Final Publishable Activity Report

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1. Project objectives and major achievements

1.1 General project objectives

The main objective of the Integrated Project GREEN is to perform research leading to sub-systems for a heavy-duty powertrain based on the intelligent integration of:

- flexible components
- an improved combustion process
- models for a model based closed loop emission control
- high power density
- integrated exhaust aftertreatment system with good reliability at low load in wide range of operating conditions

this…

- on a competitive cost base
- with the highest fuel conversion efficiency of the Diesel cycle

...to achieve near-zero real world pollutant emissions and significant reduction of CO2.

The objectives broken down to a subproject level gives the following scientific objectives to the project:

Subproject A1: Perform a gas engine with maximum thermal efficiency potential with

- Electro-hydraulic variable valves motion management (EVMG)
- Very near to valves multipoint port-gas injection and experimental study of DI injection
- Cooled EGR
- Gas quality assessment
Subproject A2:  
Evaluate the potential of different variability in combination with tailored exhaust aftertreatment systems based on:

- Novel fuel injection and variable valve actuation (VVA) system combined with
- Functional particulate filter and catalyst
- New control strategies for filter regeneration and injection
- Assessment of different concepts

Subproject A3:  
Develop the concept of a new combustion process and the first step to a model based closed loop powertrain control characterised by:

- High pressure engine with optimised combustion chamber
- Totally new amplified common rail (CR) system with variable nozzle
- Raw emission, thermodynamic and exhaust system models
- Assessment of the developed models in the context of a model based closed loop emission control

Subproject A4:  
Investigate the potential of a high BMEP engine with development of:

- One- and two-stage turbochargers
- New engine design
- Variable compression ratio system
- An exhaust gas energy recovery system.

Independent workpackage WP0.3:  
Investigate the potential for correct migration of the developed HD technologies with:

- Requirements and evaluation
- Concept development and tests
- Dissemination of GREEN results to rail sector
1.2 Project results and impact

A brief introduction about the performed work, achieved results and expected impact from GREEN is given here, more details are found in the following chapters.

During the first period (month 1-12) the focus was on identify the powertrain system specifications in order to reach the final objectives of the project and also to investigate the feasibility of the potential technologies to be used.

For the second period (month 13-24) the main objectives were to finalise the design and procurement of the sub components, both hardware and model based software. Performance tests were conducted on sub-system levels.

In the last period (month 25-39) tests with complete combustion systems were the main objective in order to reach the GREEN targets of emissions and fuel consumptions. In each sub-project the developed combustion system was tested including engine, exhaust aftertreatment system and controls.

The obtained results in third period showed that the emissions targets of NOx and PM were reach with various strategies. The fuel consumption was also improved, but more work is needed in order to reach the fuel targets in all operation points.

In the beginning of the third period some delays in procurement of hardware was identified that should affect the outcome of the project. Therefore an extension of the project with 3 month was proposed by the core group and approved by the scientific officer. The new end date of the project was 20080531.

The impact from GREEN can be divided in short term and long term. For the short term 1-4 year, we will see applications with more advance fuel injection system and more flexible valve attenuation technologies in production. Multiple fuel injection strategies will be used to enable low emission combustion, with most beneficial at low and part load. Increase in fuel injection pressure will continuous for EGR engines in order to reduce soot emission The advanced KVD injector is on this stage an early prototype which has show the potential in combustion optimisation, however if this will be a production in future, a lot of more development is required on component level.

More flexible valve timings will be used in the future, in the beginning more advanced Miller cycles on the intake and in the longer term flexible timings both on intake and exhaust in order to optimise the heat management of the complete powertrain and may increase the engine operating area in low emission combustion.

GREEN results have also show that increased cooling (system and single component level) and improved air management (turbo system etc.) are very beneficial in order to reduce the fuel consumption. These sub-systems have been pointed out to be of most interest for further development in future project in order to improve the energy efficiency of the complete powertrain.

The modelling and the close loop control management are key-technologies in order to integrate the sub-system in a complete powertrain for overall optimisation, but not at least to improve real word emission in transient operations. This is already in production to some level, but further development in electronics, sensors and fundamental modelling will constant improve the capability and performance.
SCR technique has in GREEN shown to be a reliable technique for ERUO VI level, but also potential for improvements. Therefore will SCR techniques be used in the near production. As alternative to SCR EATS, NOx absorption technologies have been tested in GREEN. However, based on GREEN results it is still more improvements needed on performance but also reducing the production costs. Due the cost and reliability is not likely to see this in an application for a long haul truck in the near future, but for other off-road application it may be a solution, together with the GREEN tested burner and filter technology. With shifting quality of fuel on different markets, the sulphur trap is may one way to ensure the functionality on future advanced EATS. However, at the moment the cost due to the amount of rare metal in the sulphur trap is a limitation for production application.

Heat recovery systems have shown in GREEN to have a large potential for fuel reduction on the complete powertrain. Based on GREEN results, future experimental work are need to verify the simulated potential. In the end the complete powertrain have to be assembled in order to do the overall heat management optimisation to achieve the best system fuel consumption.

In summation, GREEN has given unique low emissions values together with improved fuel consumption, both on heavy duty gas and diesel engine application. These practical results together with the gained fundamental knowledge will be a base in future project. Further on has the large number of test hours on components, sub-technologies and combustion system given essential information for the future. As mention above some technologies will be applied in the near future some else require more development on component level. In the end it is the cost beneficial in each technologies will the bottom line for application. To enable future fuel consumption reduction work on the complete powertrain, as mention above, is required along with continual modelling development, both on system level but also on fundamental level.

1.2.1 Main results and most important achievements for reaching the objectives

Subproject A1 Gas Engine for Urban Area (lead contractor CRF)

The conversion of an HD diesel engine to a CNG fuelled one is a complex process because it is necessary to switch from a compressed ignition engine to a spark ignited one: this means to reduce the compression ratio, normally by changing the piston shape, to integrate a throttle valve in the inlet manifold for the load control, to add the ignition system and to adapt the turbomatching to the new flow rate conditions. Moreover, the thermal flow generated by the stoichiometric combustion adopted with natural gas is higher than diesel combustion one, and the cooling circuit conditions have to be optimized when looking at the engine power density increase.

Subproject A1 aimed to develop a CNG Heavy Duty multi-cylinder engine for urban busses achieving simultaneously advantages in terms of emission (80% actual values reduction), global warming index (- 7.4%), thermal efficiency (equal to today HD Diesel engines) and power density (+20% compared to current CNG values).

The base engine selected for the research activities was an HD CNG urban bus engine of 7.8 litres displacement, 6 cylinders in line (bore 115 mm, stroke 125 mm) with 4 valves for cylinder, gas port injection and centrally located spark plug. In order to achieve the above mentioned ambitious targets, the following technologies have been considered and theoretically and experimentally developed and validated on multi-cylinder engines:
Optimised near-to-valves port-fuel injection electronically controlled (including an advanced Pressure Regulator)
Improved cylinder head cooling
Flexible Electro-Hydraulic Valve Management system for Gas engines (EVMG)
Low-pressure Cooled EGR (and Uncooled EGR)
Integrated control system

The final multi-cylinder engine validator including an advanced EVMG system @ inlet valves, an improved cylinder head cooling system, an advanced near-to-valve port-fuel injection system and an advanced integrated control allowed to reach all the targets.

Subproject A2 Enhanced Flexible Engine (lead contractor Volvo)

Subproject A2’s objectives was to design, procure and optimize an engine and EATS system that used enhanced flexibility of the FIE and valve systems to reach the GREEN emission and consumption targets. The FIE and valve systems were selected during the project and the combustion system was optimized for best functionality. The EATS system is of Lean NOx Adsorber type and it was designed for maximum conversion ratio and excellent regenerative capacity. The hardware components was designed, procured and the functionality was proven in engine test cell, where all the systems was shown to work well together. The GREEN emission targets was reached and the practicality of the system was shown from engine and EATS functionality together with the regeneration capacity of the burner system which was included in the exhaust system. The GREEN fuel consumption target was partly reached as the fuel consumption in ESC was improved with three percent compared to the Euro III reference. The GREEN target was five percent improvement in ETC and it was, as mentioned, only partly reached. Main reasons for not reaching the fuel consumption target was that the flexibility of the new systems was so large that all possibilities could not be investigated during the project. The variable valve system did therefore not give the full expected effect. Also the LNA system, although well designed, give a somewhat lower potential than a state-of-the-art SCR system with regards to NOx conversion efficiency.

Subproject A3 Innovative Control and Air Utilisation (lead contractor Daimler)

Within subproject A3 an innovative highly flexible prototype fuel injection system was developed and operated featuring multiple injection capability with independently switching needles in combination with rate shape functionality and pressure amplification. A careful optimization of the combustion system, i.e., matching piston bowl design, spray angle and number of sprays revealed advantages with post injection. On the basis of this system, single cylinder engine tests show that the GREEN targets (low emissions in combination with good fuel efficiency) have a realistic chance to be fulfilled using just one exhaust gas aftertreatment system (SCR system). Even if only minor part of the demonstrated potential could be applied to multi cylinder engines, the improvement is obviously considerable.

Additionally based on a new methodology, thermodynamic and raw emission models applicable for the complete engine map range have been derived which form the foundation of a model-based closed-loop emission control system. The validation demonstrates a good agreement
with measurement data taken from static and dynamic engine operation. The overall model concept derived is an ideal tool for optimizing the whole engine system in an efficient way.

Subproject A4 High BMEP Engine (lead contractor Iveco)

A high output engine with a BMEP of 33 bar was projected (High BMEP). It was designed for a peak firing pressure (PFP) level of 240 bar. Future emission limits had to be reached (NOx-level < 0.5 g/kWh). A particulate emission limit of 0.005 g/kWh required the use of a (closed) wall flow particulate filter. A SCRT- aftertreatment system was chosen. All test components had to be durable to reach a milage of 1.000.000 km.

![Graph showing engine power vs. engine speed]

NOx = 0.5 g/kWh  
PM = 0.002 g/kWh  
BSFC = 204 g/kWh (ETC, European Transient Cycle)  
BSFC = 185 g/kWh (full load, mid speed)  
GWI = 643 g/kWh (Global warming index)  
Max. BMEP = 33 bar  
Durability = 1.000.000 km

WPA4_1: GREEN targets for HBMEP- engine

Workpackage 0.2 Advanced EOCV, Fuel Tests (NONOX, IFP, Ford Otosan)

Task 0.2.1 Advanced EOCV system for gas approach (lead contractor NONOX)

Objectives & results achieved:  
The objectives for WP0.2.1 were twofold:  
a) Supportive actions towards (especially) the A1 project,  
NONOX has contributed to the A1 investigations concerning the impact of varying natural gas composition on behaviour of SI engines. A GET-AKR knock detection system has been supplied to JBRC University of Praha. After calibration measurements the GET-AKR system was successfully applied to the JBRC test engine. NONOX has developed a blending procedure/model by which the properties of various natural gas compositions can be harmonised with respect to their impact on combustion, vehicle range etc. The results of this model were verified on both the JBRC and NONOX test benches.
b) Further development of the NONOX EOCV engine with the purpose of further performance improvement and achieving GREEN project target compliance. In order to realise mentioned project objective, six worktasks have been executed. The results of the most successful tasks are subsequently briefly presented:

- A new cylinder deactivation concept has (theoretically) been investigated by which - in combination with the EOCV throttle free load control - specific fuel consumption can be realised at low engine loads (bmepl=2,5 bar) as low as 235 g/kWh!

- A new scavenged pre-chamber spark plug ignition system has been developed and investigated. The investigated system is found to be very contributial towards further improvement of low load specific fuel consumption – NOx trade off. At bmepl=3,5 bar isfc values have been realised as low as 198 g/kWh while, at the same time, NOx emission was as low as 0.25 g/kWh (during lean burn operation)

- A novel lambda=1+cooled EGR with water separation unit has been developed. In combination with a standard commercial available three way catalist pollutant emissions approach the "near zero level" and thus has given proof to be by far better than the IP GREEN project targets. Green House Gas emissions have also demonstrated to be significantly better than IP GREEN project targets.

c) As a co-lateral activity NONOX has initiated a study in co-operation with a students’ team from Eindhoven University. A variety of themes considered to be relevant in conjunction with the NONOX EOCV technology, (such as Renewable Natural Gas, LNG, GTL) has been investigated. Results can be regarded under: http://students.chem.tue.nl/ifp23/

**Task 0.2.2 Fuel tests for HCCI (lead contractor IFP)**

In order to reach ultra low pollutant emission levels as well as low fuel consumption, it appears possible, as demonstrated in other subproject to act positively on engine design, injection system or after-treatment. One other promising way is to use a different combustion process, such as the Homogeneous Combustion in order to act simultaneously on NOx and Particulate emissions. Nevertheless, such a combustion process suffers from the fact that it can be used only on a limited part of the engine load and speed map. The objective of this part of the research program was to assess how the fuel could help and increase the operating range of the engine keeping possible the conventional Diesel combustion mode. It has been shown that a fuel having a low cetane number and a high volatility favors the homogenisation process and allows to reach higher engine loads under HCCI conditions. Moreover, the fuel chemical composition may influence the combustion behavior in a positive way. Nevertheless, the impact of the fuel could be different depending on the combustion mode (conventional diesel or homogeneous) that implies to find a compromize for the optimum fuel formulation. The limited variations of fuel characteristics within this study, especially of the cetane number, and the fact that no parameter interaction has been studied, didn’t allow to obtain large effects on engine behavior. But, on the opposite, it demonstrated a certain robustness of the engine to these variations.

**Task 0.2.3 Fuel tests for diesel combustion (lead contractor Ford Otosan)**
The fuels, graded from A to E (where fuel coding refers to type of fuel Euro4, MK1, Fischer-Tropsch, GREEN, Mix F-T & EU4, respectively), were prepared by an accredited reference/test fuel laboratory according to FP5 RENEW Project specifications and were tested for diesel combustion:

1. Heavy Duty Engine Exhaust Emission test – ECE 24
2. Heavy Duty Engine Exhaust Emission test – ESC
3. European Transient Cycle – ETC simulation,
4. Engine Performance – full load curve

The results derived from tests above were compared. When they were analyzed, the test results showed that the Fischer-Tropsch fuel gives lower emission values than the others.

Workpackage 0.3 Rail specifications and engine development (lead contractors MTU together with UIC/UNIFE)

MTU’s, UNIFE’s and UIC’s main task in the Green project was evaluating a possible transfer of the developed HD engine to the rail sector. As the rail sector’s requirements (fitment space, weight, life cycle costs, etc.) differ from the automotive sector a list of specifications was set up and each requirement analysed and evaluated. The specification list’s set up and the evaluation was strongly supported by the UIC Diesel Expert Group.

Summarising the evaluation process it is to be stated that the GREEN HD engine can be transferred to the rail sector generally. The GREEN HD engine fulfills the rail requirements and can be transferred with slight modifications only.

This final statement is the result of vivid interactions between the automotive sector and the engine manufacturer on the one hand and the railway sector on the other hand.

The task 0.3.2 (MTU) of WP 0.3 was the development of a new combustion concept for diesel rail engines, which allows to fulfil future emissions legislation (2012 and later), by transferring promising techniques used in on-highway truck engines to rail engines. The investigations were concentrated on locomotive engines. Here the focus was on the in-cylinder reduction of NOX-emissions in order to be able to fulfill future NOx-emission legislation without aftertreatment. Tasks 0.3.1 and 0.3.3 (UIC, UNIFE) included the definition of the railway specific needs and technical requirements as well as the dissemination of the information to the railway sector. For this reason, a special rail-end user group was installed.

In order to reach the objectives, the possible in-cylinder measures for the reduction of engine-out NOx raw emissions in locomotive applications have been described and evaluated in a first step. The study has shown that technologies like EGR, homogeneous combustion and variable valve actuation are the most promising ones for rail application.

In a second step a new combustion process with full air utilization has been examined on a single cylinder engine. Some additional features which were meant to reduce the necessary EGR-rate could not be realized. This result impacts the cooling system of IIIb-compliant diesel locomotives since either the efficiency of the cooling system or the dimensions of the coolers has to be increased in the future.
In a third step, the new concept has been examined on a multi-cylinder demonstrator engine (prototype). Altogether, the outcome of Task 0.3.2 is a combustion process which meets the EU-stage-IIIb regulation. Within the scope of the Cleaner-D project (7th EU frame programme) first prototype-engines will be intensively tested in different rail applications. Therefore it can be concluded that the results of the GREEN project provide important input to the Cleaner-D project.

1.2.2 Relation to the state-of-art

Subproject A1 Gas Engine for Urban Area (lead contractor CRF)

The final CNG multi-cylinder engine validator including the advanced EVMG system at inlet valves, the improved cylinder head cooling system, the advanced near-to-valve port-fuel injection system and the advanced integrated control has been qualified, at rated power of 243 kW (more than +20% compared to current CNG values), on the ETC cycle.

The following table summarizes the ETC cycle results with reference to the GREEN targets

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>EEV</th>
<th>Euro VI (proposal)</th>
<th>GREEN targets</th>
<th>EVMG results</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>3.0</td>
<td>4.0</td>
<td>1.5</td>
<td>1.9</td>
</tr>
<tr>
<td>CH4</td>
<td>0.65</td>
<td>0.5</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>NMHC</td>
<td>0.40</td>
<td>0.16</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>NOx</td>
<td>2.0</td>
<td>0.4</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>PM</td>
<td>0.020</td>
<td>0.010</td>
<td>0.003</td>
<td>0.003</td>
</tr>
<tr>
<td>CO2</td>
<td>-</td>
<td>-</td>
<td>617</td>
<td>610</td>
</tr>
</tbody>
</table>

All the targets can be considered achieved.

The emissions on the ETC cycle are fulfilled for all pollutants (except CO): this is the consequence of a slightly rich lambda control adopted in order to respect the NOx target in a consistent way. CO emission, although higher than the target, are lower than 50% of the most stringent EU limits (Euro VI, after 2012).

The CO GREEN target can be fully achieved by increasing catalyst size from 8.5 to 13 liters. Taking into account that CO is not a critical pollutant from the air quality point of view and that Euro VI relaxes the CO limit in favour of NOx, it is worth to evaluate the cost/benefit trade-off of the GREEN CO target.

Subproject A2 Enhanced Flexible Engine (lead contractor Volvo)

The achieved results in A2 show that the novel fuel injection system give good functionality with regards to injection flexibility and fuel pressure requirements. It gives a opportunity for keeping very high injection pressures together with very good injection rate shaping capability and multiple injection capacity. The variable valve system give possibility to vary inlet valve closing timing. This was not utilized so much in the project as this influence cold not be shown to give a good total result. It is easily possible to control emissions with the variable valve capacity but most of the time it is negative to fuel consumption. However as the flexibility is very good only part of the potential could be investigated in this program and it may be possible to use the
system more efficient than is shown here. A better boosting system than what was available should also increase the possibilities to utilize the flexible valve system better. The Lean NOx Adsorber aftertreatment system showed good conversion efficiency but did not reach the capacity of a state-of-the-art SCR system in ETC. As this is a prototype system there is potential for further improvement. However to reach the levels of a good SCR system a dual LNA system is probably required. As the noble metal content is relatively high, a dual system would probably be less cost efficient than a SCR system.

Subproject A3 Innovative Control and Air Utilisation (lead contractor Daimler)

The main advantages of the developed variable fuel injection system are an adapted hydraulic flow using two different nozzle flows within one injector, adapted spray cone angle by two different angles in the nozzle and a hydraulic separation down to zero between two injection events by using both nozzle rows. These features offer the potential to a better compromise of emissions and fuel consumption at different operating points when the combustion system is accurately adapted.

Due to the inaccuracies of current open-loop control system large safety margins are needed to guarantee the compliance with the emission legislation. With the proposed more accurate control algorithms the margins can be tighter which allows reducing the fuel consumption. The derivation of this sophisticated feedback control is based on the derived transient emission models. To substitute sensors, parts of the developed models can be used directly as a virtual sensor, to estimate immeasurable states or values. This is necessary due to the lack of fast and reliable emission sensors. Additionally, virtual sensors do not deteriorate which represents another advantage.

Subproject A4 High BMEP Engine (lead contractor Iveco)

The high BMEP engine was designed for 240 bar Peak Firing Pressure (PFP). To reach a target BMEP of 33 bar, improved single-stage or two-stage turbocharging was necessary. An advanced high pressure common rail injection system was used to optimise the combustion and to keep engine out soot low in order to minimise the soot filter loading. The engine had an EGR-system and SCRT-aftertreatment (selective catalytic NOx-reduction with Urea (Ad Blue) injection, Fe-zeolite based catalysts and a wall flow particulate filter). The Fe-zeolite technology was chosen based on investigations within the aftertreatment workpackages of Subproject A4.

There is a BSFC improvement of 5% vs. Euro 3 engines in a emission test cycle (ETC). With this engine technology it seems even possible to improve BSFC of EuroV engines, inspite of stricter emission targets (GREEN-target, Euro VI-like) and 20% higher BMEP.

The feasibility of improved single stage turbocharging (axi/radial-compressor) and a variable compression ratio system (VCR) for a heavy duty HBMEP engine was demonstrated.

Workpackage 0.2 Advanced EOCV, Fuel Tests (NONOX, IFP, Ford Otosan)

Task 0.2.1 Advanced EOCV system for gas approach (lead contractor NONOX)
The main result achieved during the IP GREEN is that the NONOX EOCV throttleless load control engine, when operated with the novel Lambda=1+cooled EGR+TWC concept, can comply with - and even significantly exceed - the IP GREEN pollutant emission targets. Compared to the original lean burn concept a minor penalty in specific fuel consumption (sfc) was faced. Compared to the state of the art Diesel engines a significant improvement (up to 20%) in greenhouse gas emission (GHG) can be obtained, while system complexity and system costs of the exhaust after treatment system (EAS) are supposed to be much lower compared to current EURO IV, V, VI EAS. The absence of the necessity to make use of “ADD BLUE” (as required for SCR EAS) marks an additional advantage in terms of operational costs compared to state of the art (and future) Diesel engines. State of the art natural gas engines can also be outstanding in emission behaviour, but, compared to the GHG emission of the NONOX engine, the (potential) advantage in GHG emission of app. 20% against Diesel will almost vanish completely due to poorer fuel efficiency. One of the major advantages of the NONOX EOCV technology is the convenience of applicability to existing engines. Basically, the EOCV system can be applied as an ADD ON Technology, i.e. without the need for a structural redesign of the cylinderhead and crankcase structure.

**Task 0.2.2 Fuel tests for HCCI (lead contractor IFP)**

Among the amount of recent publications about the impact of the fuel on engine's performances and emissions, few are dedicated to Diesel HCCI engine and rare are those showing direct relations between fuel characteristics and combustion. Moreover no comparison between the fuel impact on Diesel and HCCI combustion have been found. But all the studies agree on the fact that for HCCI combustion, fuel with lower CN and higher volatility compared to EN590 fuel would be necessary. On that point, results in literature agree with IFP ones.

**Task 0.2.3 Fuel tests for diesel combustion (lead contractor Ford Otosan)**

<table>
<thead>
<tr>
<th>Test Grade</th>
<th>Fuel</th>
<th>Aromatics Total (%vol)</th>
<th>PolyAromatic Hydrocarbons (%vol)</th>
<th>Cetane number</th>
<th>Distillation 95% (°C)</th>
<th>Density (kg/m3)</th>
<th>Sulphur Content (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Euro4</td>
<td>20-25</td>
<td>&lt; 3</td>
<td>51-54</td>
<td>340</td>
<td>830</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>B</td>
<td>MK1</td>
<td>4</td>
<td>&lt; 0.1</td>
<td>54</td>
<td>285</td>
<td>810</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>C</td>
<td>Fischer-Tropsch</td>
<td>&lt; 0.5</td>
<td>-</td>
<td>&gt; 70</td>
<td>What given</td>
<td>780</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>D</td>
<td>GREEN</td>
<td>25-30</td>
<td>3-6</td>
<td>45</td>
<td>What given</td>
<td>840-850</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>E</td>
<td>Mix F-T &amp; EU4</td>
<td>10</td>
<td>60</td>
<td></td>
<td></td>
<td></td>
<td>&lt; 10</td>
</tr>
</tbody>
</table>

When the test results for the above fuels were analyzed, it was seen that Test Grade C (Fischer-Tropsch) gave lower emission values than the others.

