components which are affected by the applied system in order to reduce their emissions.

Table 4: Procedures of subsequent processing of exhaust gases and operating principles

Procedure	Operating principle	System	Component
Oxidation	Catalysis	Oxidation catalytic converter	HC, CO
Filtering	Separation	Particulate filter	PM
Reduction	Catalysis	SCR-system	HC, NO_x, PM
Oxidation + filtering	Catalysis + separation	CTR-system	HC, CO, PM
Oxidation + Reduction + filtering	Catalysis + separation	SCRT-system	HC, CO, NO_x, PM

According to the set standards the biggest problem is the simultaneous reduction of NO_x and particulate matter (PM). The emission of hydrocarbons (HC) and carbon monoxide (CO) for Diesel engines is no issue since the excess air at sufficiently high temperature ensures their subsequent oxidation.

The reduction of NO_x emission is efficiently achieved by the application of selective catalytic reduction (SCR) which in certain driving conditions has high effect. The SCR with closed loop can achieve the reduction of NO_x emission even by 90 %. The basic drawback of the SCR-system is the requirement of an additional tank for the reduction agent which is typically 32.5 %-aqueous urea solution of registered trademark AdBlue.

The emission of particulate matter (PM) is very efficiently reduced by the application of particulate filters. However, the problem remains regarding the reliable regeneration in all driving conditions. The regeneration understands the elimination of the deposited particulates by their conversion into carbon dioxide and water. This can be achieved by means of nitrogen dioxide (NO_2) or oxygen (O_2). Regeneration with nitrogen oxide occurs at somewhat lower temperatures (from 250 ºC to 450 ºC) and relatively slowly, whereas the regeneration with oxygen occurs at a temperature of about 600 ºC and represents higher temperature load for the system [3]. This temperature can be substantially reduced by coating the filter with a catalytic layer or by adding regeneration additives.

Each case of implementing the Diesel engines requires optimal selection and adjustment of the system of subsequent exhaust gases processing. In the future, combined systems of subsequent processing of exhaust gases will have to be used in order to achieve the required significant reduction of harmful emissions with concurrent reduction of specific fuel consumption or at least keeping the same level. An example of a combined system of subsequent exhaust gases processing is given in Figure 1 [3].