The basic distinction of Grade C is being composed of the specifications with maximum cetane number and minimum aromatics and minimum density.
Workpackage 0.3 Rail specifications and engine development (lead contractors MTU together with UIC/UNIFE)

Diesel rail vehicles are usually classified into Diesel locomotives and Diesel railcars (DMU). Both vehicle types are mainly used in Europe on non electrified branch lines, which are characterized by a limited allowable axle load (max. 18t/axle) and small tunnel profiles (Tunnel profiles in UK are the smallest in Europe. The maximum allowable height of rail vehicle built for UK is almost 30 cm lower than for the rest of Europe. They are designed for a service life of 30 years.

**Diesel locomotives**

European Diesel locomotives are normally powered by one high-performance engine (>560 kW-3000 kW derived from marine, mining or stationary engines) and are used for passenger and freight services. The power equipment is installed in a special machine room inside the locomotive's body.

**Diesel railcars**

Diesel railcars (or DMU) are designed for passenger service only, are either single coaches or fixed coupled consisting of 2 or max. 3 power cars. Normally, each unit is driven by one medium power engine (250kW < 560kW), which is often a derivate of off-highway industrial or on-highway truck engine. The power equipment is installed under floor, e.g. below the passenger cabins.

In contrast to electrical rolling stock both diesel driven vehicle types have to carry their own energy source onboard (1-2 tons fuel for railcars/ 2-8 tons for locomotives). Today, both the general requirements caused by the rail infrastructure (tunnel profiles, max. axle load) and the functional requirement to carry the locomotive's own energy supply onboard force the manufacturer to utilise all available space in, under or above the vehicle (refer to figure 1 and 2).

Latest investigations of the European rolling stock manufacturers show that meeting the new Stage III B emission limits of 2004/26/EC will require voluminous additional equipment to be installed in rail vehicles.

“Stage III B” will require the following additional external equipment:

- Exhaust gas after-treatment systems for NOx reduction (SCR, with urea tank, heated piping and NOx catalyst) and particulate filter (DPF) require additional space and weight.
- As cooled exhaust gas for the modified combustion cycle is required, a larger engine cooling system is the consequence.
- Space for additional auxiliary power needed (e.g. for larger cooling fans).
- Engine weight increase
- When the lengths of the locomotives increase to package all the above mentioned additional components the body has to be strengthened too, this causes an additional increase in axle load.

Realistic assumptions show a weight increase of 3 to 4 tons for a 4-axle locomotive and about 0.5 – 1 ton for railcars. Even modern existing 6-axle locomotives, which are the largest and most powerful used in Europe, have axle loads of more than 21 metric tons today. This limits its use to high capacity main lines.

Facing the general arrangements of modern diesel rail vehicles it must be stated that today's locomotives/ railcars have already reached their regulated size and weight limits. Consequences of increased weight and space, due to additional equipment for Stage III B equipment:

**Locomotives:**
– Restricted use of 4-axle locomotive on branch lines (due to weight), and into customer’s terminus (shunting).
– There is a risk that locomotives may no longer be allowed on non-electrified branch lines and in rural areas; this threatens rail freight as cost-intensive electrification as an alternative is questionable.
– Limited space and weight may be counteracted by integrating a smaller and lighter engine with reduced power but this increases the number of locos necessary for rail service thus higher transport cost
– When axle load must be increased to allow heavier equipment and vehicles must be longer, rail infrastructure must be improved. very high cost
– Avoid a Modal Shift from rail to road. (One 2000kW locomotive hauls the same freight volume as 50 trucks with 400kW each.)

**Railcars:**
– Loss of passenger capacity due to additional space requirement for After-treatment device

In order to apply the HD diesel engine technologies to diesel locomotives and multiple units UIC & UNIFE have drafted a list of rail specifications:

– **Fitment space engine + periphery < 110%**
  - Path 1: EGR-concept: 110% is possible from today’s point of view
  - Path 2: SCR-concept: only with considerable development effort achievable

– **Weight of engine + periphery < 110%**
  - Path 1: EGR-concept: 110% is possible from today’s point of view
  - Path 2: SCR-concept: ca. 115% is achievable from today’s point of view

– **Purchase cost of all traction equipment incl. engine + periphery and transmission < 110%**

– **Purchase cost of the engine incl. additional components, cooling equipment, auxiliary equipment and exhaust post-emission treatment < 120%**
  - No exact quantitation possible. From today’s point of view engines with exhaust gas after-treatment will become significantly more expensive than today’s engines without after-treatment.

– **Operating costs incl. maintenance < 105%**

– **Costs of operating substances (fuel, oil, coolant, reducing agent, etc.) < 100%**
  - No exact quantification possible. To achieve these values is the target of the MTU development strategy.

– Engine + periphery overhaul intervals (DMU traction unit < 600kW) > 800 ton km
– Engine + periphery overhaul intervals (locomotive traction > 600 kW) > 1.2 million km
  - It is expected, that the same standard as today will be reached.
– Transmission overhaul intervals (DMU traction unit < 350kW) > 800 ton km
– Transmission overhaul intervals (DMU traction unit > 350kW) > 1.6 million km
– Transmission overhaul intervals (locomotive traction > 600kW) > 2.4 million km
  - There will be no change in the required specifications of the transmission due to the emission concept.
– No second operational fluid In the case of SCR an additional fluid is necessary.
– No restrictions regarding suitability for rail sector use (idling, non-stationary load profiles, ambient temperatures, vibrations, etc.)
– Approval in accordance with UIC Leaflet 623 “Approval procedures for diesel engines of motive power units”
The new combustion system for locomotive application that fulfills emission legislation stage IIIb (NOx + HC: 4.0 g/kWh) is an EGR-concept. As mentioned in Chapter 1.2.1 the benefits of some additional features like Miller-cycle and homogeneous combustion, which were meant to reduce the necessary EGR-rate and thus the necessary cooling capacity that has to be installed, could not be realized at full load. Hence, the resulting concept is an EGR combustion system for in-cylinder NOx-reduction, completed by the use of a Diesel particulate filter (DPF) for reduction of PM emissions.

The use of EGR is completely new for locomotive applications and thus the absolute state of the art in this field of engines. Today’s stage IIIa-engines (NOx: 6.0 g/kWh) still use the Miller-cycle.

Altogether it can be concluded, that the EGR-technology, which is already well-known in on-highway heavy-duty truck applications, has been successfully transferred to the rail sector within the GREEN project in WP 0.3.

1.3 Conclusions and outlook

General

The GREEN project has now been ended after 39 month and all partners have full field their tasks. The main results and achievement are summarised and concluded as:

- All technical deliverables and milestones have been fulfilled
- Component on sub-system level have been developed and tested. Their performance and potential have been stated and recommendations for future work are given.
- The GREEN emission targets have been fulfilled, both in gas and diesel engine application
- The fuel consumption has been improved in all applications.

Different single or combinations of components and sub-technologies have enabled these promising results. But also the very good collaboration between the partners have been a determining factor in order to deliverer in time or to do the right action and priorities when delays were present in the project.

Today it is still possible to improve all the used GREEN components or sub-technologies. However, in the near future more work are required on GREEN technologies in order to improve the robustness on single components if they should be applied in production. In the future, the air management system (turbo, valves etc) and the cooling system are crucial sub-systems in order to gain the maximum from the new combustion system based on flexible engine, as multiple fuel injections and variable valve timing.

For the overall powertrain optimisation and in order to increase the energy efficiency, integration between sub-system and close loop functionality is considered to be the key-factor. Further on, is improved in-cylinder pressure and heat recovery system approaches that will improve the fuel consumption, but the effect will be different on various applications.

Subproject A1 Gas Engine for Urban Area (lead contractor CRF)

The work carried out within SPA1 allowed to reach outstanding results respect to the state-of-the-art in terms of performance, consumption and emissions.
The technologies integrated onto the final multi-cylinder CNG engine validator could be available on the market within a short-medium period (two-three years from the completion of the Project). In order to facilitate their industrial introduction some efforts should be dedicated to the development of a more advanced engine control system (integrated single ECU) for managing all the new functionalities and including the capability to adapt the regulation parameters to the gas fuel composition also taking into account the opportunity to use methane + hydrogen blends. The use of this kind of blend represents an additional step in the reduction of both pollutant emissions and CO\textsubscript{2} formation. Apart from the “natural” extra reduction of the CO\textsubscript{2} emissions due to the increase of the H/C ratio of the fuel, hydrogen represents a flame propagation booster which could provide an additional gain to the thermodynamic efficiency. Moreover, a reduction in THC emissions is also expected taking into account the reduction of the flame quenching phenomena.

**Subproject A2 Enhanced Flexible Engine (lead contractor Volvo)**

The flexible engine approach to reach the GREEN targets resulted in that the emission targets was fully reached and the fuel consumption targets was reached partly.

The F1 fuel injection is very interesting for the future as it gives the opportunity to combine very injection pressures with flexible rate shaping potential and excellent multiple injection capacity. There is also shown, on a prototype level, a good functionality in engine testing. The variable valve system have an excellent functionality, but the capacity was difficult to use fully as it was often a problem with fuel consumption penalty when using the functionality. However, a better boosting system (than available in this project) in combination with variable valve system is an interesting opportunity for the future. It is also depending in which engine out emission level that is required. The LNA system worked very well, but the NOx conversion efficiency was lower than for a state-of-the art SCR system. It is possible to reach as high conversion efficiencies with LNA system as with SCR systems, but as the noble metal content is high in such LNA systems it is probably not cost efficient to use them for heavy duty applications.

**Subproject A3 Innovative Control and Air Utilisation (lead contractor Daimler)**

A high potential of improvement has been demonstrated with the variable injection system, however, it becomes obvious that this can not be simply transferred to multi cylinder applications. On the one hand, sophisticated hardware such as the KVD nozzle will not be available for multi cylinder applications in the foreseeable future. On the other hand, the project gave an idea of the system complexity and the required efforts to apply it to multi cylinder engines and to utilize all its benefits.

The engine models derived in combination with the new methodology permit investigating

- future offline front-loading powertrain concepts involving system configuration and operation strategies
- future innovative integrated powertrain control systems.

To complete the tool chain, simplified aftertreatment models need to be derived and coupled with the engine model. Based on this virtual powertrain system, the best control concept can be derived and afterwards realized and evaluated in real-life.
Finally it is emphasized that both - any improvements in the combustion concept and any improvements in control - can be combined with other improvements which refer to the engine cycle, exhaust aftertreatment, downsizing etc.

Subproject A4 High BMEP Engine (lead contractor Iveco)

It was possible to further improve engine efficiency even at more stringent emission limits and higher BMEP. The costs of the related technologies were highlighted. A variable compression ratio system (VCR) is feasible also for heavy duty HBMEP engines and could be a way to increase the power of existing engines with standard structure with no impact on the engine outer dimensions. An improved single stage turbocharger (axi/radial compressor) was realised and tested. It fulfilled the requirements for this engine.

From studies of exhaust heat recuperation systems, further potential for BSFC- reduction was revealed by simulations. Experience was gained with different EGR- systems and related problems of condensation, corrosion and engine. Tribological and friction behaviour of a high PFP engine were evaluated.

The technologies for high BMEP engines will be used step by step for future applications. The improved single stage turbocharging can fulfill the requirements for the next performance steps with not too demanding space requirements for actual vehicles. The high pressure common rail injection, EGR and the SCRT- aftertreatment will probably become standard for onroad applications in Europe. Improved materials for castings and steel pistons will be applied in some cases to build more compact and lighter engines at the required power output. Improved structure design will fulfill short term requirements.

Workpackage 0.2 Advanced EOCV, Fuel Tests (NONOX, IFP, Ford Otosan)

Task 0.2.1 Advanced EOCV system for gas approach (lead contractor NONOX)

Major conclusion after finilising the IP GREEN, as far as NONOX is concerned, is that the NONOX EOCV technology, in combination with natural gas as a fuel, can be seen as a viable alternative by which the defined project objectives can be met and even can be exceeded. Nowadays modern society is increasingly confronted with the twin challenge of finding a solution for CO2 (GHG) emission reduction and the security of energy supply while global energy demand is steadily increasing.

Fig 1.3-1 Oil price development in US$ and € during IP GREEN
Fig 1.3-2 specific well to wheel CO2 emission as function of fuel costs
In view of this fact it can be stated that new technology will be required by which CO2 emission and energy consumption can be (more or less/ partly) un-coupled. The results obtained during the IP GREEN verify that the NONOX EOCV technology is indeed a technology that can contribute to a solution. This specifically is the case if (renewable) natural gas can be introduced as fuel. The fact that within WP02.1 the GREEN project targets were met and exceeded with only a funding of less than 1% of the overall project budget, does emphasize the potential of the NONOX EOCV technology.

Further exploitation of the NONOX technology is thought to be majorly influenced by the (reducing) reluctance of OEM’s towards natural gas engine technology and the increasing availability of infrastructure. From the fleetowners’ point of view, the possible reduction in fuel costs (> € 15,000,- savings p.a. for a HD truck at 150,000 km p.a., compared to diesel), there is a clear pro-acceptance attitude. Therefore further exploitation of the NONOX technology requires new innovative marketing methods besides series product development. In accordance to this: NONOX plans a vehicle demonstration program as the next step. NONOX has applied for this demo project in the Netherlands.

Task 0.2.2 Fuel tests for HCCI (lead contractor IFP)

Through the study carried out by IFP on a single-cylinder direct-injection Diesel engine, able to run under both HCCI or Diesel conditions, it has been demonstrated that the fuel may act on the engine behaviour. By variations of the cetane number, the volatility and the composition it appeared possible to increase the HCCI operating range of the engine.

However, additional works, by testing larger variations of fuel characteristics as well as parameter interactions, would be necessary to obtain supplementary informations and to maximize the potential of the fuel in terms of HCCI operating range enlargement.

These results will help engine manufacturers as well as oil companies to better adapt their products in order to obtain the low pollutant emissions and fuel consumption required in the future.

Task 0.2.3 Fuel tests for diesel combustion (lead contractor Ford Otosan)

IP GREEN, besides subprojects, consisted in a task dedicated to studying on how alternative fuels affects the Diesel combustion cycle. The results gained from the task will be used in other subprojects, regarding diesel combustion.

The tests were conducted on a Euro III stage reference engine that was assembled with a 100% measured parts and went through 50 hours of Break-in process to be ready for the tests. However, the fuels included a Euro IV fuel, which was chosen to be the reference fuel and given a ‘100’ value, while the rest of the fuels scaled to this value.

In the future, the fuels can be tested on a Euro IV stage engine and the results can be compared with respect to this task results.

Workpackage 0.3 Rail specifications and engine development (lead contractors MTU together with UIC/UNIFE)
Altogether, in WP 0.3 of the GREEN project a new combustion system for locomotive application has been developed, that fulfills the emission legislation stage IIIb.

UIC and UNIFE defined the railway specific needs and technical requirements and disseminated the results of the GREEN project to the railway sector.

MTU developed the new combustion process on a single-cylinder engine and validated it on a multi-cylinder engine.

MTU aimed to develop a new combustion concept for diesel rail engines which allows fulfilling future emissions legislation (2012 and later). The technologies used for HD truck engines offer possibilities to be transferred to rail engines. However, it is important to pay attention to the different operating conditions in rail applications. Engines for railcar application with power output less than 560 kW are usually derived from HD engines, and the transfer of technologies is relatively easy to realise. “Locomotive” engines with power output of typically 1000 kW to 3000 kW are not derived from HD engines. The transfer of HD technologies to these engines is much more difficult to achieve and for this reason, the investigations of task 0.3.2 are concentrated on locomotive engines. Here, the focus is on the in-cylinder reduction of NOx-emissions in order to be able to fulfil future NOx-emission legislation without after-treatment. Regarding the particulate emissions, a DPF might be possible. In a first step the possible in-cylinder measures (from on-highway heavy duty applications) for the reduction of engine-out NOx raw emissions in locomotive applications have been described and evaluated. The study has shown that technologies like EGR (Exhaust Gas Recirculation), homogeneous combustion and variable valve actuation are the most promising ones for rail application. For this reason, in a second step a new combined combustion process (conventional combustion with EGR + HCCI) has been thoroughly examined on a single cylinder engine. Altogether this combined combustion has given promising results. However, it has been shown that the benefits of this combustion can only be exploited at part load and that at full load the necessary EGR rate can not be reduced, compared to a pure heterogeneous combustion. Hence, the full load point will be operated in pure heterogeneous combustion with EGR (this is also a new HD-technology that has been transferred from on-road to rail application in task 0.3.2), and the desired reduction of the necessary cooler size in the locomotive can not be realized. This result impacts the cooling system of IIIB-compliant diesel locomotives since either the efficiency of the cooling system or the dimensions of the coolers has to be increased.

In a third step, the new EGR-concept has been examined on a multi-cylinder demonstrator engine (prototype). Altogether, the outcome of the research is a combustion process which meets the EU-stage-IIIB limits. Based on these results, an EU-stage-IIIB compliant diesel engine is currently developed at MTU. Emissions of nitrogen oxides are reduced by an EGR combustion process and the emissions of particulates are reduced by a diesel particulate filter (DPF). Within the scope of the CleanER-D project, that was submitted to the European Commission under the EU 7th Framework Programme 2nd call, the first prototype-engines will be intensively tested in different rail applications – in a mainline locomotive and in a shunting locomotive. Therefore it can be concluded that the results of the GREEN project provide important input to the CleanER-D project.
2. Project Objectives and major Achievements from each Subproject for the full duration of the GREEN project

2.1 Subproject A1 – Gas Engine for Urban Area (lead contractor CRF)

2.1.1 Subproject Objectives

Subproject A1 aimed to define a CNG Heavy Duty multi-cylinder engine for urban busses with minimum local emissions (a very sensible aspect for urban areas), with reduced impact on the Green house effect (of more and more importance for the entire World) and, at the same time, with advantages in term of fuel efficiency and power density vs. “today” HD diesel engines.

2.1.2 Relation to the state-of-the-art

The base engine selected for the research activities was an HD CNG urban bus engine of 7,8 litres displacement, 6 cylinders in line (bore 115 mm, stroke 125 mm) with 4 valves for cylinder, gas port injection and centrally located spark plug. The Target was to achieve simultaneously advantages in terms of emission (80% actual values reduction), global warming index (- 7,4%), thermal efficiency (equal to today HD Diesel engines) and power density (+20% compared to current CNG values) as reported within fig A1.1

![Fig. A1.1 SPA1 Targets Vs state-of-the-art](image)

2.1.3 Work Performed & Final Results

- Methodology and approaches

In order to achieve the above mentioned ambitious targets, the following technologies have been considered and theoretically and experimentally developed and validated:

@ Multi-cylinder Engine

- Optimised near-to-valves port-fuel injection electronically controlled (including an advanced Pressure Regulator)
Improved cylinder head cooling
Flexible Electro-Hydraulic Valve Management system for Gas engines (EVMG)
Low-pressure Cooled EGR (and Uncooled EGR)
Integrated control system
EVMG strategies for Turbocharging harmonisation (by simulation)
@ Single-cylinder Research Engine
Direct Injection

Furthermore has been carried out a detailed theoretical and experimental analysis concerning the effect of Gas quality vs. Engine behaviour

The following paragraphs summarise main activities and results for these different approaches.

EVMG Multi-cylinder Engine Development (CRF, MT)

The above mentioned technologies have been developed and tested and the most promising solutions have been integrated on a Multi-cylinder Engine Validator.

EGR technologies have been tested on the base multi-cylinder engine.

Cooled EGR allows up to 15% power increase thanks to the charge dilution, without introducing additional oxygen allowing therefore to maintain the 3-way catalyst aftertreatment. The EGR requires new components (cooler, valve, control system) and introduces additional problems: Higher heat rejection; Slower response (turbo lag); Humidity condensation (more critical with stoichiometric CNG); Difficult spark advance control in transient operation: the best efficiency spark timing adopted with EGR is dangerous for knock if the actual EGR flow is lower than the target.

Uncooled EGR allows a partial reduction of throttling losses at low loads with fuel consumption reduction up to 7% (best point) but, again, it requires new components (valve and control system).

For these reasons both Cooled and Uncooled EGR have been not integrated on the final validator.

A final multi-cylinder engine validator including an advanced EVMG system @ inlet valves, an improved cylinder head cooling system, an advanced near-to-valve port-fuel injection system and an advanced integrated control has been developed, assembled and tested.

The engine has been equipped with an advanced pressure regulator and with a fuel rail specifically designed by MT. In details, the following Table summarized the final results in comparison with the targets and the value of the same parameters of the pressure regulator and fuel rail actually present on the market.

<table>
<thead>
<tr>
<th>PRESSURE REGULATOR</th>
<th>Market value</th>
<th>Target value</th>
<th>Measured value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight [kg]</td>
<td>3</td>
<td>2</td>
<td>0.9</td>
</tr>
<tr>
<td>Flow Rate [kg/h]</td>
<td>-</td>
<td>5/65</td>
<td>2/70</td>
</tr>
<tr>
<td>Max Out Pressure Range [bar]</td>
<td>&lt;=0.6</td>
<td>&lt;=0.4</td>
<td>0.3/0.4</td>
</tr>
<tr>
<td>Min working temperature[°C]</td>
<td>-15</td>
<td>-25</td>
<td>-30</td>
</tr>
<tr>
<td>Leakage @ low temperature</td>
<td>6</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>FUEL RAIL [max flow rate &gt; 65 kg/h]</td>
<td>Market value</td>
<td>Target value</td>
<td>Measured value</td>
</tr>
<tr>
<td>Max Out Pressure Range [bar]</td>
<td>-</td>
<td>0.2</td>
<td>&lt;0.1</td>
</tr>
</tbody>
</table>

In Fig. A1.2 are reported the final configuration of the pressure regulator and the fuel rail.
An advanced EVMG (electro-hydraulic variable valves motion management for Gas engines) system, based on the lost motion concept, has been developed and set-up with the main objective to manage the air/Methane charge to the cylinders without the presence of the intake throttle valve; this valve is, in fact, necessary in a stoichiometric engine, but it has a negative impact in terms of fuel consumption due to its pressure loss. In such way there is the try to improve fuel consumption of a Methane stoichiometric engine, that shows the best potential in the emissions minimising effort. According to the concept phase and design guidelines conclusions, the flexible lift and timing control has been applied only to the intake valves.

EVMG system is mainly composed by an intermediate hydraulic circuit set between the camshaft and the valve train. When the circuit is maintained closed, the opening/closing of the inlet valve is done according to the base camshaft profile (“full lift” mode).

On the contrary, the system provides the capability to act an “early closing” of the inlet valve by discharging the lube oil circuit by means of the solenoid valve, thus realizing a ballistic closing of the valve; in this way, the air at the intake is directly controlled by the valve lift and the engine can be run dethrottled, with an immediate advantage in terms of fuel economy.

This driving mode provides also the opportunity to handle an over expansion of the inlet charge during the intake stroke, reducing the final temperature at the end of the compression, giving an extra margin versus knocking appearance and reducing NOx formation. Moreover, it is possible to optimize the full load behaviour using a camshaft profile expressly tuned for the maximum power output and realizing an early closing of the inlet valve at lower engine speed in order to avoid backflow phenomena and to have the best engine volumetric efficiency.

On the other hand, the EVMG system provides the opportunity to manage also a late inlet valve opening (“LIVO” mode) particularly adapted to control combustion stability at very low engine load: the effect realized by this driving mode is the acceleration of the turbulence inside the combustion chamber with an acceleration of the flame speed propagation.

When the engine speed is not too high, it is also possible to drive the so called “multilift” mode, starting with a early closing mode followed by a “LIVO” mode within the same combustion cycle: it is possible to obtain a maximum benefit in terms of fuel economy maintaining a good stability of the combustion. A schematic overview of the potential allowed by the EVMG system is provided in Fig. A1.3.

An advanced integrated control system able to interface via fast communication system (CAN) the Engine Control Unit, the EVMG Control Unit and the Vehicle control Unit has been developed. The control system concept is represented in Fig. A1.3.
Fig. A1.3 Concept of EVMG system and its Integrated Control System
After the preliminary debugging of the developed EVMG system, including the electronic control, the first multi-cylinder engine tests have been carried out in full load conditions in order to assess the effectiveness of the improved cylinder head cooling system.

The measurement has been carried out in Full Lift valve mode and stoichiometric conditions. The cylinder head temperature in function of engine power is shown and compared with the base engine in Fig. A1.4 (the green vertical line at 200 kW corresponds to the power setting of the base engine): the temperature is reduced at a very low level and is not limiting engine performance any more and consequently the power curve has been defined as follows:

- **Rated power:** 245 kW from 1800 to 2000 rpm versus a target of 240 kW
- **Peak torque:** 1300 Nm (corresponding to a Brake Mean Effective Pressure of 21 bar) from 1200 to 1800 rpm

At rated power, temperature before turbine is the other critical parameter affecting reliability. Thanks to the fluid dynamic optimization and to the proper turbocharger matching, combustion is stable and efficient and the exhaust temperature is 840 °C, still acceptable if proper materials are selected.

The behaviour of the electronic valve management system and its effects on engine combustion have been carefully analyzed over the engine map; the main parameters investigated were:

- the capability to control the air flow in accurate and reproducible way
- the even distribution of air and fuel between the different cylinders
- the in-cylinder pressure cycle, analyzing pumping losses, heat release rate and the Coefficient of Variation of the Indicated Mean Effective Pressure (COV of IMEP).

The system is working correctly also at very low loads and there is no need for throttling.

As an example, Fig. A1.5 shows the comparison of the pressure cycle at 1350 rpm and 3.8 bar BMEP between Full Lift mode with throttling (inlet manifold absolute pressure 600 mbar) and EIVC without throttling: pumping losses are reduced by 90% and fuel consumption is reduced by 8%.
The engine has been first optimized in Full Lift valve mode, then in EVMG mode according to the above control strategies, introducing the necessary corrections for spark advance and injection timing.

Fig. A1.6 shows the engine efficiency map: peak efficiency of 38% is an excellent figure for a stoichiometric spark ignited engine; the fuel consumption reduction versus the base engine is up to 15% at low BMEP.

The engine calibration has been further optimized in order to allow transient operation, especially the ETC cycle for emission measurement.

**EVMG-TC harmonization for Turbo-lag reduction (PT)**

The multi-cylinder engine tests showed that turbocharging is an attractive technology for CNG engines with port injection, because it allows recovering the power gap with respect to gasoline engines due to the use of gaseous fuels. However, turbolag problem is relevant to engine transient response and fun to drive. The presence of EVMG can enable flexible strategies for turbolag reduction. More specifically, EVMG could be applied to the exhaust valve and used to increase the engine exhaust gas power transferred to the turbine, thus reducing the time...
required to accelerate the turbocharger group. In addition, turbolag can be controlled by means of a suitable retard of spark timing, which can also be coupled to EVMG-based strategies.

The goal of the present activity was to investigate by calculation the potential of the above mentioned strategies for turbolag reduction using a GT-Power engine model that was specifically developed for the simulation of engine transient operations.

The following strategies for turbolag reduction were studied:

• E-EVO-VVA: immediately after the tip-in event, an Early Exhaust Valve Opening is actuated with a specific lift profile (fig. A1.7), whereas the exhaust valve closing is kept constant; then, when boost pressure reaches a selected level, EVO and valve lift are switched back to their baseline value and profile, respectively;

• AD: immediately after the tip-in event, a retard in the spark timing (AD = anchor delay) is set; then, spark timing is switched back to its baseline value after boost pressure reached a selected level.

These strategies might reduce piston work during the expansion stroke, therefore the trade-off between turbo shaft acceleration and reduced piston work has to be analyzed as a function of EVO advances, valve lift profiles, EVO and valve lift switch-back timings, ST retards and ST switch-back timings.

Two different types of load transients were used for turbolag characterization: tip-in maneuvers at constant speed and tip-in maneuvers with the engine coupled to an hydraulic converter under stall conditions. These latter are able to reproduce a typical load transient condition for an urban bus accelerating from engine idle. In order to rank the investigated strategies, several indices were defined to measure turbolag. For tip-in maneuvers at constant engine speed, the “average torque” during the transient and the “torque rising time” (i.e., the time interval required by engine torque to rise from 10% to 90% of the total torque step) were used. For the tip-in maneuvers in which the engine was linked to the torque hydraulic converter, the “engine speed rising time” (i.e., the time interval required by engine speed to rise from 10% to 90% of the total speed increase) was applied.

With reference to strategies based on EVO advance, the main limiting factor was shown to be the in-cylinder pressure at exhaust valve opening, whose value should not exceed 20 bar to guarantee valvetrain durability. When this constraint is met, combined strategies (EVO advance
& combustion timing retard) allow one to improve turbolag of 35-45%, with related fuel penalties of 6-8% with respect to baseline case. In order to reduce fuel penalties, combustion timing retard should not be applied. In this framework, “pure” EVO advance strategies showed to be able to reduce turbolag of 15-25% with acceptable fuel penalties (1-3%).

However, the application of EVO strategies requires the introduction of EVMG to the exhaust valve, thus leading to a further cost increase of the system. On the other hand, “pure” retarded combustion strategies can be easily actuated through ECU programming, with virtually no additional cost. They show a potential for reducing turbolag of 15-30% without increasing pmax at EVO. However, higher fuel penalties have to be considered (7-9%) during load transients. It should also be taken into account that, based on simulation of bus urban cycle carried out at CRF, the acceleration phases in which the selected strategies can be applied correspond to the 12-16% of the vehicle standard mission. Therefore, in order to evaluate the resulting fuel consumption for the urban cycle of a bus, the fuel penalty of each turbolag reduction strategy should be accordingly scaled.

Finally, with reference to drivability issues, the automatic transmission systems with torque converters, which equip all urban buses, should contribute to dump the effects of the steep increase of engine torque shown by all the investigated strategies during load transients.

Direct Injection (AVL)

Main objective of the activity carried out by AVL on single cylinder research engine was to show the potential of CNG direct injection compared to port injection with focus on efficiency, power density and emissions. Direct injection offers in fact more flexibility regarding combustion system design, especially regarding homogenisation and turbulence generation.

The experimental activities has been supported by 3D-CFD calculation using the software AVL-FIRE™. A complex model of the combustion chamber and the intake ports was set up. After verification of the used code the mixture formation for different injection strategies was simulated. Also combustion simulation for different conditions was carried out.

In parallel the preparation and set-up of the SCRE CNG-DI research engine on the test bed was done in a way to have highest possible flexibility regarding boosting and EGR control. So an external boosting device and an EGR blower were used to simulate realistic operating conditions of a turbocharged engine. The used injector is an in house developed electro-hydraulically activated research injector with an outwardly opening nozzle.

After set-up of the SCRE tests were performed to evaluate the performance with respect to the targets. Also reference measurements with port injection were carried out for reliable result comparison. Different valve timing and injection strategies were compared to each other. Investigations with cooled external EGR were done.

The correlation between simulation and experiment was successfully demonstrated.

Most important outcome from the simulation activities can be summarised in figure A1.8. The injection-jet introduced turbulence has a significant influence on the turbulence level at ignition and shows a very efficient possibility to increase combustion speed and EGR compatibility without loosing volumetric efficiency.

This fact can be seen as one of the most important advantages with direct injection. More freedom in combustion chamber and port design for an optimized combustion system is the consequence.
Turbulence level with direct injection at boosted full load

Late injection results in a significantly higher turbulence level, generated by the injection-jet itself and the interaction with the port generated air charge motion. This leads to a higher EGR tolerance compared to port injection in boosted full load operation.

Late injection results in a significantly higher turbulence level, generated by the injection-jet itself and the interaction with the port generated air charge motion. This leads to a higher EGR tolerance compared to port injection in boosted full load operation.

Fig. A1.8 Turbulence level with different injection strategies

The combustion system development can be seen in Table A1.1 for part load operation. Looking purely to efficiency an improvement of 18.5% could be achieved. Main drawback of stratified lean operation is the too low exhaust gas temperature for Methane conversion and the necessity for a lean NOx aftertreatment. A significant improvement regarding exhaust gas temperature at reduced fuel consumption could be reached by using early intake valve closing (IVC) strategy also called “Miller” timing. The dethrottling effect of early IVC enables a stratified lean operation with higher exhaust gas temperature at reduced Lambda values. The trade-off between efficiency and exhaust gas temperature is significantly improved, even if the relative advantage compared to homogeneous stoichiometric operation is reduced to approximately 10%. Due to the complex exhaust gas aftertreatment system for lean operation, as a short term solution homogeneous stoichiometric operation with early intake valve closing shows the best compromise because the exhaust gas aftertreatment system can be a simple 3-way-catalyst system.

<table>
<thead>
<tr>
<th>Part Load Operation 1000rpm / 4bar IMEP</th>
<th>ISFC</th>
<th>ETA_i_h</th>
<th>VPI</th>
<th>P_Intake</th>
<th>T_EX</th>
<th>NOx</th>
<th>THC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation Strategy (conventional valvetiming)</td>
<td>Indicated spec. fuel cons.</td>
<td>efficiency high pressure cycle</td>
<td>combustion stability</td>
<td>relative boost pressure</td>
<td>exhaust gas temperature</td>
<td>Spec. NOx emission</td>
<td>Spec. HC emission</td>
</tr>
<tr>
<td>Hom. Stoichiometric PFI / $\lambda=1.0$</td>
<td>240.7</td>
<td>34.6</td>
<td>0.7</td>
<td>-388</td>
<td>455</td>
<td>14.4</td>
<td>11.3</td>
</tr>
<tr>
<td>Hom. Stoichiometric DI / $\lambda=1.0$</td>
<td>245.7</td>
<td>33.7</td>
<td>1.0</td>
<td>-374</td>
<td>445</td>
<td>12.8</td>
<td>13.1</td>
</tr>
<tr>
<td>Hom. Lean PFI / $\lambda=1.6$</td>
<td>217.0</td>
<td>36.8</td>
<td>1.4</td>
<td>-222</td>
<td>375</td>
<td>2.4</td>
<td>16.9</td>
</tr>
<tr>
<td>Hom. Lean DI / $\lambda=1.6$</td>
<td>218.9</td>
<td>36.5</td>
<td>2.0</td>
<td>-226</td>
<td>387</td>
<td>2.6</td>
<td>14.8</td>
</tr>
<tr>
<td>Stratified Lean DI / $\lambda=2.5$</td>
<td>196.2</td>
<td>38.5</td>
<td>1.3</td>
<td>-3</td>
<td>252</td>
<td>15.2</td>
<td>7.7</td>
</tr>
<tr>
<td>Stratified Lean DI + 24% EGR / $\lambda=1.7$</td>
<td>202.6</td>
<td>37.7</td>
<td>1.4</td>
<td>-53</td>
<td>288</td>
<td>3.9</td>
<td>9.1</td>
</tr>
</tbody>
</table>

Tab. A1.1 Part load performance – Different combustion systems with standard valve timing
Effect of EGR at 2000 rpm / 20 bar IMEP

- Heat transfer into Cooling Water [%]
- Exhaust Temperature based on °C [%]
- Boost Pressure absolute [%]
- ISFC [%]

![Graph showing effect of EGR on various parameters at 2000 rpm / 20 bar IMEP.](image)

Fig. A1.9  EGR Variation at 2000rpm / 20bar imep

At full load operation the main focus was put on power density increase without increasing the thermal component load. The usage of 20% cooled external EGR at full load offers a 24.6% reduced heat transfer in combination with about 3% fuel consumption improvement, see figure A1.9. This offers enough margin for the target of a 20% power density increase.

The activities carried out on Direct Injection allowed to derive the following conclusions:

- The general advantage of a higher power output with DI compared to PFI was confirmed and gets even more important with low energy density fuels like Biogas.

- With low intake based charge motion (filling ports or small valve lift due to early intake closing) the DI gas-jet based turbulence shows a significant advantage in combustion speed and so EGR tolerance. For combustion systems with high intake air based charge motion (e.g. High-Tumble- or Swirl-ports) the turbulence generated by the DI gas-jet itself is of secondary importance because the effect is mostly compensated by the worse mixing with late injection.

- For a short term approach stoichiometric engine operation offers the best solution due to the easy to handle and reliable exhaust gas aftertreatment system. For the future a more advanced approach is the stratified lean operation with significant potential regarding CO2 reduction. Research has to be focused on the development of an efficient aftertreatment system for lean operation at lower exhaust gas temperature.

- External cooled EGR at full load can reduce the thermal load of the components significantly, and give the potential for increased power density. The GREEN target of +20% power density is feasible introducing EGR at high load.

**Gas quality vs. Engine behaviour**

Fuel composition influences engine / vehicle behavior in several ways. Fuel calorific value (CV) determines vehicle range decisively. CV mixture determines the energy content of cylinder charge for given boost level. Burning velocity influences the Rate-of-Heat–Release patterns which affects the engine power and/or efficiency. Knock resistance of the fuel is one of its most important features. Low knock resistance of the fuel forces engine ECU to apply deviations against optimum adjustment in particular operating points which subsequently deteriorates engine power and/or efficiency.
The impact of some of the above mentioned fuel features will be enhanced if engine with high power rating is considered. That is why the interaction between engine and fuel has to be investigated in order to determine limits of acceptable fuel composition and to describe impacts (and assets) of fuel features on engine properties.

Range of methane-based fuel was the subject of investigation.

A survey of gaseous blends which has to be considered as potential transportation fuels was carried-out. Transit Natural Gas (TNG) was chosen as a base fuel. It is the most frequently used kind of natural gas within European territory and its properties are very close to that of pure methane. A matrix of the additives to TNG was established in order to enable experimental investigation of entire range of fuel compositions derived as a result of the survey. The fuel blends for testing were mixed on-line at the engine test bench. This strategy enabled operation of the testing engine being fueled by arbitrary chosen fuel composition.

Natural gas fueled 4*102/120 engine was rearranged in order to reach in-cylinder condition similar to that expected in final target. Engine was equipped with closed loop $\lambda$-control (all measurement results were acquired at $\lambda = 1$), cooled EGR line and WG controlled turbocharger giving boost pressure sufficient enough to enable the engine to reach BMEP approx. 20 bar. Engine behavior was investigated in operating points regularly distributed along full load curve. Besides the conventional evaluation of the experimental results the relevant data were used for calibration and verification of the mathematical model of engine working cycle.

The following major results have been achieved.

As a result of the gaseous fuel survey the following set of gas additives was compiled: $\text{C}_2\text{H}_6$, $\text{C}_3\text{H}_8$, $\text{C}_4\text{H}_{10}$ (heavy gaseous hydrocarbons either as undesirable impurities or additives for tuning of Wobbe Index), $\text{CO}_2$, $\text{N}_2$ (incombustible components of weak natural gases and biogases of various origins), $\text{H}_2$ and $\text{CO}$ (to obtain as complete results as possible).

Influence of addition of high hydrocarbons is illustrated in Fig. A1.10. At the same conditions higher burning velocity of propane causes higher peak cycle pressure ($p_{\text{MAX}}$) and temperature ($T_{\text{MAX}}$) and improves engine efficiency. Drop of the knock resistance by increased carbon number of fuel calls for retarded ignition timing in order to keep given level of knock intensity which in turn deteriorates engine efficiency. Final impact on engine properties is given by prevailing from both mentioned reciprocally opposite trends.

Appearance of non-combustible gas as a fuel component (Fig. A1.11–content of $\text{CO}_2$ near the dew point limit for typical storage conditions) shows opposite trends than that mentioned in the comment to Fig. A1.10. In this case advanced ignition timing compensates lower burning velocity of $\text{CO}_2$-containing fuel. At the same time it is visible from Fig. A1.11 that vehicle range decreases (correspondingly to lowered fuel CV) and emission of $\text{CO}_2$ increases (correspondingly to increase of carbon content in fuel).
Fig. A1.10 Impact of Addition of Propane

Fig. A1.11 Impact of Carbon Dioxide Addition
As expected, engine power is not influenced by changed mixture calorific value (CV). Certain impact on engine power and/or efficiency is excited through various burning velocity of various fuels and through inevitable retardation of ignition timing when knock resistance of the fuel decreases. Knock-promoting impact of each tested individual additives is kept in reasonable range by itself through dew point limitation at typical on-board storage conditions. Superposition of several high gaseous hydrocarbons as a fuel blend components may be dangerous.

Vehicle range (expressed as amount of useful energy at engine output per volumetric unit of fuel) is influenced by fuel composition (almost) proportionally to fuel CV. As shown in Fig. A1.11 high content of incombustible component cannot be sufficiently compensated by addition of high gaseous hydrocarbon due to the dew point limitation and knock restriction. Specific emission of carbon dioxide is (almost) proportional to carbon content in fuel blend. Both mentioned circumstances can be easily estimated by simple calculation using commonly tabulated fuel properties as calculation inputs.

The mentioned general conclusions are valid for entire range of the tested fuels.

- Final Results

The following charts summarise the contribution of the different technologies compared with the initial expectations/targets.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Results versus today EEV engines</th>
<th>Expected</th>
<th>Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVMG</td>
<td>Fuel consumption reduction of BMEP increasing of</td>
<td>4 ÷ 5%</td>
<td>4 ÷ 5%</td>
</tr>
<tr>
<td>Cooled EGR</td>
<td>Power density increasing of</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Enhanced cylinder head cooling</td>
<td>Power density increasing of</td>
<td>5% ÷ 6%</td>
<td>up to 20%</td>
</tr>
<tr>
<td>Turbocharging Ignition delay + Exhaust EVMG</td>
<td>Improved load response (turbo lag reduction)</td>
<td>15%</td>
<td>20-25%</td>
</tr>
<tr>
<td>Related to power density increase</td>
<td>Fuel consumption reduction of</td>
<td>2% ÷ 3%</td>
<td>3% ÷ 4%</td>
</tr>
<tr>
<td>DI injection</td>
<td>Turbo lag reduction (reduction of boost pressure)</td>
<td>5%</td>
<td>10%</td>
</tr>
<tr>
<td>Combined Technologies</td>
<td>NOx: – 50%; CO₂: – 7%; GVI: – 7%</td>
<td>(even higher reduction)</td>
<td></td>
</tr>
</tbody>
</table>

The experimental assessment of combined technologies integrated in the multi-cylinder engine has been carried out for the EVMG system and new cylinder head casting (improved cooling) combination. EGR have been tested on Multi-cylinder Base engine and on Single Cylinder Research engine. The injection system optimization has to be considered as a transversal technology necessary in order to optimize all combustion concepts using PFI.

Direct Injection has been tested in combination with low pressure EGR on SCRE.

Fig. A1.12 summarizes the expected benefits of a grid of possible technology combinations, increasing complexity and costs from the left to the right.
Starting from the left, the first two columns are referred to 2 different EGR systems that can be integrated without major modifications to the base engine:

- **uncooled EGR** at low loads will reduce throttling losses and therefore CO2
- **cooled EGR** allows to increase the power density. Thanks to downsizing, it can offer limited benefits in term of CO2 reduction.

In the third column, the **improved cylinder head cooling** is very effective on the power density increase. As for cooled EGR, the possible downsizing offers limited benefits on CO2.

The fourth column shows the first technology combination which integrates cylinder head cooling and EVMG system. This combination is logic because both technologies are concentrated in a new cylinder head. The experimental tests demonstrated the effectiveness of this combination both in terms of power density end CO2 reduction.

The fifth column shows the most complex system using PFI adding also cooled EGR in order to further increase the power density but with negative effects on the transient behaviour and system complexity. The combination of EVMG with uncooled EGR has not been included because no additional benefit in fuel consumption is expected if compared with the EVMG system alone.

The sixth column corresponds to the combustion concept adopted for the single cylinder engine using **Direct Injection**. From the improvement in turbulence generation coming from the fuel jet a faster combustion process is expected also using EGR, allowing a higher combustion efficiency. The 10% increase of air flow for the same intake manifold pressure improves the transient behaviour if compared with PFI.

The last column integrates also the **EVMG applied on the exhaust valves** in order to improve the transient response. Even if the engine efficiency is worsened during the tip-in phases, the estimated CO2 reduction is similar to the previous combination. The reason is that the better transient response allows a full downsizing without affecting vehicle performance.
The final multi-cylinder engine validator (fourth column in fig. A1.12) including the advanced EVMG system @ inlet valves, the improved cylinder head cooling system, the advanced near-to-valve port-fuel injection system and the advanced integrated control has been qualified, @ rated power of 243 kW, on the ETC cycle.

The following table summarizes the ETC cycle results with the GREEN targets:

<table>
<thead>
<tr>
<th></th>
<th>EEV</th>
<th>Euro VI (proposal)</th>
<th>GREEN targets</th>
<th>EVMG results</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>3.0</td>
<td>4.0</td>
<td>1.5</td>
<td>1.9</td>
</tr>
<tr>
<td>CH4</td>
<td>0.65</td>
<td>0.5</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>NMHC</td>
<td>0.40</td>
<td>0.16</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>NOx</td>
<td>2.0</td>
<td>0.4</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>PM</td>
<td>0.020</td>
<td>0.010</td>
<td>0.003</td>
<td>0.003</td>
</tr>
<tr>
<td>CO2</td>
<td>-</td>
<td>-</td>
<td>617</td>
<td>610</td>
</tr>
</tbody>
</table>

The emissions on the ETC cycle are fulfilled for all pollutants (except CO): this is the consequence of a slightly rich lambda control adopted in order to respect the NOx target in a consistent way. CO emission, although higher than the target, are lower than 50% of the most stringent EU limits (Euro VI, after 2012).

The CO GREEN target can be fully achieved by increasing catalyst size from 8.5 to 13 liters. Taking into account that CO is not a critical pollutant from the air quality point of view and that Euro VI relaxes the CO limit in favour of NOx, it is worth to evaluate the cost/benefit trade-off of the GREEN CO target.

Impact of the results on industry and research sector

The conversion of an HD diesel engine to a CNG engine is a complex process because it is necessary to switch from a compressed ignition engine to a spark ignited one: this means to reduce the compression ratio, normally by changing the piston shape, to integrate a throttle valve in the inlet manifold for the load control, to add the ignition system and to adapt the turbomatching to the new flow rate conditions. Moreover, the thermal flow generated by the stoichiometric combustion adopted with natural gas is higher than diesel combustion one, and the cooling circuit conditions have to be optimized when looking at the engine power density increase. The optimization of the injection control and the cylinder head in terms of geometry and cooling conditions carried out within SPA1 allowed to significantly increase the engine performance and, due to the related effect on power density, to reduce consumption.

The introduction of the EVMG system on the final engine validator allowed to reach outstanding results compared to the state-of-the-art in terms of fuel consumption and emissions. Apart from the clear advantages regarding operating costs and greenhouse effect contribution, the reduced fuel consumption allows to mitigate the main drawback of the CNG vehicle: the trade-off between operating range and tank volume.

The multi-cylinder validator could be industrialised in a short-medium period (two – three years from the completion of the project) and, in a longer perspective, the product could be optimised with the implementation of the road map showed in fig. A1.12.

In order to facilitate its introduction to the market some efforts should be dedicated to the development of a more advanced engine control system (integrated single ECU) for managing all the new functionalities and including the capability to adapt the regulation parameters to the gas fuel composition also taking into account the opportunity to use methane + hydrogen blends. The use of this kind of blend represents an additional step in the reduction of both...
pollutant emissions and CO$_2$ formation. Apart from the “natural” extra reduction of the CO$_2$ emissions due to the increase of the H/C ratio of the fuel, hydrogen represents a flame propagation booster which could provide an additional gain to the thermodynamic efficiency. Moreover, a reduction in THC emissions is also expected taking into account the reduction of the flame quenching phenomena in the crevices of the combustion chamber.