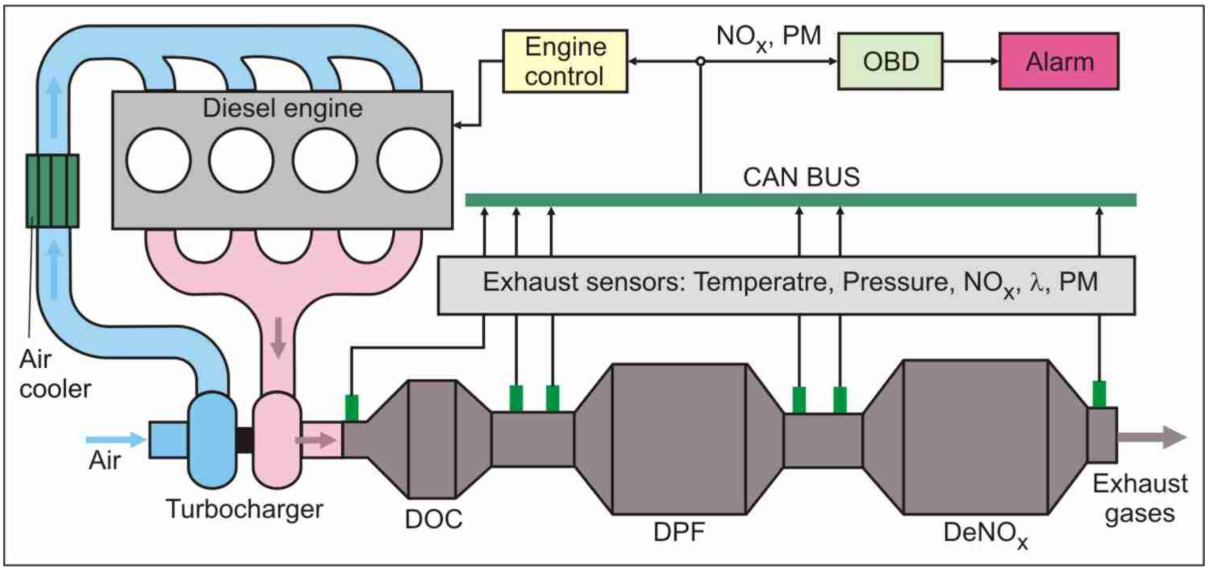

Figure 1: Combined system of subsequent exhaust gas processing

The system is fitted with an oxidation catalytic converter (DOC - Diesel Oxidation Catalyst) in which CO and HC oxidize into CO_2 and water. The DOC has the role of creating an optimal relation between NO_2 and soot for the regeneration of particle filter (DPF - Diesel Particles Filter) with NO_2. The nitrogen monoxide (NO), which in nitrogen oxides NO_x amounts up to 95 %, oxidises into NO_2. At the end a $DeNO_x$-catalytic converter is installed and it has the task of reducing the NO_x emission. It substitutes the catalytic converter of selective catalytic reduction (SCR). This avoids the need for the catalytic agent and the respective equipment. One should have in mind that $DeNO_x$-catalytic converter achieves lower reduction of NO_x than SCR-catalytic converter so that in order to achieve the permitted NO_x emissions it is necessary to use internal measures in the engine to ensure sufficient reduction of its emission (turbocharging with air cooling). The exhaust system is fitted with sensors to measure the essential parameters, such as the temperature, pressure, NO_x concentration, air factor λ (oxygen content) and concentration of particulate matter PM (still in the development phase). On the basis of these data the Diesel engine is operated by means of an adequate control unit (Engine control), and the on-board diagnose device (OBD) signalizes the possible exceeding of the permitted values of NO_x and PM emissions (Alarm).

4 EXAMPLES OF THE DEVELOPED SYSTEMS

Forced by the adopted standards and by the market competition, the Diesel engine manufacturers for rail vehicles, i.e. rail traction vehicle manufacturers actively develop engines that satisfy the requirements of the permitted harmful emissions and minimal fuel consumption. Thus developed engines are introduced into the trial operation of individual railways or are already used in a limited scope on railway vehicles. For the moment this refers mainly to the vehicles of relatively lower power, such as railcars or shunting engines.

As part of joint research of the German Railways (DB) and MTU Friedrichshafen Company the "cleanest" shunting engine of series BR 294 was introduced in trial operation in 2008 at the shunting yard Kornwestheim. The engine for heavy shunting operation under the number 294 635-8 has been fitted with a 1,000 kW power engine. The test project entitled LOCEX (**Loc**omotive with **C**lean **Ex**haust) is planned to take two years. The engine was developed by the MTU Company with subsequent processing of exhaust gases which consist of the oxidation catalytic converter (DOC), particulate filters (DPF) and catalytic converter of selective catalytic reduction (SCR-catalyst) (Figure 2). The engine tests have given good results, i.e. it meets the Stage III B standards. HC emission is reduced by more than 90 %, the particle emissions by more than 90 %, and NO_x emission by more than 60 % [4]. The results are now verified in practical use. Since for the subsequent processing of exhaust gases (exhaust gases after-treatment) also SCR-catalytic converter is used which uses aqueous urea solution as catalytic agent, it is necessary to use a tank for this agent and the regulation dosage device. For a wider application on the railways it is also necessary to adapt the infrastructure with tanks for the reduction agent where the vehicles would be supplied.

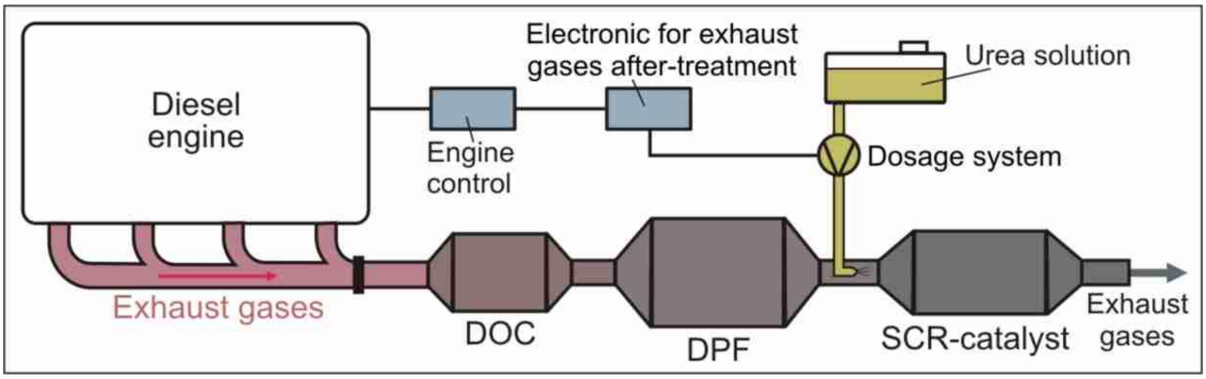

Figure 2: System of subsequent exhaust gas processing according to LOCEX project

The Voith Company in cooperation with the MAN Company has developed complete drive systems as registered trademark ECOpack which feature low fuel consumption, low noise and low harmful emissions. For the reduction of fuel consumption the devices for energy regeneration are used, such as hydropneumatic or steam ones. They use the braking power which they use for vehicle reacceleration or for the on-board electricity generation which can be used for passenger cabin heating. In order to reduce NO_x emissions the measures inside the engine are used (double turbocharging with air cooling after single steps and return of exhaust gases which are cooled before entering the engine cylinders) and particulate filter which reduces particulate emission by more than 95 % [5]. The filter regeneration is carried out by burning the deposited particulates by means of a burner. An example of a drive system for railcar suitable for fitting below the floor is presented in Figure 3.