**2.1.4 Contractors Involved**

- List of contractors and main activity area

  CRF: SP leader; systems integration on multi-cylinder; analysis and development of advance Electro-Hydraulic Valve Management (EVMG) for Gas engines, (cooled and uncooled) EGR, integrated control, highly efficient cooling system, near-to-valve port fuel injection

  MT: development of advanced pressure regulator & fuel rail

  PT: analysis and models for TC+EVMG harmonisation for turbo-lag reduction

  AVL: analysis and development of direction injection combustion process on single cylinder; analysis for coupling direct injection with low pressure cooled EGR and Variable Valve Actuation system

  JBRC: theoretical and experimental characterisation of the effects of gas quality on engine performances

**2.1.5 List of acronyms**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD</td>
<td>Anchor Delay</td>
</tr>
<tr>
<td>bshc</td>
<td>Brake specific heat consumption</td>
</tr>
<tr>
<td>BMEP</td>
<td>Brake Mean Effective Pressure</td>
</tr>
<tr>
<td>bTDC</td>
<td>before top dead center</td>
</tr>
<tr>
<td>CA</td>
<td>Crank Angle measured from TDC</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational fluid dynamics</td>
</tr>
<tr>
<td>CNG</td>
<td>Compressed Natural Gas</td>
</tr>
<tr>
<td>COV</td>
<td>Coefficient of Variation</td>
</tr>
<tr>
<td>CRA</td>
<td>Crank Angle measured from TDC</td>
</tr>
<tr>
<td>CV</td>
<td>Calorific Value</td>
</tr>
<tr>
<td>DI</td>
<td>Direct Injection</td>
</tr>
<tr>
<td>IMEP</td>
<td>Indicated Mean Effective Pressure</td>
</tr>
<tr>
<td>IVC</td>
<td>Intake Valve Closing</td>
</tr>
<tr>
<td>ECU</td>
<td>Electronic control Unit</td>
</tr>
<tr>
<td>E-EVO</td>
<td>Early Exhaust Valve Opening</td>
</tr>
<tr>
<td>EGR</td>
<td>Exhaust Gas Recalculation</td>
</tr>
<tr>
<td>EIVC</td>
<td>Early Intake Valve Closing</td>
</tr>
<tr>
<td>ETC</td>
<td>European Transient Cycle</td>
</tr>
<tr>
<td>EVC</td>
<td>Exhaust Valve Closing</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>EVMG</td>
<td>Electronic Valve motion Management for Gas engine</td>
</tr>
<tr>
<td>EVO</td>
<td>Exhaust Valve Opening</td>
</tr>
<tr>
<td>HD</td>
<td>Heavy Duty</td>
</tr>
<tr>
<td>LIVO</td>
<td>Late Intake Valve Opening</td>
</tr>
<tr>
<td>mCO2</td>
<td>Specific Emission of Carbon Dioxide</td>
</tr>
<tr>
<td>PFI</td>
<td>Port fuel injection</td>
</tr>
<tr>
<td>SCRE</td>
<td>Single cylinder research engine</td>
</tr>
<tr>
<td>ST</td>
<td>Spark timing</td>
</tr>
<tr>
<td>TC</td>
<td>Turbo-charging</td>
</tr>
<tr>
<td>THC</td>
<td>Total Hydro-Carbon</td>
</tr>
<tr>
<td>TKE</td>
<td>Turbolent Kinetic energy</td>
</tr>
<tr>
<td>TNG</td>
<td>Transient Natural Gas</td>
</tr>
<tr>
<td>VVA</td>
<td>Variable Valve Actuation</td>
</tr>
<tr>
<td>WG</td>
<td>Waste-gate</td>
</tr>
</tbody>
</table>
2.2 Subproject A2 – Enhanced Flexible Engine (lead contractor Volvo)

2.2.1 Subproject Objectives

The subproject objectives is to reach the GREEN emission and fuel consumption targets using novel, flexible fuel injection and valve actuation systems together with an advanced aftertreatment system. The systems are to be designed, procured and tested in an engine test rig.

2.2.2 Relation to the state-of-the-art

The novel fuel injection system to be used give a better opportunity to combine high fuel injection pressures with excellent capacity for injection rate shaping. Multiple injection capacity is also extensive. Being able to vary also the valve actuation give almost endless possibilities to optimize the air and fuel situation in the engine cylinders. This is not available in engines of today. The after treatment system is of Lean NOx Adsorber type. Compared to what is used on the market today for heavy duty (SCR systems) it has the advantage that no extra fluid must be used (Ad blue for SCR systems). It has also good potential for high NOx conversion efficiencies but may suffer some on the cost efficiency for heavy duty applications.

2.2.3 Work Performed & Final Results

Subproject A2 consisted of six work packages interconnected as described in the figure A2.1. Wp A2.1 runs for the whole project time, involved partners are Volvo and Deutz. The analysis and optimization work is performed in this work package. Wp A2.3 is active the first 18 months, involved partners are Volvo, Ricardo and Delphi. Wp A2.4 is also active the first 18 months, involved partners are Volvo and UPLVC (University of Valencia). Different engine systems are tested in Wp A2.3 and Wp A2.4 and evaluated together with Wp A2.1. The task includes to choose the best engine system for the the continuation of the work in the second 18 months of the program (within Wp A2.6). Wp A2.5 has activities during the whole project time, involved partners are Volvo, Deutz, Chalmers KCK and Johnson Mathey. The first tasks include developing and designing the after treatment system. Also optimization work is performed together with Wp A2.1. Thereafter, when the system testing and optimization starts, WpA2.5 is involved in the complete system work together with WpA2.6 and WpA2.1. Wp A2.6 is active the last 18 months of the project, involved partners are Volvo, Ricardo, Delphi and Chalmers TFD. The work consists of complete system testing (engine+EATS) together with Wp A2.5 and analysis and optimization together with WpA2.1. It also contains studies of alternative fuels. Wp A2.7 runs for the whole project time, involved partner is Volvo. This work package is responsible for subproject management.
The selected and optimized systems for final evaluation was the F1 fuel injection system which combines a fuel rail with unit injectors. The variable valve actuation system was chosen to be of added motion type, where you can “hold” the valve open longer than your mechanical cam lobe is active by hydraulic functionality. The after treatment system was selected to be of LNA (Lean NOx Adsorber) type. The systems were designed, procured and tested in an engine test rig in steady state mode. The combustion system and other variables was optimized during the work to have good capability and work well together. The transient functionality was simulated by an interaction between engine testing in steady state and knowledge of the different systems thermodynamic behaviour (modelled) and also the control system behaviour in a transient (modelled). The work flow is described in figure A2.2.

![Diagram](image)

**Fig. A2.1:** A2 Subproject organization

**Fig. A2.2:** Overview of interactions between simulation and engine tests

The final results of the subproject can be summarized as follows: All the project deliveries and milestones were fulfilled. The prototype parts were all designed, procured and tested in engine test rig showing good functionality. The GREEN emission were reached. The GREEN fuel consumption targets were partly reached. The fuel consumption improvement was three percent compared to the Euro III reference in ESC. The GREEN target was five percent in ETC and this was subsequently only partly reached. Reasons for not reaching the target include that there...
was not enough time to investigate all the possibilities that the flexibility the novel systems makes possible in the frames of this program. More optimization potential is available. The variable valve system did not give as much advantage as expected. One reason for that is that the boosting system on the engine was limited. Better potential for the variable valve system will probably be found with an improved turbo system. Finally the LNA after treatment system, although well designed, did not reach the NOx conversion ratio of a state of the art SCR system. The LNA system has potential to reach very high NOx conversion efficiencies but then with a dual system. As the noble metal content of a LNA system is high, a dual system will probably not be as cost effective as a SCR system for a heavy duty application.

2.2.4 Contractors Involved

- **Deutz AG**, Burner system and PM filters for after treatment
- **Ricard Consulting Engineers**, Single and multi cylinder engine testing of the flexible engine systems
- **Chalmers University of Technology, Dep of applied mechanics**, Single cylinder testing of alternative fuels including optical analysis of the combustion
- **UPVLC, University of Valencia**, Single cylinder testing of the flexible engine systems
- **Delphi Diesel Systems**, Design, procurement and experimental support of single and multi cylinder engine fuel injection systems
- **Johnson Matthey**, development and procurement of the after treatment parts for all the different systems (DOC, deSOx, PM filters, LNA)
- **Chalmers university of Technology, Competence centre for catalysis**, de SOx formulation development
- **Volvo**, Lead contractor, single and multi cylinder engine testing, concept selection and design responsible, optimization of combustion system

2.2.5 List of acronyms

SCR = Selective Catalytic Reduction
NOx = Nitrous oxides
DOC = Diesel oxidation catalyst
PM = Particulate Matter
LNA = Lean NOx Adsorber
SOx = Sulphur oxides
ESC = European Steady state Cycle
ETC = European Transient Cycle
VGT=Variable Geometry Turbine
EGR=Exhaust Gas Recirculation
BSFC=Break Specific Fuel Consumption
CFD=Computational Fluid Dynamics
g/kWh= gram/kilo Watt hour
2.3 Subproject A3 – Innovative Control and Air Utilisation (lead contractor Daimler)

2.3.1 Subproject Objectives

Subproject A3 can be separated in two parts and therefore in two independent objectives.

Part 1: New comb. system with complete air utilisation
The main objective of subproject A3 part 1 “New combustion system” is to achieve tail pipe emissions of NOx lower than 1.0 g/kWh, PM lower than 0.002 g/kWh and a fuel consumption that is better than EURO 3 applying either a diesel particulate filter or a selective catalytic reduction catalyst. The new combustion system is based on an innovative variable fuel injection system.

Part 2: Models for a model based closed loop emission control
The primary target of the second part of the subproject A3 is the development of control-oriented thermodynamic and raw emission models for HD diesel engines as the foundation for a future model-based closed-loop emission control system.

2.3.2 Relation to the state-of-the-art
In comparison to conventional injection systems, the developed system features a variable nozzle in the sense that it possesses two rows of nozzle holes which are operated independently by two needles (inner and outer needle). Thus this systems has an additional flexibility concerning
- spray angle
- hydraulic flow (number and diameter of nozzle holes)
depending on the row(s) activated.

This flexibility allows a new combustion system with optimum adaptation of the mixture formation and air utilisation for the operation in part load as well as for full load. With this approach best results (emissions, fuel economy and NVH) can be obtained in the whole engine map.

Regarding current control strategies for engine and aftertreatment systems, mainly open-loop controlled methods are applied. As an example, the AdBlue (aqueous urea solution) dosing of an SCR (Selective Catalytic NOx Reduction) system is typically controlled in an open loop fashion. Therefore within Part 2 of the project, important elements for the realisation of a closed loop emission control system are developed, including control-oriented models in combination with development strategies.

2.3.3 Work Performed & Final Results

In the following, for each of the different development steps an evaluation, a summary, as well as a conclusion is drawn and recommendation is given:

Part1: KVD development:
The new flexible FIE was developed in the framework of the GREEN-Project as a highly sophisticated engineering and research tool for testing and analyzing of advanced combustion processes.

The flexible vario nozzle injection tool is characterized by the multiple injection capability with independently switching needles of the upper or lower nozzle hole row in combination with rate shape functionality and pressure amplification.

The built samples could confirm all defined specifications on the hydraulic test bench and on the single cylinder engine.

Operating time limitation of research injectors and limitation of feasible hydraulic flow posed certain restrictions to the engine test program.

Combustion design development:

- A new combustion concept has been developed characterised by an improved air utilization for low emissions at full load and part load, with additional capability for homogeneous combustion at part load (wall-guided combustion with high potential for an effective use of post-injection strategies).
- Based on test bench and simulation results the nozzle configuration for the "KVD (Koaxial Vario Düse)" injection system and the piston bowl design has been defined.

![Fig. A3.1: Multiple injection event as combination of inner (lower hole row) and outer (upper hole row needle)](Image)

**Simulation and diagnostics:**
- Development and application of innovative methods for diagnostics and simulation to support combustion design development.
- The adapted KIVA simulation tool could be used effectively for analyzing the different effects of spray-to-spray interaction as well as the effects of spray-to-wall interaction.
- The KIVA simulation could be used effectively for predictive optimization of design parameters (bowl-nozzle geometry, injection strategies ...).
- To extract the potential of the high flexibility of the KVD injector the KIVA simulation was combined with DOE analysis tools (DOE for injection strategies).

**KVD engine testing:**

It can be concluded that the overall best configuration is based on the approach with map-distributed adapted hydraulic flow rates and post injections. The investigations at Bosch and Daimler showed that there is a big area up to higher part load where the reduced flow rate of the inner needle is beneficial.

![Fig. A3.3: Post injection strategies (PoI) with outer Needle (ON) / inner needle (IN)](image)

The outer needle with the large hydraulic flow is used at high load to full load operation. This mapping presumably could be further optimized by using smaller nozzle holes at part load (inner needle) bigger ones at medium load (outer needle) and both for high load.

Based on a conventional combustion concept with one nozzle, nearly 75% soot reduction could be achieved in the NOx-soot trade off (projection to ESC) by application of –

- Two nozzles with different flow rates
- Alternative combustion concepts (partial homogeneous)
- “Advanced” post injection
- Mapped settings and optimum combination of ESC modes

Based on an SCR system, the GREEN targets (low emissions in combination with good fuel efficiency) have a realistic chance to be fulfilled using just one exhaust gas aftertreatment system. This conclusion is derived from an ESC test result extrapolation.

**Part 2:** Based on a “simulation-oriented” measurement campaign, an extended quasi-stationary raw emission model concept has been derived. The resulting raw emission models are embedded in a mean-value gas path model, which predicts the thermodynamic states of the surrounding receivers of the cylinder. The mean-value model is implemented in Simulink®.
Together they build a virtual powertrain of the whole engine system which is the ideal tool for a model based optimization of the engine system including the interactions with the aftertreatment devices. The models are calibrated with a special engine test plan which guarantees a fast application of the models to new engines. The complex models are used to analyze the chemical and physical mechanisms during the combustion process and pollutant formation. Additionally, they provide variables needed to calibrate the control-oriented models (e.g. heat release rate, turbulence in the chamber) which are impossible to be measured directly. The capacity of operating point inter- and extrapolation not only assures the availability of the control-oriented models on a preferably large engine-map range, but also enables to reduce engine tests significantly.

The modelling approach developed within this project demonstrates a good agreement with measurement data taken from static and dynamic engine operation.

![Graph](image)

**Fig. A3.4:** Calculated emissions (NOx and PM with gas path dynamic) during a load step (QSS=quasi-static-simulation)

Four scenarios are considered to illustrate the application field of the control-oriented models. The first and most important application of the control-oriented models is the optimisation of various operation strategies for the HD diesel engine and the aftertreatment system. In a second step, a feed forward control strategy can be derived based on these models. As a last step, a feedback controller can be implemented, which is based on the linearized control-oriented models. An additional application field of the control-oriented models is their usage as virtual sensors to substitute real sensors.

### 2.3.4 Contractors Involved

**Part 1:** *New comb. system with complete air utilisation*

Project partners involved are BOSCH, Daimler, FEV and RWTH Aachen. The new combustion system is based on an innovative variable fuel injection system developed by BOSCH. The combustion design is determined by single cylinder engine testing (all partners) supported by...
Part 2: Models for a model based closed loop emission control
Project partners involved are AVL, Daimler, ETHZ. The control-oriented thermodynamic and raw emission models are developed by the ETH Zurich. Complex models are further developed and applied by AVL and Daimler. Engine measurement data are delivered by AVL. A study for fast aftertreatment models is carried out by Daimler.

2.3.5 List of acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFD</td>
<td>Computational fluid dynamics</td>
</tr>
<tr>
<td>DOE</td>
<td>Design of experiment</td>
</tr>
<tr>
<td>EGR</td>
<td>Exhaust gas recirculation</td>
</tr>
<tr>
<td>ESC</td>
<td>European stationary cycle</td>
</tr>
<tr>
<td>FIE</td>
<td>Fuel injection equipment</td>
</tr>
<tr>
<td>HD</td>
<td>Heavy-duty</td>
</tr>
<tr>
<td>IN</td>
<td>Inner needle</td>
</tr>
<tr>
<td>KVD</td>
<td>Koaxial-Vario-Düse</td>
</tr>
<tr>
<td>MI</td>
<td>Main injection</td>
</tr>
<tr>
<td>NOx</td>
<td>Nitrogen oxides</td>
</tr>
<tr>
<td>NVH</td>
<td>Noise vibration harshness</td>
</tr>
<tr>
<td>ON</td>
<td>Outer needle</td>
</tr>
<tr>
<td>PI</td>
<td>Pilot injection</td>
</tr>
<tr>
<td>PM</td>
<td>Particle matter</td>
</tr>
<tr>
<td>Po1</td>
<td>1st post injection</td>
</tr>
<tr>
<td>QSS</td>
<td>Quasi-static-simulation</td>
</tr>
<tr>
<td>SCR</td>
<td>Selective catalytic reduction</td>
</tr>
</tbody>
</table>
2.4 Subproject A4 – Gas Engine for Urban Area (lead contractor CRF)

2.4.1 Subproject Objectives

**Subproject A 4 Subproject Objectives**

- Increasing peak firing pressure
- Reinforcement of engine structure
- Improved turbo charger
- Future emission standards & High BMEP
- Controlling peak firing pressure
- Improved combustion process to reach GREEN targets 0.5g NOx, 0.002g soot and 204g/kWh
- Variable Compression Ratio
- Improved turbo charger

**Aftertreatment: improved catalysts and thermal management**

**Exhaust heat recuperation study**

2.4.2 Relation to the state-of-the-art

2.4.3 Work Performed & Final Results

- Methodology and approaches

The target was approached with a 2-stage turbocharged high PFP engine with SCRT-aftertreatment. A LPL- EGR- system and a high pressure common rail injection system was used.

- Final Results

The GREEN project targets were fulfilled with a validator engine:

<table>
<thead>
<tr>
<th>Target description</th>
<th>dimension</th>
<th>Target value</th>
<th>reached</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx (ETC)</td>
<td>[g/kWh]</td>
<td>0.5</td>
<td>0.49</td>
</tr>
</tbody>
</table>
BSFC (ETC) | [g/kWh] | 204 | 202
--- | --- | --- | ---
GWI (ETC) | [g CO₂/kWh] | 643 | 620
BSFC (Full load) | [g/kWh] | 185 | 186 (*)

**WPA4_2: table of target numbers and reached values**

- Degree of which objectives were reached (*)

In general all WPA4- targets were reached except one. The best full load consumption was failed by only a very small amount (186 vs. 185 g/kWh target). This was related to the problem in achieving the necessary high EGR- flow at this high BMEP levels without deteriorating the engines gas exchange efficiency.

- Relation of the results to the state of the art

There is a BSFC improvement of 5% vs. Euro 3 engines in a emission test cycle (ETC). With this engine technology it seems even possible to improve BSFC of EuroV engines, inspite of stricter emission targets (GREEN- target, Euro VI- like) and 20% higher BMEP.

- Impact of the results on industry and research sector

The technologies for high BMEP engines will be used step by step for future applications. The improved single stage turbocharging can fulfill the requirements for the next performance steps with not too demanding space requirements for actual vehicles. The high pressure common rail injection, EGR and the SCRT- aftertreatment will probably become standard for onroad applications in Europe. Improved materials for castings and steel pistons will be applied in some cases to build more compact and lighter engines at the required power output. Improved structure design will fulfill short term requirements.
2.4.4 Contractors Involved

AVL Anstalt für Verbrennungsmotoren List in Graz (Austria)
CTT Cummins Turbo Technology (Holset, UK)
FEV FEV Forschungs- und Entwicklungszentrum für Verbrennungskraftmaschinen in Aachen (Germany)
IMF Iveco Motorenforschung AG (Switzerland)
Iveco SpA Heavy Duty Vehcile Manufacturer (Italy)
NTUA National Technical University Athens (Greece)

AVL designed the high PFP- cylinderhead and the gasket/liner concept. Iveco was responsible for the design and procurement of the engines. IMF was responsible for engine testing. CTT designed and provided the turbochargers. FEV validated the VCR- system. NTUA made simulations and studies for heat recuperation systems.
### 2.4.5 List of acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/T</td>
<td>Aftertreatment System</td>
</tr>
<tr>
<td>AFR</td>
<td>Air fuel ratio</td>
</tr>
<tr>
<td>CGI</td>
<td>Compact Graphite Iron</td>
</tr>
<tr>
<td>CRS</td>
<td>Common Rail System</td>
</tr>
<tr>
<td>CR</td>
<td>Compression ratio</td>
</tr>
<tr>
<td>CV</td>
<td>Commercial Vehicle</td>
</tr>
<tr>
<td>ECU</td>
<td>Electronic Control Unit</td>
</tr>
<tr>
<td>EGR</td>
<td>Exhaust Gas Recirculation</td>
</tr>
<tr>
<td>ETC</td>
<td>European Transient Cycle</td>
</tr>
<tr>
<td>FMEP</td>
<td>Friction Mean Effective Pressure</td>
</tr>
<tr>
<td>GWI</td>
<td>Global Warming Index (in the case of diesel engine equal to CO2-emission)</td>
</tr>
<tr>
<td>HBMEP</td>
<td>High Brake Mean Effective Pressure</td>
</tr>
<tr>
<td>HCF</td>
<td>high cycle fatigue</td>
</tr>
<tr>
<td>MWE</td>
<td>Map Width Enhancement (compressor map)</td>
</tr>
<tr>
<td>NTE</td>
<td>Not to Exceed Limit</td>
</tr>
<tr>
<td>PFP</td>
<td>Peak Firing Pressure</td>
</tr>
<tr>
<td>SCR</td>
<td>Selective Catalytic Reduction (NOx reduction system with AdBlue)</td>
</tr>
<tr>
<td>SCRT</td>
<td>SCR- system combined with (closed!) particulate filter (Trap)</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite element analysis</td>
</tr>
<tr>
<td>TMF</td>
<td>Thermomechanical fatigue</td>
</tr>
<tr>
<td>T/C</td>
<td>Turbocharger</td>
</tr>
<tr>
<td>VCR</td>
<td>Variable Compression Ratio System</td>
</tr>
</tbody>
</table>
2.5 Workpackage 0.2 (NONOX, IFP, Ford Otosan)

2.5.1 Subproject Objectives

Task 0.2.1 Advanced EOCV system for gas approach (lead contractor NONOX)

The objectives for WP0.2.1 were twofold:
A) Supportive actions towards (especially) the A1 project,
Technical supportive action regarding the planned investigations on the impact of varying natural gas composition on behaviour of SI engines was identified as the most important issue. Varying natural gas composition can be seen as a major difficulty for the introduction of natural gas for automotive use. Varying natural gas composition independently affects several independent phenomena. Most important influences are: knock sensitivity, gasmetering properties of gas injection equipment and vehicle range variety.
Two sub-objectives were defined in co-operation with JBRC University during the beginning stage of the project:
1) The application of a GET-AKR system applied as a knock detection system by which a reproducible knock-intensity information is provided to the investigation approach of JBRC
2) Development of a blending model in order to harmonise variations in natural gas composition.

B) Further development of the NONOX EOCV natural gas engine with the purpose of achieving the GREEN project targets and further improvement of the engine performance. Assigned to the overall objective of further engine development, the following sub-objectives were defined:

1. Improvement of lean burn combustion behaviour and primary HC emission by means of a new piston design
2. Improvement of lean burn and high EGR content combustion behaviour by means of the application of scavenged pre-chamber spark plugs
3. Exploring the potential benefit of cylinder deactivation on specific fuel consumption
4. Exploring the possibility of EOCV pulse charging operation mode in order to increase volumetric efficiency and to improve turbo response at low engine speeds.
5. Realisation of a novel Lambda=1+cooled EGR concept with TWC EAS and exhaust gas water separation unit, with the aim of achieving equal specific fuel consumption as in lean burn operation

Task 0.2.2 Fuel tests for HCCI (lead contractor IFP)

The main objective of the work done by IFP within the GREEN project was to evaluate if the fuel could have an impact on the operating range of an HCCI Diesel engine. In addition, obtained results aimed to increase our knowledge on the impact of fuel characteristics (i.e. cetane number, volatility and composition) on the combustion behaviour, the performances and the emissions of the engine.
**Task 0.2.3 Fuel tests for diesel combustion (lead contractor Ford Otosan)**

The objective of this task is to examine the effects of different fuel formulations on the conventional diesel engine performance and emissions.

The main target is to test alternative fuels running the below tests:

1. Heavy Duty Engine Exhaust Emission test – ECE 24
2. Heavy Duty Engine Exhaust Emission test – ESC
3. European Transient Cycle – ETC
4. Engine Performance – full load curve

Beforehand performing the task, in order to prove the repeatability of the tests, reference tests were conducted with the conventional diesel fuel and the repeatability of our test center was reported to the consortium.

**2.5.2 Relation to the state-of-the-art**

**Task 0.2.1 Advanced EOCV system for gas approach (lead contractor NONOX)**

The NONOX EOCV natural gas engine technology is basically characterised by the novel **Electromagnetic Operated Control Valve** throttleless load control device/operation mode.

![Throttleless load control](image1)

![Throttle load control](image2)

Compared to state-of-the-art gas engines, the EOCV based operation mode significantly reduces the pumping losses and allows the application of higher values of compression ratio because of the ability to apply Miller timing. Both, lower pumping losses and higher compression ratio, contribute to substantial higher engine efficiency.
During the IP GREEN further innovative developments were introduced. Most promising innovative solutions that further distinguish NONOX technology against the state of the art technology are the novel EGR system with integrated water separator and the scavenged pre-chamber spark plug. Former system allows the application of EGR in conjunction with the throttleless load control.

Without the extra means of the water separation unit, a segregation of the condensed water content of the recirculated exhaust gas would occur during the intake stroke following EOCV the closure event, which would have deteroriated the subsequent combustion process.

The application of the scavenged pre-chamber spark plug was thought – and proved- to enable a further extension of the lean burn ability and an Improvement of the NOx sfc trade off function. The state of development of the applied scavenged pre-chamber spark plug is still in an early R&D phase.

**Task 0.2.2 Fuel tests for HCCI (lead contractor IFP)**

Among the different technical possibilities to reduce the pollutant emissions of a Diesel engine, the HCCI combustion appears to be a promising way. Indeed, HCCI combustion, when
applicated to a Diesel engine, allows a significant reduction of both NOx and particulate emissions, the two main pollutants of this type of engine. This is due to the dilution of the fuel and air mixture which induces a decrease of combustion temperature as well as a decrease of the local air and fuel ratio. Nevertheless, this new type of combustion process suffers to be limited at high loads and high engine speeds by noise emissions. If a lot of studies have been dedicated to fuel and engine relationships, few of them are focused on the impact of fuel on the operating range of an HCCI Diesel engine. Furthermore, few data are available on the impact of fuel composition on the HCCI combustion process.

Task 0.2.3 Fuel tests for diesel combustion (lead contractor Ford Otosan)

Specification of tests performed:

**Heavy Duty Engine Exhaust Emission test – ECE 24** will be performed to measure emissions of visible exhaust pollutants.

**Heavy Duty Engine Exhaust Emission test – ESC** will measure emissions of gaseous and particulate pollutants from the engine. Gaseous pollutants mean CO, hydrocarbons and NOx (the last-named being expressed in nitrogen dioxide (NO2) equivalent). Particulate pollutants means any material collected on a specified filter medium after diluting diesel exhaust to gases with clean filtered air.

**AVL 8 mode state Cycle – ETC simulation**, European Transient Cycle with using AVL 8 mode steady state test will be performed.

**Engine Performance – full load curve**, The power in EEC kW obtained on the test bench at the end of the crankshaft, or its equivalent, measured in accordance with the EEC method of measuring power as set out in Directive 80/1269/EEC.

The tests were conducted on a Euro III stage reference engine, engaged for this project.

2.5.3 Work Performed & Final Results

Task 0.2.1 Advanced EOCV system for gas approach (lead contractor NONOX)

- Methodology and approaches

For the further development of the NONOX EOCV engine basically two approaches were chosen that will be shortly discussed within this final activity report:

**Lean burn operation mode:**

The lean burn operation mode already have demonstrated very good specific fuel consumption values. However, due to more severe NOx targets and especially due to the still not satisfyingly solved problem regarding HC emission i.e. the catalytic conversion of methane, the focus of the development work was concentrated on improvement of the lean burn combustion process. Two means were identified in order to do so: the development of a new piston bowl shape and the application of a scavenged pre-chamber spark plug. Unfortunately, because of a.o. budgetary reasons, there was no possibility for the NONOX development team to apply more sophisticated
tools such as CFD. Instead, the applied methodology was a straightforward test bench empiric approach supported by simplified modelling.

**Lambda=1+cooled EGR concept**

As an alternative approach to the lean burn approach, a novel Lambda=1+ cooled EGR concept has been considered. This concept allows the application of a TWC by which NOx and HC emission targets can be reached much easier than within the lean burn mode. The known disadvantage in sfc compared to the lean burn mode are considered to be reduced with more enhanced NOx emission target. The novel EGR is equipped with a water separation unit in order to avoid water condensation of the cylinder charge when exposed to throttle free load control. The throttle free load control adds an important advantage in combination with the lambda=1+EGR mode with respect to max exhaust temperature. Due to the possibility of applying higher CR T-exhaust will be reduced.
Final result

For both the supportive action objectives and the further development objectives very satisfying results have been obtained. The GET-AKR knock detection system was successfully applied to the JBRC engine test bench and has proven to be a very useful tool for the JBRC investigation on varying gas composition. NONOX has developed a blending procedure by which varying composition of natural gas can be harmonised. This blending procedure was validated on the test bench.

Table 2.5-1 varying natural gas composition

<table>
<thead>
<tr>
<th>Task number: 0.2.1.5 NG Blending</th>
<th>RESULTS 1</th>
<th>Methane number can be equalised to preset value (80) for different base NG compositions.</th>
<th>Preset value of 80 is arbitrary.</th>
<th>Other preset values are possible.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane number</td>
<td>un-blended</td>
<td>blended</td>
<td>methane number can be equalised to preset value (80) for different base NG compositions.</td>
<td></td>
</tr>
<tr>
<td>NG1</td>
<td>(Gronings)</td>
<td>81.8</td>
<td>88.59</td>
<td>91.05</td>
</tr>
<tr>
<td>NG2</td>
<td>(Chinese 1)</td>
<td>0.4</td>
<td>0.06</td>
<td>1.64</td>
</tr>
<tr>
<td>NG3</td>
<td>(Chinese 2)</td>
<td>2.7</td>
<td>2.02</td>
<td>2.7</td>
</tr>
<tr>
<td>NG4</td>
<td>(Northsea)</td>
<td>0.3</td>
<td>1.54</td>
<td>2.36</td>
</tr>
<tr>
<td>NG5</td>
<td>(GUS-gas)</td>
<td>0.3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>98.21</td>
<td>97.62</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 2.5-1 shows how composition of natural gas can vary depending on from which source it is produced. It can be noticed that big differences in methane index and energy density do occur. Fig 2.5-1 shows that the Methane Index of mentioned natural gas compositions can be harmonised by the new developed blending procedure. Basic means for harmonization: Methane index can be increased by adding CO2 and can be decreased by adding C3H8. Similar can be stated with respect to the energy density of the CNG storage system.

Fig 2.5-1 harmonisation of methane index

The final result of the investigation of the lambda=1+cooled EGR demonstrates that all GREEN emission targets can not only be met, but, can even be obviously exceeded.

Fig 2.5-2 emission result set of against GREEN project targets
The obtained result concerning the lean burn operation mode did not yield a final solution for the primary HC emission problem. The newly developed piston bowl shape proved to be not sufficient in order to solve the problem. However, the investigation with the scavenged pre-chamber spark plug showed very good results in conjunction with the lean burn operation mode regarding the NOx-isfc trade off (see Fig.2.5-3).

Fig.2.5-3 NOx-isfc trade off @ low bmep=3.5 bar

Fig.2.5-4 fuel conversion functions

- Degree to which objectives were reached
  The degree to which objectives were reached set off against the GREEN project targets can be read in the previous subchapter. In general, for all project task the following picture represents an overall judgement of the work performed.

### Integrated Project: GREen Heavy Duty ENgine

<table>
<thead>
<tr>
<th>Deliverable No.</th>
<th>Deliverable title</th>
<th>Result judgement</th>
</tr>
</thead>
<tbody>
<tr>
<td>D02.1</td>
<td>New piston design</td>
<td>Approach did not yield adequate piston design and lean burn combustion process improvement.</td>
</tr>
<tr>
<td>D02.2</td>
<td>Scavenged pre-chamber spark plug</td>
<td>Very positive result regarding improved ignition- and lean burn behaviour. Positive effect expected also for EGR diluted mixture combustion.</td>
</tr>
<tr>
<td>D02.3</td>
<td>Cylinder deactivation concept</td>
<td>Theoretical study predicts sfc value as low as 2.25 g/kWh @ bmep=2.5bar. to be achievable.</td>
</tr>
<tr>
<td>D02.4</td>
<td>Impulse charging</td>
<td>Results demonstrate principle possibility of pulse charging capability. However current design of EOCV is not sufficient in order to exploit benefits.</td>
</tr>
<tr>
<td>D02.5</td>
<td>Lambda = 1 + cooled EGR concept</td>
<td>Results obtained emphasis end of emission problem occurred status.</td>
</tr>
<tr>
<td>D02.6</td>
<td>NG – blending/supportive action towards A1</td>
<td>Knock detection system supplied and applied at Prague University. New NG Blending procedure developed.</td>
</tr>
</tbody>
</table>
Relation of the results to the state of the art

It is evident that the obtained results do clearly distinguish the investigated technology from the state of the art technology. Especially the low GreenHouseGas-emission level marks a very important key advantage. Another major advantageous issue is the fact that the NONOX EOCV technology can be implemented on existing engines, which substantially tributes to lower development costs compared to other investigated (diesel) technologies which were subject to the GREEN project. Similar applies to the Exhaust gas After treatment System (EAS). A normal off the shelf –commercially available - TWC can be made use of. Not necessary to mention that system costs of such an EAS are considerably lower than advanced SOX-DOC-SCR- etc EAS’s

Impact of the results on industry and research sector

The question on how the obtained results, as far as the NONOX natural gas engine technology is concerned, would have an impact on the industry and research sector, is not easily to be answered. Idealy major european OEM partners will give more attention to the NONOX alternative power train technology. OEM partners from the ASEAN countries appear as more pro-active concerning further industrialisation of the technology. This could be explained by the fact that development of fuel infrastructure allows a simultaneous role out of liquid and gaseous fuel dispensors

Task 0.2.2 Fuel tests for HCCI (lead contractor IFP)

Methodology and approaches

Tests have been performed on a single cylinder research engine able to run under both HCCI and conventional Diesel conditions. The main characteristics of this engine are the following:

- Bore x Stroke : 115 mm x 125 mm (1.298 liter)
- Common-rail injection system (1600 bar max.)
- Reduced compression ratio (14:1)
- Specific piston design
- Adapted injector with narrow spray angle

All the tested running conditions are presented in the table below. In addition to these tests, the maximum HCCI range has been also evaluated at the three operating speeds.

<table>
<thead>
<tr>
<th>Engine speed (rpm)</th>
<th>Load (%)</th>
<th>Conventional combustion</th>
<th>HCCI with single injection</th>
<th>HCCI with multiple injection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1300</td>
<td>25</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>1300</td>
<td>50</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>1300</td>
<td>75</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1300</td>
<td>100</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1580</td>
<td>25</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>1580</td>
<td>50</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>1580</td>
<td>75</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1580</td>
<td>100</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1870</td>
<td>25</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
Table 1: Tested running conditions

The fuel matrix has been designed using a reference EN590 Diesel fuel into which specific components or petroleum cuts have been added to vary its cetane number, volatility or composition. The main characteristics of the five tested fuels are given in the following Table 2 and in Figure 1 and Figure 2.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Cetane number</th>
<th>Initial boiling point</th>
<th>Final boiling point</th>
<th>Aim</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>52.1</td>
<td>≈ 170</td>
<td>≈ 350</td>
<td>Reference EN590 Diesel fuel</td>
</tr>
<tr>
<td>Fuel 1</td>
<td>52.9</td>
<td>≈ 160</td>
<td>≈ 350</td>
<td>volatility by addition of a light petroleum cut</td>
</tr>
<tr>
<td>Fuel 2</td>
<td>48.5</td>
<td>≈ 170</td>
<td>≈ 350</td>
<td>CN by addition of low CN petroleum cut</td>
</tr>
<tr>
<td>Fuel 3</td>
<td>52.3</td>
<td>≈ 170</td>
<td>≈ 350</td>
<td>+10% Linear Olefins</td>
</tr>
<tr>
<td>Fuel 4</td>
<td>52.9</td>
<td>≈ 170</td>
<td>≈ 350</td>
<td>+ 10% Branched Olefins</td>
</tr>
</tbody>
</table>
Table 2: Fuel matrix design

<table>
<thead>
<tr>
<th>Distillation Temperature (°C)</th>
<th>Fuel 1</th>
<th>Fuel 2</th>
<th>Fuel 3</th>
<th>Fuel 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>Ref</td>
<td>150</td>
<td>170</td>
<td>190</td>
</tr>
<tr>
<td>20%</td>
<td></td>
<td>170</td>
<td>190</td>
<td>210</td>
</tr>
<tr>
<td>40%</td>
<td></td>
<td>190</td>
<td>210</td>
<td>230</td>
</tr>
<tr>
<td>60%</td>
<td></td>
<td>210</td>
<td>230</td>
<td>250</td>
</tr>
<tr>
<td>80%</td>
<td></td>
<td>230</td>
<td>250</td>
<td>270</td>
</tr>
<tr>
<td>100%</td>
<td></td>
<td>250</td>
<td>270</td>
<td>290</td>
</tr>
</tbody>
</table>

Figure 1: Boiling range of the tested fuels

Figure 2: Cetane number of the tested fuels

The criteria limiting the HCCI operating range are the following:
- maximum indicated NOx = 0.35 g/kWh
- maximum calculated particulates = 0.03 g/kWh
- maximum in-cylinder peak pressure = 225 bar
- maximum noise level = 95 dBA
- maximum intake pressure = 3.5 bar absolute
- intake temperature = 45 °C

- Final Results

A. Diesel combustion results
Under Diesel conditions, fuel comparison tests have been performed using a single injection and the following fixed parameters:

- Equivalence ratio
- Intake air flow and temperature
- No EGR
- Injection timing

A significant impact of the fuel volatility has been observed under these conditions: the fuel having a higher volatility (i.e. a lower Initial Boiling Point) leads to a decrease of Nox and Noise emissions compared to the reference fuel. This is due to the fact that the higher volatility of the fuel favors the mixing process that induces less heterogeneity of the fuel and air mixture and, consequently, less noise and NOx.

If no clear effect of the cetane number decrease has been noticed, the fuel composition and in our case, the addition of olefins (linear or branched) in the reference fuel is followed by an increase of the smoke emissions. Combustion analyses, giving the combustion duration in terms of Crank Angle (CA) showed that the final part of the process is slowed down when such components are added in the fuel. Longer combustion durations, and particularly the final part, are known to be linked with higher smoke emission as well as higher fuel consumption (decrease of combustion efficiency).

Fuels giving a too fast start of combustion (Decrease of CA50 – CA10) also induce, in general, higher noise emissions. That is the case when linear Olefins are added to the reference fuel.

The following table summarizes the effects of the fuel characteristic variation on the Diesel Engine emissions, consumption and combustion.

<table>
<thead>
<tr>
<th>Fuel / EN590</th>
<th>HC</th>
<th>CO</th>
<th>NOx</th>
<th>Smoke</th>
<th>CA50</th>
<th>CA90-CA10</th>
<th>CA50-CA10</th>
<th>CA90-CA50</th>
<th>Noise</th>
<th>Fuel Cons.</th>
</tr>
</thead>
<tbody>
<tr>
<td>+Volat</td>
<td>→</td>
<td>♦</td>
<td>♦</td>
<td></td>
<td></td>
<td>→</td>
<td></td>
<td></td>
<td></td>
<td>→</td>
</tr>
<tr>
<td>-CN</td>
<td>→</td>
<td>♦</td>
<td>♦</td>
<td></td>
<td></td>
<td>→</td>
<td></td>
<td></td>
<td></td>
<td>→</td>
</tr>
<tr>
<td>LinearOlef</td>
<td>♦</td>
<td>♦</td>
<td>→</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BranchOlef</td>
<td>♦</td>
<td>♦</td>
<td>→</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Fuel effect under Diesel conditions

B. HCCI combustion (Single Injection) results

First, it appeared that the impact of the fuel characteristics could be different than when tested under conventional Diesel conditions. In these HCCI conditions, and for all the tested fuels, the engine emits ultra-low NOx emissions. In that case, the compromise has to be found between noise and smoke emissions.

Increasing the volatility of the fuel generates mainly an increase of CO and smoke emissions and a decrease of noise. On the opposite, the fuel having a lower cetane number leads to significantly lower CO and smoke emissions but also to an increase of noise. The nature of the olefins used (linear or branched) has an impact on the fuel effect on combustion duration. Branched olefins are more reactive and reduce the combustion duration. These observed effects are summarized in the following table.
C. HCCI combustion (Multiple Injections) results

Similar test have been carried out using a multiple injection strategy. Moreover, the limit of the HCCI operating range has been evaluated for each fuel of the matrix.

The effects of the fuels on this HCCI limit appeared lower than expected (Figure 3). The maximum load increase that has been measured is 1.5 bar which is less that other results obtained at IFP but on a passenger car engine and with a different combustion chamber and an other injection strategy. It has been also noticed the fuel impact varies with engine speed. At low engine speed (A), a high volatility or a low cetane number or the appropriate amount of reactive components lead to an increase of the maximum possible IMEP. At average (B) and high (C) engine speeds, we observe only a positive effect for the fuel having a higher volatility.

![Figure 3: Fuel effect on the maximum HCCI load](image)

- Degree of which objectives were reached

Even if it has been demonstrated that the fuel may act on the combustion and, consequently on the performances of an HCCI engine, the extent of these effect is quite low compared to IFPO's
experience on other type of engines and injection systems. The first reason is certainly the small variations of fuel characteristics that have been tested. The second one seems to be that fuel parameter variations have been evaluated separately and not in combination. On the other hand, this type of engine appears quite robust to such fuel variations, which is also an interesting result.

- Impact of the results on industry and research sector

These results are a first step in the comprehension of the interactions between fuel characteristics and HCCI engine behaviour, emissions and performances. They showed that it is possible, acting on the fuel, to enhance the interest of such an engine. Supplementary works have to be carried out to take the more advantages of this approach.

**Task 0.2.3 Fuel tests for diesel combustion (lead contractor Ford Otosan)**

In order to perform the tests on the specified fuels, a Euro III stage reference engine, was assembled with a 100% measured parts and went through 50 hours of Break-in process to be ready for the tests, as defined in the description of work at our Engine Development Plant in Inonu.

At the same time, in our test center in Kocaeli Plant, test dynometer and reference Euro III calibration of ECU unit were prepared. When the engine arrived to Golcuk facilities, the reference engine was also calibrated to Euro III level.

Before start running tests, in order to observe the accuracy of the tests results, this engine went through a reference repeatability test and the results were approved by the core group.

The tests performed were as follows:

1. Heavy Duty Engine Exhaust Emission test – ECE 24
2. Heavy Duty Engine Exhaust Emission test – ESC
3. European Transient Cycle – ETC
4. Engine Performance – full load curve

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Ford Otosan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working principle</td>
<td>CI, 4 stroke</td>
</tr>
<tr>
<td>Number/arrangement of cylinders</td>
<td>6 inline</td>
</tr>
<tr>
<td>Bore</td>
<td>112 mm</td>
</tr>
<tr>
<td>Stroke</td>
<td>124 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dynamometer</th>
<th>AFA 404/8 ; AVL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque Capacity</td>
<td>1867 Nm constant up to 4000 rpm</td>
</tr>
<tr>
<td>Power Capacity</td>
<td>440 kW between 4000-8000 rpm</td>
</tr>
<tr>
<td>Type of Operation</td>
<td>Active and Passive mode</td>
</tr>
<tr>
<td>Sense of Rotation</td>
<td>CW &amp; CCW</td>
</tr>
</tbody>
</table>

European-Integrated Project “GREEN”
<table>
<thead>
<tr>
<th>Firing order</th>
<th>1-5-3-6-2-4</th>
<th>Overall Accuracy</th>
<th>0.3 % full scale Torque ± 1 rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working principle</td>
<td>DI</td>
<td>Control Accuracy</td>
<td>0.5 % Torque ± 5 rpm</td>
</tr>
<tr>
<td>Engine Capacity</td>
<td>7330 cm³</td>
<td>Torque Response</td>
<td>~ 10-20 ms for 0-maximum Torque</td>
</tr>
<tr>
<td>Volumetric CR</td>
<td>17.6 ± 0.5:1</td>
<td>Speed Response</td>
<td>5000 rpm/sec for nominal Torque</td>
</tr>
<tr>
<td>Max. net Power</td>
<td>221 kW @ 2400 rpm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Above are the test engine and test cell specifications.

In the summary tables below, average values of emission results of ESC and ETC tests, test grade A (Euro 4) is chosen to be the reference fuel and given a '100' value to make comparison between different fuel types easier and analyse the results better.

### ESC Tests Results – Summary Table

<table>
<thead>
<tr>
<th>g/kW.h</th>
<th>GRADE A</th>
<th>GRADE B</th>
<th>GRADE C</th>
<th>GRADE D</th>
<th>GRADE E</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx</td>
<td>100</td>
<td>96</td>
<td>95</td>
<td>102</td>
<td>95</td>
</tr>
<tr>
<td>PM</td>
<td>100</td>
<td>79</td>
<td>66</td>
<td>103</td>
<td>90</td>
</tr>
<tr>
<td>CO</td>
<td>100</td>
<td>115</td>
<td>105</td>
<td>120</td>
<td>111</td>
</tr>
<tr>
<td>HC</td>
<td>100</td>
<td>133</td>
<td>144</td>
<td>122</td>
<td>100</td>
</tr>
</tbody>
</table>

### ETC Tests Results – Summary Table

<table>
<thead>
<tr>
<th>g/kW.h</th>
<th>GRADE A</th>
<th>GRADE B</th>
<th>GRADE C</th>
<th>GRADE D</th>
<th>GRADE E</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx</td>
<td>100</td>
<td>97</td>
<td>95</td>
<td>102</td>
<td>94</td>
</tr>
<tr>
<td>PM</td>
<td>100</td>
<td>78</td>
<td>78</td>
<td>88</td>
<td>81</td>
</tr>
<tr>
<td>CO</td>
<td>100</td>
<td>105</td>
<td>91</td>
<td>123</td>
<td>94</td>
</tr>
<tr>
<td>HC</td>
<td>100</td>
<td>114</td>
<td>114</td>
<td>114</td>
<td>86</td>
</tr>
</tbody>
</table>

**BSFC @ max. Torque**

|          | 100 | 99.5 | 96.7 | 99.7 | 100.5 |

When the test results are analyzed, Test Grade C (Fischer-Tropsch) gives lower emission values than the others. The basic distinction of Grade C is being composed of the specifications with maximum cetane number and minimum aromatics and density.

When compared with the reference fuel Grade A (Euro 4), Grade C fuel gives;

a. Apprx. 3.3 % reduction in fuel consumption at maximum torque,

b. 5% improvement in NOx emissions,

c. PM reduces 34% in ESC test and 22% in ETC test.
2.6 Workpackage 0.3 – Rail Specifications and Engine Development

2.6.1 Subproject Objectives

WP 0.3 aimed in developing a new combustion concept for diesel rail engines which allows to fulfill future emissions legislation (2012 and later). The technologies used for HD truck engines offer possibilities to be transferred to rail engines. However, it is important to pay attention to the different operating conditions. Engines for railcar application with power output less than 560 kW are usually derived from HD engines, and the transfer of technologies is relatively easy to realize. “Locomotive” engines with power output of typically 1000 kW to 3000 kW are not derived from HD engines. The transfer of HD technologies to these engines is much more difficult to achieve and for this reason, the investigations of task 0.3.2 are concentrated on locomotive engines. Here the focus is on the in-cylinder reduction of NOx-emissions in order to be able to fulfill future NOx-emission legislation without aftertreatment. Regarding the particulate emissions, a DPF might be possible.