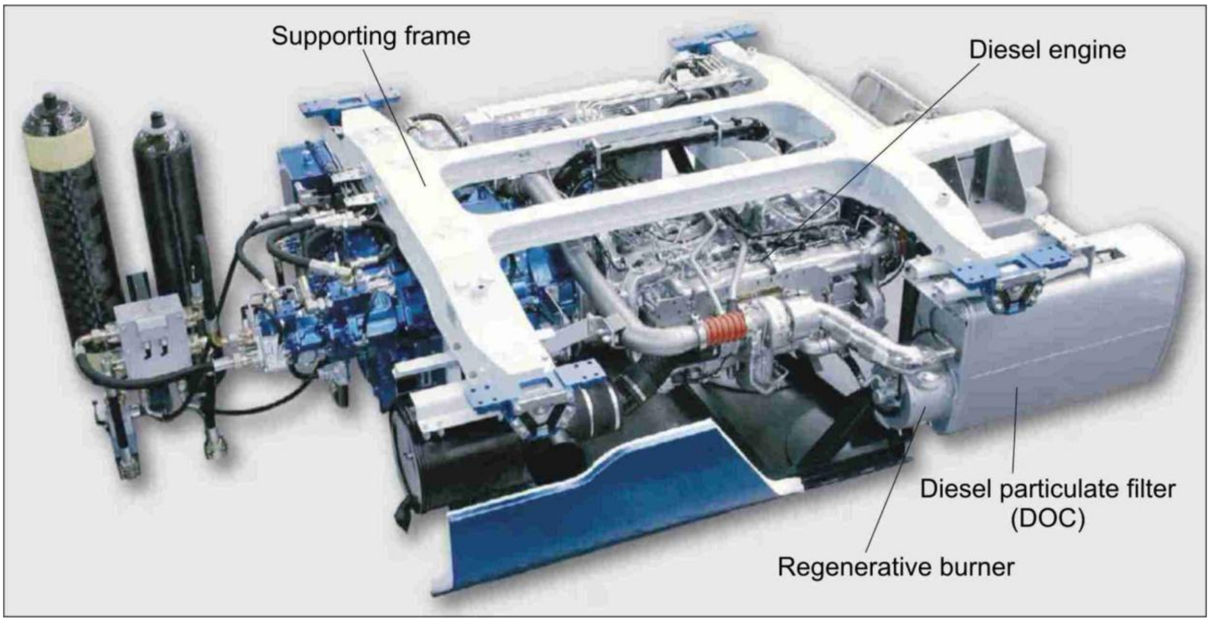

Figure 3: Drive system Voith-Turbo ECOpack

A well-known manufacturer of track vehicles, the Bombardier Transportation is trying to contribute to environmental preservation and energy saving, which is shown in the ECO4 program (ECO4 = Energy, Efficiency, Economy, Ecology). The program means optimisation of energy usage, reduction of energy consumption, reduced CO_2 emission to a minimum, higher economy and total improvement of performances. The program development concept allows application on all types of rail vehicles. For railcars the operators set very high requirements. Apart from the economical propulsion, high availability and reliability are required as well as low purchase price and low maintenance costs. More recently the emphasis has also been on the environmental protection so that this represents a special challenge for the manufacturers.

The Bombardier Transportation has developed as part of ECO4 program, a drive concept for railcars under the name of C.L.E.A.N. (**C**atalyst based **L**ow **E**mission **A**pplicatio**N**) Diesel Powerpack. The project started in 2006 with the following development objectives [6]:

- to develop the Diesel engine which will comply with the Stage III B standards for harmful emissions of exhaust gas components;
- to develop highly effective power transmitter in order to reduce the losses and fuel consumption;
- to reduce significantly the drive assembly mass;
- installation into vehicles without special modification of space regarding the auxiliary drives and cooling device;
- to reduce the maintenance costs.

For subsequent processing of exhaust gases the SCR-catalytic converter is used, which uses aqueous urea solution (AdBlue) as reduction agent. This ensures the reduction of NO_x emission by about 85 %, which satisfies the future regulations according to Stage III B. The engine has been designed with high turbocharging and air cooling and Common rail device for fuel injection. Due to high combustion temperatures very few particulates are formed so that no filter is required.