UIC and UNIFE defined the railway specific needs and technical requirements and disseminated the results of the GREEN project to the railway sector. MTU developed the new combustion process on a single-cylinder engine and validated it on a multi-cylinder engine.

2.6.2 Relation to the state-of-the-art

Altogether it can be concluded, that the EGR-technology, which is already well-known in on-highway heavy-duty truck applications, has been successfully transferred to the rail sector within the GREEN project in WP 0.3. The use of EGR is completely new for locomotive applications and thus the absolute state of the art in this field of engines. Today's stage IIIa-engines (NOx: 6,0 g/kWh) still use the Miller-cycle.

Diesel rail vehicles are usually classified into Diesel locomotives and Diesel railcars (DMU). Both vehicle types are mainly used in Europe on non electrified branch lines, which are characterized by a limited allowable axle load (max. 18t/axle) and small tunnel profiles (Tunnel profiles in UK are the smallest in Europe. The maximum allowable height of rail vehicle built for UK is almost 30 cm lower than for the rest of Europe. They are designed for a service life of 30 years.

**Diesel locomotives**

European Diesel locomotives are normally powered by one high-performance engine (>560 kW-3000 kW derived from marine, mining or stationary engines) and are used for passenger and freight services. The power equipment is installed in a special machine room inside the locomotive’s body.

**Diesel railcars**

Diesel railcars (or DMU) are designed for passenger service only, are either single coaches or fixed coupled consisting of 2 or max. 3 power cars. Normally, each unit is driven by one medium power engine (250kW < 560kW), which is often a derivate of off-highway industrial or on-highway truck engine. The power equipment is installed under floor, e.g. below the passenger cabins.
In contrast to electrical rolling stock both diesel driven vehicle types have to carry their own energy source onboard (1-2 tons fuel for railcars/ 2-8 tons for locomotives). Today, both the general requirements caused by the rail infrastructure (tunnel profiles, max. axle load) and the functional requirement to carry the locomotive’s own energy supply onboard force the manufacturer to utilise all available space in, under or above the vehicle (refer to figure 1 and 2). Latest investigations of the European rolling stock manufacturers show that meeting the new Stage IIIB emission limits of 2004/26/EC will require voluminous additional equipment to be installed in rail vehicles.

“Stage III B” will require the following additional external equipment:

- Exhaust gas after-treatment systems for NOx reduction (SCR, with urea tank, heated piping and NOx catalyst) and particulate filter (DPF) require additional space and weight.
- As cooled exhaust gas for the modified combustion cycle is required, a larger engine cooling system is the consequence.
- Space for additional auxiliary power needed (e.g. for larger cooling fans).
- Engine weight increase
- When the lengths of the locomotives increase to package all the above mentioned additional components the body has to be strengthened too, this causes an additional increase in axle load.

Realistic assumptions show a weight increase of 3 to 4 tons for a 4-axle locomotive and about 0.5 – 1 ton for railcars. Even modern existing 6-axle locomotives, which are the largest and most powerful, used in Europe, have axle loads of more than 21 metric tons today. This limits its use to high capacity main lines.

Facing the general arrangements of modern diesel rail vehicles it must be stated that today’s locomotives/ railcars have already reached their regulated size and weight limits.

Consequences of increased weight and space, due to additional equipment for Stage III B equipment:

Locomotives:

- Restricted use of 4-axle locomotive on branch lines (due to weight), and into customer’s terminus (shunting).
- There is a risk that locomotives may no longer be allowed on non-electrified branch lines and in rural areas; this threatens rail freight as cost-intensive electrification as an alternative is questionable.
- Limited space and weight may be counteracted by integrating a smaller and lighter engine with reduced power but this increases the number of locos necessary for rail service thus higher transport cost
- When axle load must be increased to allow heavier equipment and vehicles must be longer, rail infrastructure must be improved.
- Avoid a Modal Shift from rail to road. (One 2000kW locomotive hauls the same freight volume as 50 trucks with 400kW each.)

Railcars:

- Loss of passenger capacity due to additional space requirement for After-treatment device

2.6.3 Work Performed & Final Results

In order to reach the objectives, the possible in-cylinder measures for the reduction of engine-out NOx raw emissions in locomotive applications have been described and evaluated in a first
step. The study has shown that technologies like EGR, homogeneous combustion and variable valve actuation are the most promising ones for rail application. In a second step a new combustion process with full air utilization has been examined on a single cylinder engine. In a third step, the new concept has been examined on a multi-cylinder demonstrator engine (prototype). Altogether, the outcome of Task 0.3.2 is a combustion process which meets the EU-stage-IIIb regulation. Within the scope of the Cleaner-D project (7th EU frame programme) first prototype-engines will be intensively tested in different rail applications. Therefore it can be concluded that the results of the GREEN project will be directly used as input to the Cleaner-D project.

The use of EGR is completely new for locomotive applications and thus the absolute state of the art in this field of engines, see 2.2. Some additional features which were meant to reduce the necessary EGR-rate could not be realized. This result impacts the cooling system of IIIb-compliant diesel locomotives since either the efficiency of the cooling system or the dimensions of the coolers has to be increased in the future.

**Task 0.3.1/0.3.3:**

- Methodology and approaches

Interaction between the GREEN project, the automotive sector and the engine manufactures (MTU) and the rail sector (UNIFE and UIC).

A list of railway specifications for a Heavy Duty engine was drafted by the UNIFE and UIC experts, evaluated by MTU and commonly discussed in the GREEN workshop. (Automotive sector and rail sector) at the UIC Headquarters in Paris on May 4th, 2007. The result is an evaluated list underlining the transferability of the technology and highlighting the future needs for adaptation.

- Final Results

Evaluated List of Specifications
State-of-the-art-Report Diesel traction in the world
Final Report “GREEN” and the railway sector

- Degree of which objectives were reached 100%

- Relation of the results to the state of the art

The final result of this work package is a careful consideration between the state-of-the-art, the railway sector’s needs and requirements and the achievements of the Green project (automotive sector)

- Impact of the results on industry and research sector

The encouraging GREEN results will be the input for the FP 7 2nd call project (submitted on May 7th, 2008 and still to be approved by the EC) CLEANER-D
2.6.4 Contractors Involved

- **MTU Friedrichshafen**

MTU Friedrichshafen GmbH is one of the world’s leading manufacturers of large diesel engines and complete drive systems. Together with Detroit Diesel, the company represents the two core brands of the Tognum Group. Covering diesel engines and gas turbines, its product range is the widest and most modern in the sector. Applications range from ships to heavy land and rail vehicles and from vehicles and equipment for the construction, industrial and agricultural sectors to decentralized power generation plant. During a history spanning almost 100 years, MTU Friedrichshafen and its predecessors, including Maybach-Motorenbau GmbH in particular, have been responsible for repeated innovation and have continually been at the forefront of technological progress.

- **UNIFE (Union of European Railway Industries)**

UNIFE represents the interest of the European railway industry towards the European Institutions, international railway associations and other business relations. The railway industry consists of trend setting industries in the field of rolling stock, infrastructure, information technology & signalling, provision of part and services. UNIFE represents the largest and medium sized companies of the railway supply industry. Further equipment suppliers are associated members through their National Associations.

- **UIC (Union Internationale des Chemin de Fer)**

The International Union of Railways (UIC) is the world-wide organisation for international cooperation among railways and promotion of the rail transport mode. It was founded in 1922. Its initial purpose was standardisation and improvement of conditions for railway construction and operations, especially in view of international traffic. In 2005 a “New UIC” has been designed in order to cope with a series of new challenges, in particular railway liberalisation, increasing competition from other modes, the growing economic constraints on railways together with the challenge of globalisation of the transport market which creates new opportunities for railways. The UIC mission in 2006 consists in promoting Rail transport at World level in order to meet challenges of Mobility and Sustainable Development. UIC groups 171 members (railways, rail operators, infrastructure managers, railway service providers, public transport companies, etc.) on all 5 continents. The Headquarters are located in Paris, France.

2.6.5 List of acronyms

- DMU – Diesel Multiple Unit
- DPF – Diesel Particulate Filter
- EGR - Exhaust Gas Recirculation
- KW – Kilo Watt
3. Final plan for using and disseminating the knowledge

3.1 Introduction

It has been the goal of GREEN to effectively disseminate the results and the knowledge gathered by all project partners. This has ensured the coherence of the project and helped to reach the social, economical and political exploitation of its results.

This Annex describes the approach undertaken by GREEN to disseminate the results of the project to a broader public, scientific and technical audience.

3.2 Exploitable knowledge and its Use - overview table

This section will present exploitable results for the period 2005.03.01 to 2008.05.31 of the IP GREEN, defined as knowledge having a potential for industrial or commercial application in research activities or for developing, creating or marketing a product or process or for creating or providing a service.

<table>
<thead>
<tr>
<th>#</th>
<th>Exploitable Knowledge (description)</th>
<th>Exploitable product(s) or measure(s)</th>
<th>Sector(s) of application</th>
<th>Timetable for commercial use</th>
<th>Patents or other IPR protection</th>
<th>Owner &amp; Other Partner(s) involved</th>
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<tbody>
<tr>
<td>1</td>
<td>Electronically Controlled Valve Motion Management for HD CNG Engines</td>
<td>EVMG system for HD CNG-Engine -PRODUCT</td>
<td>1. Automotive</td>
<td>3 years after the end of the Project</td>
<td>Several existing Patents owned by CRF on Variable Valve Management and CNG engines</td>
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<tr>
<td>2</td>
<td>Advanced System for Pressure Regulation</td>
<td>Advanced Pressure Regulator -PRODUCT</td>
<td>1. Automotive</td>
<td>2 years after completion of the Project</td>
<td>Evaluations are on-going</td>
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<tr>
<td>3</td>
<td>Combustion System Development for CNG- Direct Injection for HD-CNG engine</td>
<td>CNG-Direct Injection for HD-CNG engine -TECHNOLOGY Direct Injectors for HD CNG engine -PRODUCT</td>
<td>1. Automotive</td>
<td>2 years after completion of the Project</td>
<td>A Patent for DMI (Direct Mixture Injector) owned by AVL exists</td>
<td>AVL</td>
</tr>
<tr>
<td>4</td>
<td>CNG gas qualification and knock behaviour analysis models</td>
<td>Engineer services - METHODOLOGY</td>
<td>1. Automotive</td>
<td>End of the Project</td>
<td>Implementation into commercial simulation code</td>
<td>JBRC</td>
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<tr>
<td>5</td>
<td>Turbo-lag analysis by EVMG and Turbo</td>
<td>Engineer services - METHODOLOGY</td>
<td>1. Automotive</td>
<td>End of the Project</td>
<td>Implementation into commercial simulation</td>
<td>PT</td>
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<td>#</td>
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<tr>
<td>6</td>
<td>Improved models for combustion and emissions</td>
<td>services and computer code offered to clients</td>
<td>engine P&amp;E engine control</td>
<td></td>
<td></td>
<td>AVL</td>
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<tr>
<td>7</td>
<td>Cylinderhead design with new casting material</td>
<td>Cylinderhead Engine housing</td>
<td>1. Transport and stationary applications.</td>
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<td>8</td>
<td>Steel pistons</td>
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<td>1. Transport</td>
<td>2012</td>
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<td>9</td>
<td>New Turbocharging technology</td>
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<td>2012</td>
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<td>New Injection system</td>
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<td>1. Transport</td>
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<td>Vehicles</td>
<td>1. Transport</td>
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<td>Heat recuperations</td>
<td>Vehicles</td>
<td>1. Transport</td>
<td>2012</td>
<td>1</td>
<td>IMF</td>
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<tr>
<td>15</td>
<td>Improved and validated models for layout and design of parts with demanding thermal and mechanical loads</td>
<td>services offered to clients</td>
<td>Engine design</td>
<td>Immediately after achievement of result</td>
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<td>AVL</td>
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<td>16</td>
<td>Simul. model for mechanical &amp; electrical turbocompounding</td>
<td>Simulation Software in Executable formt</td>
<td>1. Industrial-Engine Manufacturer 2. Education-Training tool.</td>
<td>2008</td>
<td>NTUA (owner)</td>
<td></td>
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<td>17</td>
<td>Improved NOx trap formulations</td>
<td>Advanced LNA catalysts for thermal durability and increased sulfur</td>
<td>Engine aftertreatment</td>
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<td></td>
<td>Johnson Matthey Plc.</td>
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<td>18</td>
<td>Electronically Controlled Valve Motion Management for HD CNG Engines</td>
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<td>19</td>
<td>Advanced System for Pressure Regulation</td>
<td>Advanced Pressure Regulator -PRODUCT</td>
<td>1. Automotive</td>
<td>2 years after completion of the Project</td>
<td>Metatron deposited a patent claim (N.61.M3624.4 2 IT.5 LF, Title: Riduttore di pressione per gas - gas pressure regulator) in October 2006.</td>
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<td>21</td>
<td>CNG gas qualification and knock behaviour analysis models</td>
<td>Engineer services - METHODOLOGY</td>
<td>1. Automotive</td>
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<td>Implementation into commercial simulation code</td>
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<td>Turbo-lag analysis by EVMG and Turbo charging combined simulation</td>
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<td>Advanced engine structure for 240 bar PFP</td>
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<td>Iveco, AVL</td>
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<td>Heavy Duty-VCR- system</td>
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<td>Axi-radial compressor design</td>
<td>High pressure ratio diesel engine turbocharger</td>
<td>Heavy duty automotive &amp; industrial diesel engines</td>
<td>2012</td>
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<td>Engine evolution</td>
<td>Industrial production</td>
<td>2012</td>
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<td>New EGR system</td>
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<td>Industrial production</td>
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<td>Iveco, Behr, Modine</td>
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<td>New SCR catalyst</td>
<td>Vehicle with advanced aftertreatment system</td>
<td>Industrial production</td>
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<td>Iveco, JM, Eminox</td>
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<td>30</td>
<td>New control approach for integrated system engine-aftertreatment</td>
<td>Software</td>
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<td>2012</td>
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<td>IMF, Bosch</td>
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<tr>
<td>31</td>
<td>Simulation model for mechanical &amp; electrical turbocompounding</td>
<td>User friendly Simulation tool in Executable format</td>
<td>1. Industrial-Engine Manufacturer 2. Education-Training tool.</td>
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<td>Simulation for Rankine Bottoming Cycle</td>
<td>Simulation Software in Executable format</td>
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<td>Iveco, IMF</td>
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<td>New approach, Further research with hardware</td>
<td></td>
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<td>IMF, Iveco, Voith</td>
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<td>35</td>
<td>Advanced engine structure for 240 bar PFP</td>
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<td>Iveco, AVL</td>
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<td>Iveco, AVL</td>
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<td>High power engines</td>
<td>transport</td>
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<td></td>
<td>Iveco, AVL</td>
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<tr>
<td>#</td>
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<td>improved cylinder liners</td>
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<td>Iveco, AVL</td>
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<td>Improved cranktrain</td>
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<td>2014</td>
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<td>High power engines</td>
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<td>ELRING</td>
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<td>Steel pistons</td>
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<td>transport</td>
<td>2014</td>
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<td>Iveco, suppliers, other OEM’s</td>
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<td>42</td>
<td>Advanced Injection System</td>
<td>engines</td>
<td>transport</td>
<td>2012</td>
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<td>Iveco, Bosch</td>
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<tr>
<td>43</td>
<td>New controls for engine and aftertreatment</td>
<td>engines</td>
<td>transport</td>
<td>2012</td>
<td></td>
<td>Iveco, Bosch</td>
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<td>44</td>
<td>Design and arrangement of compact 2-stage turbocharging</td>
<td>High power engines</td>
<td>transport</td>
<td>2014</td>
<td></td>
<td>CTT, Iveco</td>
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<td>45</td>
<td>Improved single stage turbocharging with axi/radial compressor</td>
<td>High power engines</td>
<td>transport</td>
<td>2014</td>
<td></td>
<td>CTT, Patents existing</td>
</tr>
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<td>46</td>
<td>Improved EGR- systems</td>
<td>engines</td>
<td>transport</td>
<td>2012</td>
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<td>Iveco</td>
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<td>47</td>
<td>Heavy duty VCR- system</td>
<td>High power engines</td>
<td>transport</td>
<td>2014</td>
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<td>FEV</td>
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<td>48</td>
<td>Potential of heat regeneration systems</td>
<td>engines</td>
<td>transport</td>
<td>2020</td>
<td>IVECO- Patent existing</td>
<td>NTUA, Iveco</td>
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<td>49</td>
<td>Arrangement of heat recuperation in a truck, cooling layout</td>
<td>engines</td>
<td>transport</td>
<td>2020</td>
<td>IVECO- Patent existing</td>
<td>NTUA, Iveco</td>
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<tr>
<td>50</td>
<td>Simulation for Rankine Bottoming cycle</td>
<td>Simulation software in executable form</td>
<td>1.) Industrial manufacturer 2.) Education training tool</td>
<td></td>
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<td>NTUA</td>
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<tr>
<td>51</td>
<td>Simulation model for mechanical</td>
<td>Simulation software in executable form</td>
<td>1.) Industrial manufacturer 2.) Education</td>
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<td></td>
<td>NTUA</td>
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<td>Exploitable Knowledge (description)</td>
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<td>52</td>
<td>Exhaust heat recuperation system</td>
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<td>transport</td>
<td>2020</td>
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<td>Iveco, IMF, Voith</td>
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<td>53</td>
<td>New Combustion system for high EGR and high injection pressure</td>
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<td>2012</td>
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<td>Iveco</td>
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<td>Iveco, suppliers, other OEM’s</td>
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<td>Software</td>
<td>transport</td>
<td>2012</td>
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<td>Iveco - Patent existing IMF, Iveco, Bosch</td>
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<td>56</td>
<td>A Burner/vaporizer unit for exhaust aftertreatment</td>
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<td>transport</td>
<td>Patent pending</td>
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<td>Deutz</td>
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</tbody>
</table>

### 3.3 Description of the exploitable results (dummy)

Detailed description of each result mentioned in the chapter 3.2 Exploitable knowledge and its Use - overview table

1) The EVMG system is an electronically controlled electro-hydraulic variable valve actuation system for HD CNG engine. In the GREEN framework the EVMG (PRODUCT) will be fully integrated in CNG engine system, to implement an advanced engine management. Thanks to the direct charge (quantity and motion) control at intake valves both engine performance and fuel efficiency can be significantly improved.

2) The pressure regulator (PRODUCT) is a double stage pressure regulator that can be used in the CNG fuel system of a spark-ignited engine. It can be installed in the engine compartment, reducing the tank pressure (20/200bars) to the injection pressure of 9 bars. It will be equipped with a shut off valve, a pressure relief valve and will be connect with the inlet manifold in order to have the proper outlet gas pressure according to the engine conditions. It will be connected to the engine cooling system to supply the heat needed to compensate the gas temperature reduction caused by the gas expansion. It could be electronically controlled.
3) The direct injection technology (TECHNOLOGY) will be assessed for HD CNG applications. The disadvantage of actual CNG port injection engines in terms of full load performance can be nearly eliminated by direct injection and boosting. The definition of the requirements of a suitable injector (PRODUCT) type and ignition system for HD CNG engine will be a secondary output of the combustion system development.

CRF, MT and AVL will evaluate the opportunity to apply for new and/or extended patents’ claims in order to protect their results.

4 & 5) The developed knowledge, referred to the modelling and the experimental techniques for CNG qualification, Knock behaviour analysys and turbo-lag simulation might have application in research activities developed within the automotive sector (vehicle and/or components manufacturers) but at the moment it is not possible estimate their commercial potentials (Implementa-tion into commercial simulation code).

PT and JBRC will use their advanced Know How in further commercial projects with their automotive customers and will evaluate the opportunity to protect their Know-How by an appropriate IPR policy.

6) AVL List GmbH is an independent company for internal combustion engine research and development. Improved tools and knowledge on combustion and emissions will be directly utilised in projects for clients. Specific software products for engine research and development are also directly commercialised.

The exploitable results are an improved computer code for the calculation of diesel combustion and emissions and the methodology to calibrate and apply the models for the optimisation of engine performance and emissions and for engine control.

From the current point of view no partners will be involved in the exploitation.

**Iveco SpA:**

The HBMEP engine presents a step into new technologies, required by higher cylinder pressures. The higher pressures are necessary to fulfill the future emission limits, improving at the same time power density and fuel consumption. Alternatively a variable compression ratio system (VCR) could be applied to avoid high peak pressures at full load. Thus the technology steps for the high cylinder pressure structure could be partially avoided, with impact on BSFC. Alternatively, the system could be used as an “enabler” for alternative combustion. An comparison of technical and economical aspects should provide the basis for selecting the proper concept.

7.) The cylinderhead design has to be adapted for the new material and its thermomechanical properties. Partners: AVL (Design), Winter (Supplier). Some competitors have already made that step. The limits with the existing material can be extended by optimised design and standard material improvements. The new material will require special attention in the casting process and will be more difficult to machine.

7.1) New cylinder liners have to applied. Features are top end liner cooling, material, hardening. Partners: AVL (Design), Pleuco (Supplier), FM (Supplier). This technology is already adapted by US – truck industry in connection with the high EGR – concept to reduce liner wear.
7.2) New cylinderhead gasket for elevated cylinder pressures. Partners: AVL (Design), Elring (Supplier). The concept is already adapted by two main truck manufacturers in Europe. The design is focused partially to reduce load on the cylinderhead.

8.) A change from aluminum- to steel- pistons might be required. Partners: FM (Design and supplier). This type of piston are already used in the US. This is from one side traditional for the US – market, on the other hand this technology may be forced by the high cylinder pressure and thermal loading.

9.) New turbocharging technology for higher boost pressures will be necessary. Partners: Holset (Design and Supplier, BEHR). The single stage arrangement is limited for several reasons (material related compressor outlet temperature, useful map width) for the achievable pressure ratio. A combined axial radial compressor wheel from Ti-material can overcome this limit up to a pressure ratio of ca. 5. Above that 2-stage Turbocharging has to be used. 2-stage TC has the advantage of possible intercooling, which increases the thermodynamic efficiency and keeps temperatures within standard material limits. A disadvantage is the more difficult packaging and arrangement. For the single stage compressor advanced charge air coolers have to be used to cope with the increased pressures and temperatures.

10.) A variable compression ratio system (VCR) will be developed. Partners: FEV (design). The system will be an alternative to a high PCP engine structure. The targets could be reached with an optimised standard engine structure. The economy of the alternative has to be compared to the other solution. It would be worldwide the first VCR system for truck application. Its application could also be optimised for application of alternative combustion.

11.) New injection system. Partners: BOSCH (Design and supplier) For fulfilling the future emission limits and low noise requirements, the change to a CR-system may be necessary. The engine is designed as a Unit Injector engine, therefore considerable design efforts have to be made. Related to the new system will be a change of the Electronic Diesel Control Unit (ECU) with additional features for new emission limiting functions. This requires considerable effort in transition of existing and design of new software, which is not covered by GREEN.

12.) The impact onto the auxiliary drive train has to be checked. Partners: (Iveco internal). The increased BMEP will cause higher crankcase oscillations. This could damage the auxiliaries located on the engine (steering pump, alternator, air compressor, PTO, fan) or the following gear train. Free running devices for alternators or a 2-mass flywheel for gearbox protection are known countermeasures.

13.) The aftertreatment components and their control have to be defined. Partners: Iveco internal, JM, BOSCH, others. A SCRT- aftertreatment system will be applied. Also proper controls and sensors have to be applied for reaching the GREEN target.

14.) The possibility of heat regeneration from exhaust gas should be investigated and compared for different systems. Partners: (NTUA). There are different technologies known to recuperate waste heat from exhaust and coolant. Application is more or less complex and the energy density of the whole package (engine and recuperation system) will more or less decrease. Mechanical and electrical turbocompounding are attractive from installation point of view. However the combined Rankine Cycle technologies have big potential for BSFC improvement. The potential for CO2 reduction (GWI) is related to BSFC also very high.

The field is already covered by a large amount of patents (e.g. Enginion, Webasto). IMF has procured a patent search and placed an European patent describing arrangements and interactions of a rankine cycle with aftertreatment.
NTUA:

15.) Simulation Model for Mechanical & Electrical Turbocompounding.

- The result is a general simulation code for HD DI diesel engines including mechanical & electrical turbocompounding. It allows the selection of various turbocompounding layouts and has the ability to simulate any DI diesel engine.

- NTUA will be involved in its exploitation by producing relevant documentation for its use, user manual and distribution to the various sectors of possible application.

- The results may be exploited indirectly i.e. through licensing to potential users or even directly through a spin off.

- The simulation will be improved by cooperating with T/C manufacturers in order to use realistic maps for T/C and Turbine equipment.

- The basic software has already provided in the past to Caterpillar USA and Robert Bosch SA in its executable form. The software already provided does not include turbocompounding capability. From Robert Bosch a positive feedback has been obtained after trial use of the simulation.

16.) Simulation Model for a Rankine Bottoming Cycle.

- The result will be a complete simulation code for Rankine Bottoming cycles using steam as base working media and provision for use of organic compounds.

- NTUA will be involved in its exploitation by producing relevant documentation for its use, user manual and distribution to the various sectors of possible application.

- The results may be exploited indirectly i.e. through licensing to potential users or even directly through a spin off.

- To improve the simulation it will be required cooperating with expander and heat exchanger manufacturers.

JM:

17.) Improved NOx trap formulations. Johnson Matthey's Environmental Catalysts and Technologies (ECT) business is involved in the manufacture of catalysts for automobile emission control and the reduction of emissions from industrial processes. Improved knowledge in the formation of advance after treatment systems will be utilised for clients and these products will be directly commercialised. Exploitable results are the development of next generation lean NOx absorber catalysts and diesel oxidation catalysts applicable for heavy duty diesel applications, tailored for meeting future emissions targets.

Currently no partners will be involved in this exploitation.

18) The EVMG system is an electronically controlled electro-hydraulic variable valve actuation system for HD CNG engine. In the GREEN framework the EVMG (PRODUCT) will be fully
integrated in CNG engine system, to implement an advanced engine management. Thanks to the direct charge (quantity and motion) control at intake valves both engine performance and fuel efficiency can be significantly improved.

19) The pressure regulator (PRODUCT) is a double stage pressure regulator that can be used in the CNG fuel system of a spark-ignited engine. It can be installed in the engine compartment, reducing the tank pressure (20/200bars) to the injection pressure of 9 bars. It will be equipped with a shut off valve, a pressure relief valve and will be connect with the inlet manifold in order to have the proper outlet gas pressure according to the engine conditions. It will be connected to the engine cooling system to supply the heat needed to compensate the gas temperature reduction caused by the gas expansion. It could be electronically controlled.

20) The direct injection technology (TECHNOLOGY) will be assessed for HD CNG applications. The disadvantage of actual CNG port injection engines in terms of full load performance can be nearly eliminated by direct injection and boosting. The definition of the requirements of a suitable injector (PRODUCT) type and ignition system for HD CNG engine will be a secondary output of the combustion system development.

CRF, MT and AVL will evaluate the opportunity to apply for new and/or extended patents’ claims in order to protect their results.

21) The developed knowledge, referred to the modelling and the experimental techniques for CNG qualification, Knock behaviour analysis and turbo-lag simulation might have application in research activities developed within the automotive sector (vehicle and/or components manufacturers) but at the moment it is not possible estimate their commercial potentials (Implementation into commercial simulation code).

PT and JBRC will use their advanced Know How in further commercial projects with their automotive customers and will evaluate the opportunity to protect their Know-How by an appropriate IPR policy.

22) Advanced engine structure
For fulfilling future emission targets with lowest possible fuel consumption and, if possible, the todays power to weight ratio, higher Engine- Peak- Firing- Pressures have to be handled. This could require some changes in engine technology as the use of special casting material (as e.g. CGI) and steel pistons. The new casting material implies the application of new design rules and a change in parts machining. Because the casting process is also more difficult, all this leads to an increased cost. At the beginning of the project attempts were made to improve the structure with the conventional head material. This turned out as not feasible, also the attempt to include an exhaust- duct- isolation. An unexpected obstacle was the lack of suitable suppliers and the refusing of a supplier to support research work.

Modified parts as top- end- cooled- cylinder- liners, smaller valves to support the higher PFP, a new type of cylinderhead gasket are also necessary.

23) Heavy Duty VCR- System
A VCR- system for heavy- duty- application was designed and procured. It is seen as a engine- add- on- system to allow higher engine- power without a basic change of the engine structural components. The system could also be used as an enabler for alternative combustion modes.

24) New turbocharging System
For providing high EGR together with a suitable air fuel ratio and high engine power, new charge air systems providing higher pressure ratios are necessary. It has to be verified, which
system, improved- single- stage or 2 stage- in combination with a chosen EGR- system will be applied. The project gives information for decisions.

25) Axi-radial compressor design
This is a design of turbocharger compressor which has been demonstrated to achieve significantly higher pressure ratios compared to conventional automotive turbocharger compressors. It can potentially allow increased engine performance without the added complexity of a two-stage turbocharger system. Design and development is the responsibility of Cummins TurboTechnologies (formerly Holset Turbochargers). There are no known IP rights held by other parties which would limit the exploitation of this design, CTT intends to protect details of the new design by a patent application. The design has not yet been developed for volume production, several areas related to manufacturing processes and development for long term durability need to be addressed.

26) Advanced Injection system:
The search for a suitable injection system is always actual. The next approach is to find a system, which will provide low enough soot levels for “passive soot filter operation”. This is difficult because of the necessary application of high EGR- amounts also at full load. The system should provide also in lower engine noise.

Flexibility in the sense of enabling early and splitted injections for alternative combustion modes and late injections for active soot filter regeneration are maybe required. Also the exchangeability with less sophisticated parts for other applications (offroad, other markets) are an issue. For enabling the use of Common Rail Systems existing Unit- Injector- engines have to be modified in design.

The demand for alternative fuels is a critical item. Whereas GTL or GTL would cause no problem, neat biofuels or ethanol mix or diesel/water emulsions are not suitable for this highly sophisticated injection system components (very high injection pressures, small gaps, high temperatures etc.). They would cause corrosion, cavitation and sticking due to residuals.

27) New EGR- system
For Euro 6 and Tier 4 applications it will be necessary to combine NOx- aftertreatment with cooled EGR. Basical decisions on the EGR- path and the necessary amount of EGR have to be made. Problems are condensation, engine weare and cooler fouling, transient engine response. Basically a high pressure loop (HPL) or a low pressure loop (LPL) can be applied. Both solutions are already present on the american market.

28) New SCR- catalyst
Because of the eventually needed active soot filter regeneration, a SCR catalyst with a very high resistance to repeated high exhaust temperatures is needed. The catalyst should provide optimal conversion efficiency over a broad temperature range, also in aged condition. Usually the space for aftertreatment devices is also restricted, so a compromise has to be made between efficiency, pressure drop and space requirement.

29) New Control Approach for integrated control system for engine and aftertreatment
The application of SCR and EGR requires an interaction of the control systems to achieve optimal compromise between regulated emissions and CO2- emission.

For achieving optimum results and guaranteeing the durability of the power train system, it has to be adequately controlled in the homologation cycle and in daily use. Cold operating phases and fast transients make this a challenging task.. A way for integrated control of EGR with a
variable Turbocharger, together with “thermal management” of engine and aftertreatment components has to be found, also with integration of a heat recuperation system.

An IMF-patent in this field is existing.

31) Simulation Model for Mechanical & Electrical Turbocompounding.

- A general simulation code for HD DI diesel engines including mechanical & electrical turbocompounding has been developed. It allows the selection of various turbocompounding layouts and has the ability to simulate any type of DI diesel engine.

- NTUA has already produced relevant documentation for its use. This is to be completed in the last year of the project so that it can be used for training. This material will be distributed to various sectors of possible application. The code has already been provided to AVL for testing and will be provided to DC for evaluation.

- The results may be exploited indirectly i.e. through licensing to potential users or even directly through a spin off.

- The simulation is currently being improved with T/C and engine manufacturers.

- The basic software has already provided in the past to Caterpillar USA and Robert Bosch SA in its executable form. The software already provided does not include turbocompounding capability. From Robert Bosch a positive feedback has been obtained after trial use of the simulation.

- The improved software has been, as mentioned, provided to AVL and DC for testing. From AVL a positive feedback is available and indicative results were presented at A3 subproject during the 24 month meeting.

32) Simulation Model for a Rankine Bottoming Cycle.

- A complete simulation code for Rankine Bottoming cycles using various working media is now available. Two versions have been developed, an analytical one and a second with graphic environment suitable for training. The development of the second will be completed by month 36.

- NTUA is already involved in its exploitation by producing relevant documentation for its use, user manual and distribution to the various sectors of possible application.

- The results may be exploited indirectly i.e. through licensing to potential users or even directly through a spin off.

- To improve the simulation it will be required cooperating with expander and heat exchanger manufacturers.

33) New Combustion system:
It might be necessary to adapt the combustion system to the new boundary- conditions of a high- charge- density- high- EGR- concept and new injection- system- characteristics. Also application of alternative combustion modes have to be considered. There are side- impacts on engine- oil- change- interval and sensitivity to production- tolerances.
34) Exhaust heat recuperation system:
This point has to be evaluated in the future. The work done in GREEN enables a continuation in this field.

A further markable reduction of fuel consumption is offered by heat recuperation. However this is accompanied by lower energy density of the propulsion system, high cost and complexity. Anyway this can be economically recovered in a short time period by the fuel savings, together with the CO2 reduction. Several approaches were already made in the past or are presented at the moment in USA, were the “50% thermal efficiency engine” is propagated.

Companies for the supply of single components or complete systems are contacted. Partners for a economical realisation of this concept are searched.

An obstacle is the additional required space in the vehicle, also the restrictions of size of a transport vehicle and in consequence of the tractor by transport laws.

35) For fulfilling future emission targets with lowest possible fuel consumption and, if possible, the todays power to weight ratio, higher Engine- Peak- Firing- Pressures have to be handled. This could require some changes in engine technology as the use of special casting material (as e.g. CGI) and steel pistons. The new casting material implies the application of new design rules and a change in parts machining. Because the casting process is also more difficult, all this leads to an increased cost. At the beginning of the project attempts were made to improve the structure with the conventional head material. This turned out as not feasible, also the attempt to include an exhaust- duct- isolation. An unexpected obstacle was the lack of suitable suppliers and the refusing of a supplier to support research work.

Modified parts as top- end- cooled- cylinder- liners, smaller valves to support the higher PFP, a new type of cylinderhead gasket are also necessary.

36) The cylinderhead design has to be adapted for the new material and its thermomechanical properties. Partners: AVL (Design), Winter (Supplier). Some competitors have already made that step. The limits with the existing material can be extended by optimised design and standard material improvements. The new material will require special attention in the casting process and will be more difficult to machine.

3.) improved engine structure

37) New cylinder liners have to applied. Features are top end liner cooling, material, hardening. Partners: AVL (Design), Mahle (Supplier), FM (Supplier). This technology is already adapted by US – truck industry in connection with the high EGR – concept to reduce liner wear.

38) The impact of a high PFP engine onto the auxiliary drive train has to be checked. Partners: (Iveco internal). The increased BMEP will cause higher cranktrain oscillations. This could damage the auxiliaries located on the engine (steering pump, alternator, air compressor, PTO, fan) or the following gear train. Free running devices for alternators or a 2-mass flywheel for gearbox protection are known countermeasures.

39) New cylinderhead gasket for elevated cylinder pressures. Partners: AVL (Design), Elring (Supplier). The concept is already adapted by two main truck manufacturers in Europe. The design is focussed partially to reduce load on the cylinderhead.

40) A change from aluminum- to steel- pistons might be required. Partners: FM (Design and supplier). This type of piston are already used in the US. This is from one side traditional for the
US – market, on the other hand this technology may be forced by the high cylinder pressure and thermal loading.

41) New injection system. Partners: BOSCH (Design and supplier) For fulfilling the future emission limits and low noise requirements, the change to a CR-system may be necessary. The engine is designed as a Unit Injector engine, therefore considerable design efforts have to be made. Related to the new syste will be a change of the Electronic Diesel Control Unit (ECU) with additional features for new emission limiting functions. This requires considerable effort in transition of existing and design of new software, which is not covered by GREEN.

The search for a suitable injection system is always actual. The next approach is to find a system, which will provide low enough soot levels for “passive soot filter operation”. This is difficult because of the necessary application of high EGR- amounts also at full load. The system should provide also in lower engine noise. Flexibility in the sense of enabling early and splitted injections for alternative combustion modes and late injections for active soot filter regeneration are maybe required. Also the exchangeability with less sophisticated parts for other applications (offroad, other markets) are an issue. For enabling the use of Common Rail Systems existing Unit-Injector-engines have to be modified in design.

The demand for alternative fuels is a critical item. Whereas GTL or GTL would cause no problem, neat biofuels or ethanol mix or diesel/water emulsions are not suitable for this highly sophisticated injection components (very high injection pressures, small gaps, high temperatures etc.). They would cause corrosion, cavitation and sticking due to residuals.

42) The aftertreatment components and their control have to be defined. Partners: Iveco internal, JM, BOSCH, others. A SCRT- aftertreatment system will be applied. Also proper controls and sensors have to be applied for reaching the GREEN target.

43) Compact two stage turbocharging is needed for real vehicle application. For the now needed pressure ratios, the wheel diameters can be reduced. The ducts and housings can be arranged as combined parts and optimised for vehicle application. The CTT- design shows the possibilities.

44) New turbocharging technology for higher boost pressures will be necessary. Partners: Holset (Design and Supplier, BEHR). The single stage arrangement is limited for several reasons (material related compressor outlet temperature, useful map width) for the achievable pressure ratio. A combined axial radial compressor wheel from Ti-material can overcome this limit up to a pressure ratio of ca. 5. Above that 2-stage Turbocharging has to be used. 2-stage TC has the advantages of possible intercooling, which increases the thermodynamic efficiency and keeps temperatures within standard material limits. A disadvantage is the more difficult packaging and arrangement. For the single stage compressor advanced charge air coolers have to be used to cope with the increased pressures and temperatures.

45) A variable compression ratio system (VCR) will be developed. Partners: FEV (design). The system will be an alternative to a high PCP engine structure. The targets could be reached with an optimised standard engine structure. The economy of the alternative has to be compared to the other solution. It would be worldwide the first VCR system for truck application. Its application could also be optimised for application of alternative combustion.

46) improved EGR- system. For the validator engines different EGR- systems were used (HPL, LPL). The special requirements for corrosion, wear and controls were investigated. For Euro 6 and Tier 4 applications it will be necessary to combine NOx- aftertreatment with cooled EGR. Basical decisions on the EGR- path and the necessary amount of EGR have to be
made. Problems are condensation, engine wear and cooler fouling, transient engine response. Basically a high pressure loop (HPL) or a low pressure loop (LPL) can be applied. Both solutions are already present on the american market.

47) The HBMEP engine presents a step into new technologies, required by higher cylinder pressures. The higher pressures are necessary to fulfill the future emission limits, improving at the same time power density and fuel consumption. Alternatively a variable compression ratio system (VCR) could be applied to avoid high peak pressures at full load. Thus the technology steps for the high cylinder pressure structure could be partially avoided, with impact on BSFC. Alternatively, the system could be used as an “enabler” for alternative combustion. An comparison of technical and economical aspects should provide the basis for selecting the proper concept.

48) The possibility of heat regeneration from exhaust gas should be investigated and compared for different systems. Partners: (NTUA). There are different technologies known to recuperate waste heat from exhaust and coolant. Application is more or less complex and the energy density of the whole package (engine and recuperation system) will more or less decrease. Mechanical and electrical turbocompounding are attractive from installation point of view. However the combined Rankine Cycle technologies have big potential for BSFC improvement. The potential for CO2 reduction (GWI) is related to BSFC and also very high. The field is already covered by a large amount of patents (e.g. Enginion, Webasto). IMF has procured a patent search and placed an european patent describing arrangements and interactions of a rankine cycle with aftertreatment.

49) Arrangement of a exhaust heat recuperation system in a truck is challenging. The space would have to be in addition to the space required from the aftertreatment systems. Combinations of heat exchangers and catalysts seem possible. An IMF patent is existing. The space and weight requirements will require a vehicle redesign, but the rising fuel costs will make it also from the economical point of view interesting.

50) Simulation Model for a Rankine Bottoming Cycle.
- The result will be a complete simulation code for Rankine Bottoming cycles using steam as base working media and provision for use of organic compounds.
- NTUA will be involved in its exploitation by producing relevant documentation for its use, user manual and distribution to the various sectors of possible application.
- The results may be exploited indirectly i.e. through licensing to potential users or even directly through a spin off.
- To improve the simulation it will be required cooperating with expander and heat exchanger manufacturers.

51) Simulation Model for Mechanical & Electrical Turbocompounding.
- The result is a general simulation code for HD DI diesel engines including mechanical & electrical turbocompounding. It allows the selection of various turbocompounding layouts and has the ability to simulate any DI diesel engine.
- NTUA will be involved in its exploitation by producing relevant documentation for its use, user manual and distribution to the various sectors of possible application.
- The results may be exploited indirectly i.e. through licensing to potential users or even directly through a spin off.
- The simulation will be improved by cooperating with T/C manufacturers in order to use realistic maps for T/C and Turbine equipment.
- The basic software has already provided in the past to Caterpillar USA and Robert Bosch SA in its executable form. The software already provided does not include turbocompounding
capability. From Robert Bosch a positive feedback has been obtained after trial use of the simulation.

52) Exhaust heat recuperation system:
This point has to be evaluated in the future. The work done in GREEN enables a continuation in this field. A further markable reduction of fuel consumption is offered by heat recuperation. However this is accompanied by lower energy density of the propulsion system, high cost and complexity. Anyway this can be economically recovered in a short time period by the fuel savings, together with the CO2- reduction. Several approaches were already made in the past or are presented at the moment in USA, were the “50% thermal efficiency engine” is propagated. Companies for the supply of single components or complete systems are contacted. Partners for a economical realisation of this concept are searched. An obstacle is the additional required space in the vehicle, also the restrictions of size of a transport vehicle and in consequence of the tractor by transport laws.

53) New Combustion system:
It might be necessary to adapt the combustion system to the new boundary- conditions of a high- charge- density- high- EGR- concept and new injection- system- characteristics. Also application of alternative combustion modes have to be considered. There are side- impacts on engine- oil- change- interval and sensitivity to production- tolerances. Further investigations will be done, including multiinjection, higher injection pressure and different combustion systems.

54) Fe-Zeolite SCR- catalyst technology: Because of the eventually needed active soot filter regeneration, a SCR catalyst with a very high resistance to repeated high exhaust temperatures is needed. The catalyst should provide optimal conversion efficiency over a broad temperature range, also in aged condition. Usually the space for aftertreatment devices is also restricted, so a compromise has to be made between efficiency, pressure drop and space requirement. The up to now used Vanadium catalysts will release the catalytic material at higher exhaust temperatures. Zeolites are more temperature resistant. The sensitivity to water content in the exhaust has been overcome, so that it will be a key technology already for Euro VI.

55) New Control Approach for integrated control system for engine and aftertreatment
The application of SCR and EGR requires an interaction of the control systems to achieve optimal compromise between regulated emissions and CO2- emission For achieving optimum results and guaranteeing the durability of the power train system, it has to be adequately controlled in the homologation cycle and in daily use. Cold operating phases and fast transients make this a challenging task. A way for integrated control of EGR with a variable Turbocharger, together with “thermal management” of engine and aftertreatment components has to be found, also with integration of a heat recuperation system. An IMF-patent in this field is existing.

56) A burner/vaporizer unit where fuel is vaporized. This passes then an oxidation catalyst where the fuel is oxidized and the temperature rises significantly. This high temperature is then used to regenerate a particulate trap.

### 3.4 Dissemination of knowledge

The activities listed in the table below are planned activities of dissemination of the generated knowledge from the IP GREEN.
<table>
<thead>
<tr>
<th>Planned/actual Dates</th>
<th>Type</th>
<th>Type of audience</th>
<th>Countries addressed</th>
<th>Size of audience</th>
<th>Partner responsible / involved</th>
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<td>2006</td>
<td>1. Journal Publication</td>
<td>Higher Education &amp; Research</td>
<td>EU &amp; USA</td>
<td></td>
<td>NTUA</td>
</tr>
<tr>
<td>2006</td>
<td>2. Conference</td>
<td>Higher Education &amp; Research</td>
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<tr>
<td>June 2007</td>
<td>5. Toptec Conference</td>
<td>Industry (Automotive heavy duty)</td>
<td>Italy</td>
<td>75</td>
<td>CTT(Holset)</td>
</tr>
<tr>
<td>Sept 2009</td>
<td>6. Graz Engine congress</td>
<td>Engine professionals</td>
<td>Austria</td>
<td>500</td>
<td>IMF</td>
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<tr>
<td>2006</td>
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<td>Industry (Automotive heavy duty)</td>
<td>Italy</td>
<td>75</td>
<td>CTT(Holset)</td>
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<td>Austria</td>
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<td>Sept 2009</td>
<td>7. Graz Engine congress</td>
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<td>Higher Education &amp; Research</td>
<td>EU &amp; USA</td>
<td></td>
<td>CTH</td>
</tr>
</tbody>
</table>
1. A publication has been prepared with the title “STUDY OF AVAILABLE EXHAUST GAS HEAT RECOVERY TECHNOLOGIES FOR HD DIESEL ENGINE APPLICATIONS” and submitted to an International Journal for Publication.

In the publication are presented results for three different exhaust heat recovery technologies i.e. mechanical turbocompounding, electrical turbocompounding & Rankine Bottoming Cycle. The advantages of each solution are analyzed and figures are provided for potential fuel economy.

This publication was originally submitted to the ASME 2006 ICE conference and was accepted for presentation. Due to late submission, it was not possible to include it in the proceedings and therefore it has been submitted to a Journal as mentioned above. It is estimated to have it published within 2006.

2. Another publication is currently being prepared for improved calculation for e-turbocompounding and Rankine bottoming cycle. In this version, results will be presented using maps for the T/C (pending) and detailed simulation of the Rankine cycle using a model for the heat exchanger. Results for the last are already available for both steam and organic working fluid and are currently being processed. The intention is to produce a paper for presentation in a conference within 2006.


5. SAE Toptec conference in Torino, June 2007, CTT is presenting a paper at this conference relating to variable geometry turbocharger applications for heavy duty engines. The axi-radial compressor performance is planned to be included amongst other topics in this paper

6. Graz Congress on Diesel Process 2009, a contribution of IMF is planned
The advantages of each solution are analyzed and figures are provided for potential fuel economy.

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5. SAE Toptec conference in Torino, June 2007, CTT is presenting a paper at this conference relating to variable geometry turbocharger applications for heavy duty engines. The axi-radial compressor performance is planned to be included amongst other topics in this paper

6. ÖVK presentation in Graz, January 16th 2008, Dr. W. Gstrein, Iveco Motorenforschung AG (Österreichischer Verein für Kraftfahrzeugtechnik, Austrian Society of Automotive Engineers) Title: Nutzung weiterer Potenziale zur Erhöhung des Wirkungsgrades von Dieselantrieben, „Exploitation of further potentials to increase the efficiency of Heavy Duty Diesel Powertrains”


10. Applied Catalysis B “Regenerable CeO2-based SOx-traps for sulfur removal in lean exhausts”, Lisa Kylhammar, Per-Anders Carlsson, Hanna Härelind Ingelsten, Henrik Grönbeck, and Magnus Skoglundh, Competence Centre for Catalysis, Chalmers University of Technology, SE-412 96 Göteborg, Sweden


**Planned Presentations:**

Contribution of Iveco Motorenforschung AG at the 2-years event of the technical University in Graz: “Der Arbeitsprozess des Verbrennungsmotors“, September 2009.

Proposed Title: Possibilities to “Improve Bottoming Cycle Performance and Overall Heat Rejection for HD Diesel Applications by Utilization of EGR & CAC Heat”. Scheduled to be Presented at the SAE 2009 World Congress, Detroit Michigan, 2009. (Abstract to be submitted to GREEN Core Group for Approval before preparing draft paper having received from SAE initial approval of proposed subject).