For the mentioned project the 8-cylinder V-engine type FVQE2883z*c200 of the Fiat Company Powertrain 570 kW at 1750 ^{o}/min was selected. The engine together with the power transmitter and auxiliary devices is located in a special frame which enables installation into rail vehicles as a unit. It is a drive block (Powerpack) which is planned for installation into railcars under the floor (Figure 4) [7].

Such drive block was installed for the first time in the ITINO railcar. The first models of railcars were intended for suburban traffic in Germany and Sweden. They were introduced in regular traffic in Germany in 2010 as railcars ITINO VT 123.

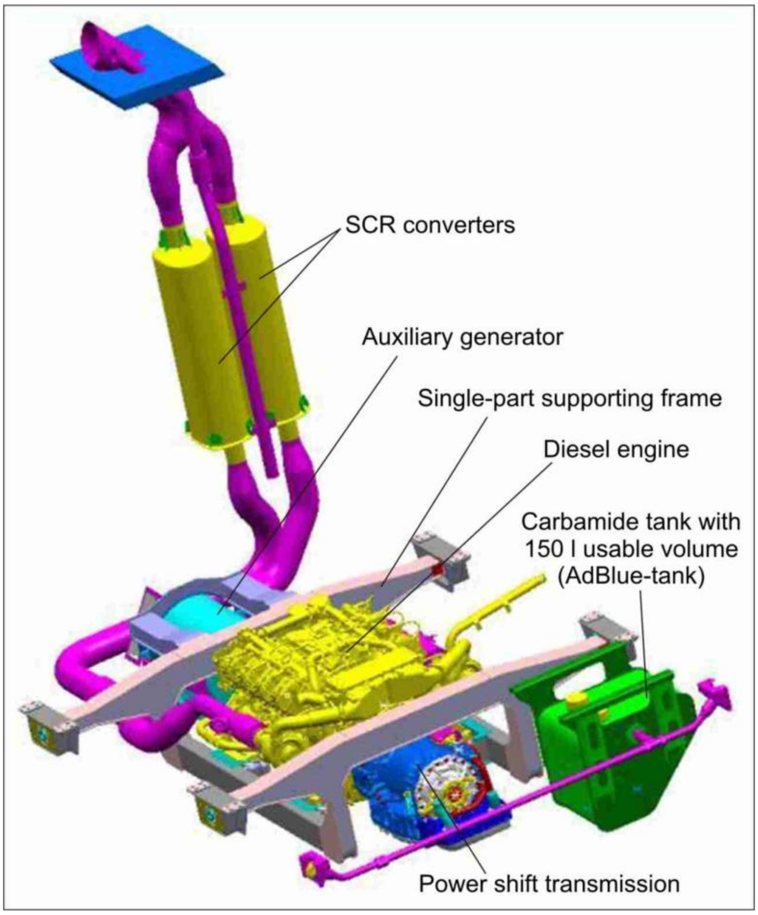

Figure 4: Drive block of the Bombardier Transportation Company for motor wagons

5 CONCLUSION

Rail transport has a relatively small share in relation to other transport modes, and the major part of rail traction is operated by electrical traction (in EU about 80 %). This means that there is very low share of Diesel rail traction and therefore also relatively low environmental pollution from this source. Nevertheless, the regulations regarding limits of the permitted harmful emissions from exhaust gases generated by Diesel traction vehicles have been brought. From January 2012 these values are to be significantly reduced. This refers primarily to nitrogen oxides and particulate matter.

In order to reduce harmful emissions, the measures inside the engine are undertaken as well as the measures of subsequent processing of exhaust gases. Since the permitted emissions are very low, mainly both methods are combined in order to achieve such low emissions.

The measures within the engine mainly mean optimisation of the processes of combustion, injection, turbocharging and returning of exhaust gases with prior cooling. To optimise fuel injection it is necessary to apply the Common rail device which allows electronic control injection according to a set program and at a very high pressure.

Subsequent processing of exhaust gases can be differently conceived depending on the effect of the intra-engine measures. Generally speaking, the oxidation catalytic converter can be used for the oxidation of hydrocarbons and carbon monoxide, particulate filter for particles separation from the exhaust gases as well as SCR-catalytic converter for the reduction of nitrogen oxide emissions. Since a reduction agent has to be used for the SCR-catalytic converter, which complicates this system and makes it more expensive, also $DeNO_x$-catalytic converter can be used, if it can sufficiently reduce NO_x emissions.

The well-known world manufacturers of Diesel engines and rail traction vehicles have developed engines which already meet the future regulations on the exhaust gas emissions which will come into force as of January 2012. For railcars usually the entire drive assemblies are built which in adequate frame have an installed engine, power transmitter and a device for the processing of exhaust gases, and they are typically installed beneath the railcar floor.

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