ETH, Zürich, Proposed Title “An Extended Quasi-Stationary Emission Model for a DI Diesel Engine”

Abstract: This paper describes the development of a control-oriented model for the prediction of the raw emissions (NOx, PM, CO) of a DI Diesel engine.

The extended quasi-stationary modeling approach is based on relevant combustion process variables as e.g. combustion center or cylinder charge states which are chosen by a novel input selection algorithm using genetic programming techniques. The regression value of the selection is tested by a model assumption based on neural networks. The nonlinear structure of the model is built up by a hybrid symbolic regression algorithm to reduce the calibration effort.

The symbolic regression model with 6-8 parameters is comparable with the feedforward neural network results.

The control-oriented emission model is combined with a state-of-the-art mean-value model to simulate the whole engine system. Possible applications of the combined model are engine system operating strategies optimization, model-based control system design, and the virtual sensor derivation. Results from experiments under stationary and transient operating conditions are presented, which demonstrate the prediction capabilities of the proposed methodology.

**3.5 Publishable Results**

1. Simulation Model for Mechanical and Electrical Turbocompounding:
Simulation code using FORTRAN-90 for HD-DI diesel engines including mechanical & electrical turbocompounding. Simulation offers ability to simulate any type of HD DI diesel engine, consider various turbocompounding arrangements and auto calibration using experimental data at one operating point.

At the present stage, the simulation can use either given efficiencies for T/C equipment or maps if available. Contact will be made with HOLSET to obtain actual maps for T/C equipment and methodology will be developed to introduce them in digital form in the code.

The software in its executable can be offered to engine manufacturers for development work, to T/C manufacturers for T/C equipment matching and to universities for training.

2. Simulation of Rankine Bottoming Cycle:

Simulation code using FORTRAN-90 and Visual Basic for Rankine Bottoming cycles. Simulation offers ability to simulate a bottoming cycle for a HD DI diesel engine application using various working media.

At its present form, the simulation can be used to make estimates for exhaust heat recovery potential. The simulation will be improved by contacting manufacturers of expanders and heat exchangers.

The software in its executable can be provided to expander manufacturers to derive the characteristics for the expander and the heat exchanger.

3. “STUDY OF AVAILABLE EXHAUST GAS HEAT RECOVERY TECHNOLOGIES FOR HD DIESEL ENGINE APPLICATIONS”

Summary:

The present work makes an effort to evaluate the potential bsfc improvement of HD diesel engines using mechanical turbocompounding, electrical turbocompounding and Rankine bottoming cycle. The analysis is performed on a heavy-duty truck diesel engine at various speeds and loads. For the study, an engine simulation model is used to predict engine performance and obtain the exhaust gas characteristics for the basic engine configuration. The parameters investigated for turbocompounding are power turbine pressure ratio to estimate an optimum value and power turbine efficiency. A similar investigation is conducted considering for the effect of turbocharger efficiency and pressure increase before the turbine. From the analysis it is revealed that bsfc of diesel engines can be significantly improved the benefit depending mainly on the technology. For mechanical turbocompounding, the optimum expansion ratio of the power turbine is in the range of 1.7-1.8. This value increases slightly with engine load and power turbine efficiency. The overall bsfc benefit increases with the increase of engine load. As observed mechanical turbocompounding can offer a maximum bsfc reduction of 4.7%, the value depending strongly on the efficiency of the power turbine. Electrical turbocompounding can result to a bsfc reduction of 8-9% for relatively high T/C efficiencies and to 3-6% for existing technology T/C. As revealed from the parametric investigation conducted it is feasible to achieve a bsfc reduction using a Rankine cycle with steam in the range of 8-9%. However, in the case of the Rankine Cycle, we have to be careful and consider the complexity, volume and weight constraints especially due to the large heat exchanging surfaces required.
4. Investigation of Fuel Injection strategies on low emission heavy duty Diesel engine with high EGR rates

Abstract: "A test programme has been carried out to investigate fuel injection strategies on a single cylinder heavy-duty Diesel engine. The programme was designed to use high rates of cooled exhaust gas recirculation (EGR) to control NOx to below 1.5 g/kWh. A novel, flexible fuel injection system capable of up to 2500 bar maximum injection pressure was employed to explore the optimum trade-offs between NOx, soot emissions and fuel consumption. This paper addresses the potential of the system to control emissions using pilot and post injection. Post injections were found to reduce soot emissions at half load by a factor two or more. With early pilot injection the soot-NOx trade-off was significantly improved at 25% load but with the drawbacks of high emissions of CO and fuel dilution of oil"

This article will be published at the conference "Internal Combustion Engines: Performance, Fuel Economy and Emissions at the Institution of Mechanical Engineers, London on December 11-12, 2007

5. Potential of Atkinson cycle combined with EGR for pollutant control in a HD Diesel engine

Abstract:

An experimental investigation has been performed on the potential of the Atkinson cycle and reducing intake oxygen concentration for pollutant control in a heavy-duty Diesel engine. In this study the Atkinson cycle has been reproduced advancing the intake valve closing angle towards the intake stroke. In addition, the intake oxygen concentration has been reduced introducing exhaust gas recirculation. This research has been carried out at low engine load (25%), where Atkinson cycle is known to improve the efficiency of the spark ignition engines. The main interest of this investigation has been the comparison between the Atkinson cycle and the conventional Diesel cycle at the same oxygen concentration in the intake gas. This analysis has been focused on incylinder gas thermodynamic conditions, combustion process, exhaust emissions and engine efficiency. In compression ignition engines, Atkinson cycle basically promotes the premixed combustion, but in the range of the tests, a complete premixed combustion cannot be attained. Regarding exhaust emissions, Atkinson cycle reduces notably the nitrous oxides but increases soot emissions. However, better global results have been found reducing intake oxygen concentration by the recirculation of exhaust gas than by the operation of an Atkinson cycle.

Key words:

Diesel combustion, Atkinson cycle, Diesel engine, Exhaust Gas Recirculation, Premixed combustion.

This article will be published in the journal "Energy conversion and management". It is planned to be published some time later 2007.

6. Simulation Model for Mechanical and Electrical Turbocompounding
Simulation code using FORTRAN-90 for HD-DI diesel engines including mechanical & electrical turbocompounding. Simulation offers ability to simulate any type of HD DI diesel engine, consider various turbocompounding arrangements and auto calibration using experimental data at one operating point.

The simulation can use either given efficiencies for T/C equipment or maps if available. The software in its executable can be offered to engine manufacturers for development work, to T/C manufacturers for T/C equipment matching and to universities for training. The last is now possible due to development of user friendly environment and user manual. This work will be completed by month 36.

7. Simulation of Rankine Bottoming Cycle:

Simulation code using FORTRAN-90 and Visual Basic for Rankine Bottoming cycles. Simulation offers ability to simulate a bottoming cycle for a HD DI diesel engine application using various working media.

In its present form, the simulation can be used to make estimates for exhaust heat recovery potential. The simulation has been improved by including detailed model of the heat exchanger.

The software in its executable can be provided to expander manufacturers to derive the characteristics for the expander and the heat exchanger.

A second version of the Rankine Cycle software has been developed with graphical environment. The code is suitable for both RTD work and training. This will be completed by month 36.

8. “Study of available exhaust gas heat recovery technologies for HD diesel engine applications


Abstract:

Diesel engines reject a considerable amount of energy to the ambience through the exhaust gas. Significant reduction of engine brake specific fuel consumption (bsfc) could be attained by recovering a significant part of exhaust gas heat. Various techniques have been proposed in the past to recover exhaust energy: mechanical, electrical turbocompounding and Rankine Bottoming Cycles. In the present it is examined the potential bsfc improvement of heavy-duty (HD) diesel engines using the aforementioned technologies. The analysis is performed on a HD Diesel engine. An engine simulation model is used to estimate exhaust gas characteristics and examine mechanical and electrical turbocompounding. For mechanical turbocompounding it is investigated the effect of power turbine pressure ratio and efficiency while for electric the effect of T/C efficiency and exhaust pressure increase. Finally, a parametric study has been conducted using a ‘Rankine bottoming cycle’. The analysis includes the effect of evaporator pressure and expander efficiency.

Abstract:
Considering future emission legislation and the global thermal problem, two are the main issues that are of specific concern for the future of the diesel engine, specific gaseous pollutants and CO2 emissions. Both parameters are related to engine bsfc consumption directly or indirectly. The last is becoming even more important considering current fuel prices and the projection for the future indicating a trend for increasing fuel prices. The last decade significant improvement has been accomplished in the field of diesel engine efficiency that has resulted to considerable reduction of engine bsfc. It is obvious that despite improvements in diesel engine efficiency still a considerable amount of energy is rejected to the environment through the exhaust gas. Approximately 30-40% of the energy supplied by the fuel is rejected to the ambience. Therefore, it appears a possibility for further considerable increase of diesel engine efficiency with the utilization of exhaust gas energy and its conversion to mechanical energy. In this case, the following technological solutions exist: turbocompounding, bottoming cycles (i.e. Rankine with various working media) and use of thermoelectric generators. An attractive technological solution concerning applicability appears to be turbocompounding. In the present work, a thorough investigation is conducted using modelling to estimate the potential of energy recovery from the exhaust of a heavy-duty diesel engine using turbocompounding and its variation with engine operating conditions and exhaust manifold pressure. Two turbocompounding techniques are examined theoretically, mechanical and electrical turbocompounding. The produced results are evaluated comparing engine performance and especially bsfc with the one corresponding to normal diesel operation on the entire engine operating range i.e. speed and load. Results are derived concerning the effect of both technologies on exhaust manifold pressure and temperature that can be a problem especially for future downsized engines. Using the produced data, the two technological solutions are comparatively evaluated. Finally, indicative results are derived concerning the effect of each technology on specific engine out emissions.

9. Simulation Model for Mechanical and Electrical Turbocompounding:
Simulation code using FORTRAN-90 for HD-DI diesel engines including mechanical & electrical turbocompounding. Simulation offers ability to simulate any type of HD DI diesel engine, consider various turbocompounding arrangements and auto calibration using experimental data at one operating point.

At the present stage, the simulation can use either given efficiencies for T/C equipment or maps if available. Contact will be made with HOLSET to obtain actual maps for T/C equipment and methodology will be developed to introduce them in digital form in the code.

The software in its executable can be offered to engine manufacturers for development work, to T/C manufacturers for T/C equipment matching and to universities for training.

10. Simulation of Rankine Bottoming Cycle:
Simulation code using FORTRAN-90 and Visual Basic for Rankine Bottoming cycles. Simulation offers ability to simulate a bottoming cycle for a HD DI diesel engine application using various working media.

At its present form, the simulation can be used to make estimates for exhaust heat recovery potential. The simulation will be improved by contacting manufacturers of expanders and heat exchangers.

The software in its executable can be provided to expander manufacturers to derive the characteristics for the expander and the heat exchanger.
11. "STUDY OF AVAILABLE EXHAUST GAS HEAT RECOVERY TECHNOLOGIES FOR HD DIESEL ENGINE APPLICATIONS"

Summary:
The present work makes an effort to evaluate the potential bsfc improvement of HD diesel engines using mechanical turbocompounding, electrical turbocompounding and Rankine bottoming cycle. The analysis is performed on a heavy-duty truck diesel engine at various speeds and loads. For the study, an engine simulation model is used to predict engine performance and obtain the exhaust gas characteristics for the basic engine configuration. The parameters investigated for turbocompounding are power turbine pressure ratio to estimate an optimum value and power turbine efficiency. A similar investigation is conducted considering for the effect of turbocharger efficiency and pressure increase before the turbine. From the analysis it is revealed that bsfc of diesel engines can be significantly improved the benefit depending mainly on the technology. For mechanical turbocompounding, the optimum expansion ratio of the power turbine is in the range of 1.7-1.8. This value increases slightly with engine load and power turbine efficiency. The overall bsfc benefit increases with the increase of engine load. As observed mechanical turbocompounding can offer a maximum bsfc reduction of 4.7%, the value depending strongly on the efficiency of the power turbine. Electrical turbocompounding can result to a bsfc reduction of 8-9% for relatively high T/C efficiencies and to 3-6% for existing technology T/C. As revealed from the parametric investigation conducted it is feasible to achieve a bsfc reduction using a Rankine cycle with steam in the range of 8-9%. However, in the case of the Rankine Cycle, we have to be careful and consider the complexity, volume and weight constraints especially due to the large heat exchanging surfaces required.

12. Investigation of Fuel Injection strategies on low emission heavy duty Diesel engine with high EGR rates

Abstract: "A test programme has been carried out to investigate fuel injection strategies on a single cylinder heavy-duty Diesel engine. The programme was designed to use high rates of cooled exhaust gas recirculation (EGR) to control NOx to below 1.5 g/kWh. A novel, flexible fuel injection system capable of up to 2500 bar maximum injection pressure was employed to explore the optimum trade-offs between NOx, soot emissions and fuel consumption. This paper addresses the potential of the system to control emissions using pilot and post injection. Post injections were found to reduce soot emissions at half load by a factor two or more. With early pilot injection the soot-NOx trade-off was significantly improved at 25% load but with the drawbacks of high emissions of CO and fuel dilution of oil"

This article will be published at the conference "Internal Combustion Engines: Performance, Fuel Economy and Emissions at the Institution of Mechanical Engineers, London on December 11-12, 2007

13. Potential of Atkinson cycle combined with EGR for pollutant control in a HD Diesel engine

Abstract:
An experimental investigation has been performed on the potential of the Atkinson cycle and reducing intake oxygen concentration for pollutant control in a heavy-duty Diesel engine. In this study the Atkinson cycle has been reproduced advancing the intake valve closing angle towards the intake stroke. In addition, the intake oxygen concentration has been reduced introducing exhaust gas recirculation. This research has been carried out at low engine load (25%), where Atkinson cycle is known to improve the efficiency of the spark ignition engines. The main interest of this investigation has been the comparison between the Atkinson cycle and the
conventional Diesel cycle at the same oxygen concentration in the intake gas. This analysis has been focused on incylinder gas thermodynamic conditions, combustion process, exhaust emissions and engine efficiency. In compression ignition engines, Atkinson cycle basically promotes the premixed combustion, but in the range of the tests, a complete premixed combustion cannot be attained. Regarding exhaust emissions, Atkinson cycle reduces notably the nitrous oxides but increases soot emissions. However, better global results have been found reducing intake oxygen concentration by the recirculation of exhaust gas than by the operation of an Atkinson cycle.

Key words:
Diesel combustion, Atkinson cycle, Diesel engine, Exhaust Gas Recirculation, Premixed combustion.

This article will be published in the journal "Energy conversion and management". It is planned to be published some time later 2007.

14. Simulation Model for Mechanical and Electrical Turbocompounding
Simulation code using FORTRAN-90 for HD-DI diesel engines including mechanical & electrical turbocompounding. Simulation offers ability to simulate any type of HD DI diesel engine, consider various turbocompounding arrangements and auto calibration using experimental data at one operating point.

The simulation can use either given efficiencies for T/C equipment or maps if available. The software in its executable can be offered to engine manufacturers for development work, to T/C manufacturers for T/C equipment matching and to universities for training. The last is now possible due to development of user friendly environment and user manual. This work will be completed by month 36.

15. Simulation of Rankine Bottoming Cycle:
Simulation code using FORTRAN-90 and Visual Basic for Rankine Bottoming cycles. Simulation offers ability to simulate a bottoming cycle for a HD DI diesel engine application using various working media.

In its present form, the simulation can be used to make estimates for exhaust heat recovery potential. The simulation has been improved by including detailed model of the heat exchanger.

The software in its executable can be provided to expander manufacturers to derive the characteristics for the expander and the heat exchanger.

A second version of the Rankine Cycle software has been developed with graphical environment. The code is suitable for both RTD work and training. This will be completed by month 36.

16. “Study of available exhaust gas heat recovery technologies for HD diesel engine applications

Abstract:
Diesel engines reject a considerable amount of energy to the ambience through the exhaust gas. Significant reduction of engine brake specific fuel consumption (bsfc) could be attained by recovering a significant part of exhaust gas heat. Various techniques have been proposed in the past to recover exhaust energy: mechanical, electrical turbocompounding and Rankine Bottoming Cycles. In the present it is examined the potential bsfc improvement of heavy-duty
(HD) diesel engines using the aforementioned technologies. The analysis is performed on a HD Diesel engine. An engine simulation model is used to estimate exhaust gas characteristics and examine mechanical and electrical turbocompounding. For mechanical turbocompounding it is investigated the effect of power turbine pressure ratio and efficiency while for electric the effect of T/C efficiency and exhaust pressure increase. Finally, a parametric study has been conducted using a ‘Rankine bottoming cycle’. The analysis includes the effect of evaporator pressure and expander efficiency.


Abstract:
Considering future emission legislation and the global thermal problem, two are the main issues that are of specific concern for the future of the diesel engine, specific gaseous pollutants and CO2 emissions. Both parameters are related to engine bsfc consumption directly or indirectly. The last is becoming even more important considering current fuel prices and the projection for the future indicating a trend for increasing fuel prices. The last decade significant improvement has been accomplished in the field of diesel engine efficiency that has resulted to considerable reduction of engine bsfc. It is obvious that despite improvements in diesel engine efficiency still a considerable amount of energy is rejected to the environment through the exhaust gas. Approximately 30-40% of the energy supplied by the fuel is rejected to the ambience. Therefore, it appears a possibility for further considerable increase of diesel engine efficiency with the utilization of exhaust gas energy and its conversion to mechanical energy. In this case, the following technological solutions exist: turbocompounding, bottoming cycles (i.e. Rankine with various working media) and use of thermoelectric generators. An attractive technological solution concerning applicability appears to be turbocompounding. In the present work, a thorough investigation is conducted using modelling to estimate the potential of energy recovery from the exhaust of a heavy-duty diesel engine using turbocompounding and its variation with engine operating conditions and exhaust manifold pressure. Two turbocompounding techniques are examined theoretically, mechanical and electrical turbocompounding. The produced results are evaluated comparing engine performance and especially bsfc with the one corresponding to normal diesel operation on the entire engine operating range i.e. speed and load. Results are derived concerning the effect of both technologies on exhaust manifold pressure and temperature that can be a problem especially for future downsized engines. Using the produced data, the two technological solutions are comparatively evaluated. Finally, indicative results are derived concerning the effect of each technology on specific engine out emissions.

17. Regenerable CeO$_2$-based SO$_x$-traps for sulfur removal in lean exhausts, Lisa Kylhammar, Per-Anders Carlsson, Hanna Härelind Ingelsten, Henrik Grönbeck, and Magnus Skoglundh, Competence Centre for Catalysis, Chalmers University of Technology, SE-412 96 Göteborg, Sweden

Abstract
A possible solution for preventing NOx storage catalysts from being poisoned by sulfur is to place a SOx trap upstream of the catalyst in the exhaust aftertreatment system. In this study CeO$_2$, Al2O3 and Al2O3:MgO with and without Pt have been investigated for regenerable SOx traps, i.e., materials that under lean conditions can store SOx in the temperature interval 200-500 °C and release SOx above 500 °C. For this purpose flow-reactor measurements and in-situ DRIFT spectroscopy have been employed. The results from flow-reactor experiments performed with synthetic gas mixtures (100 ppm SO2 and 7% O2 in Ar) show that Pt/CeO2 is a promising SOx trap material since it has the highest SOx storing ability of the investigated materials at 250 °C and releases the highest amount of stored SOx around 600 °C under lean conditions.
Furthermore, studies of the influence of Pt on the storage and release of SOx from CeO2-based samples showed that the SOx storage capacity under lean conditions at 250 °C increases with increased Pt-loading (0, 1 or 5 wt% Pt). At 400 °C the SOx storage capacity is even higher for a 1 wt% Pt/CeO2 sample than at 250 °C. From the DRIFTS experiments it could be seen that SO2 adsorption on CeO2 samples under lean conditions results in formation of both surface and bulk sulfates. The rate of bulk sulfate formation is higher for the Pt/CeO2 sample than for the CeO2 sample at 250 °C. During adsorption at 400 °C the rate of bulk sulfate formation is even higher for the Pt/CeO2 sample compared to when adsorption is performed at 250 °C. When comparing fresh CeO2 samples with samples that have been exposed to high amounts of SO2 at 250 and 400 °C both a lower SOx storage capacity as well a higher release of SOx can be seen from the exposed samples. This indicates that some of the storage sites on CeO2 samples are non-regenerable at 700 °C or below under lean conditions.


Abstract
A test programme has been carried out to investigate fuel injection strategies on a single cylinder heavy-duty diesel engine. The programme was designed to use high rates of cooled Exhaust Gas Recirculation (EGR) to control NOx to below 1.0 g/kWh. A novel, flexible fuel injection system capable of up to 250 MPa maximum injection pressure was employed to explore the optimum trade-offs between NOx, soot emissions and fuel consumption. This paper addresses the potential of the system to control emissions using pilot and post injection. Post injections were found to reduce soot emissions at half load by a factor of two or more. With early pilot injection the soot-NOx trade-off was improved at 25% load but with the drawbacks of high emissions of CO and fuel dilution of oil.
Potential of Atkinson cycle combined with EGR for pollutant control in a HD Diesel engine

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Abstract
An experimental investigation has been performed on the potential of the Atkinson cycle and reducing intake oxygen concentration for pollutant control in a heavy-duty Diesel engine. In this study the Atkinson cycle has been reproduced advancing the intake valve closing angle towards the intake stroke. In addition, the intake oxygen concentration has been reduced introducing exhaust gas recirculation. This research has been carried out at low engine load (25%), where Atkinson cycle is known to improve the efficiency of the spark ignition engines. The main interest of this investigation has been the comparison between the Atkinson cycle and the conventional Diesel cycle at the same oxygen concentration in the intake gas. This analysis has been focused on in-cylinder gas thermodynamic conditions, combustion process, exhaust emissions and engine efficiency. In compression ignition engines, Atkinson cycle basically promotes the premixed combustion, but in the range of the tests, a complete premixed combustion cannot be attained. Regarding exhaust emissions, Atkinson cycle reduces notably the nitrous oxides but increases soot emissions. However, better global results have been found reducing intake oxygen concentration by the recirculation of exhaust gas than by the operation of an Atkinson cycle.


Abstract
An experimental investigation has been performed on the modification of in-cylinder gas thermodynamic conditions by advancing the intake valve closing angle in a HD Diesel engine. The consequences on the diffusion-controlled combustion process have been analysed in detail, including the evolution of exhaust emissions and engine efficiency. This research has been carried out at full load (100%) and low engine speed (1200 rpm) with the aim of generating a long and stable diffusion-controlled combustion process. The intake oxygen mass concentration was kept at 17.4% to obtain low NOx levels in all cases. The required flexibility on intake valve motion has been attained by means of an electro-hydraulic variable valve actuation system. The results obtained from advancing the intake valve closing angle (IVC) have shown an important reduction on in-cylinder gas pressure and density, whereas the gas temperature showed less sensitivity. Consequently, the diffusion-controlled combustion process is slowed
down mainly due to the lower in-cylinder gas density and oxygen availability. Important effects of advancing IVC have also been observed on pollutant emissions and engine efficiency. Where NOx production decreases, soot emissions increase. Finally, the results of pollutant emissions and engine efficiency have been compared with those obtained retarding the start of injection.

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Abstract
For further reduction of the NOx-rain emission levels of truck- and industrial engines the combustion development at FEV concentrates on achieving higher EGR-rates also by reduction of the air fuel ratio. Additional targets are to achieve this NOx-reduction without particulate emission and BSFC disadvantages and additional with advantages in NVH while remaining a high power output of the engine. To achieve this one major key is to significantly improve the air utilization of the combustion process, which can be achieved by increase of injection pressure. With the FEV-AHDCS combustion system the increase of injection pressure can be used even more effective and allows A/F-ratio’s significantly below 1.4 at injection pressures above 2500 bar. By additionally using the increased flexibility of modern injection systems for optimization of pilot and post injection further improvement of particulate and NOx emission, BSFC and NVH is possible. For the calibration, due to the increased number of parameters, DOE methods need to be applied. Additionally investigations with the FEV-First injection system show further potentials by variable control of the injection rate shape with regard to NVH, emissions and BSFC.

Tagung "DER ARBEITSPROZESS DES VERBRENNUNGSMOTORS" Graz 20./21. September 2007