CO2RE

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# PROJECT FINAL REPORT

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**Project acronym: CORE**

**Project title: CO2 Reduction for long distance transport**

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## 4.1 Final publishable summary report

### *Executive summary*

The CORE project involves 16 partners from truck manufacturers, automotive industries and universities. The main objective for CORE is to demonstrate a substantial reduction of $CO_2$ emissions through improved powertrain efficiency for long haul applications, with technologies having the potential to be implemented in production around 2020. The main focus areas are improved engine concepts featuring:

- turbocharger systems
- variable valve actuation
- reduced friction
- aftertreatment, low temperature range

In addition, hybridisation and natural gas will be utilised. The goal is at the end of the project demonstrate different powertrains that fulfil the targets of the project. All results will be evaluated over legislation test cycles EURO VI and in real life driving cycles.

Developments have been done on all levels reaching from new design and improved performance of components, improving control strategies and implementation of components to complete engine system tests. Results show that improved fuel efficiency has been obtained in all areas of investigation.

The best experimentally achieved result was 13% reduced $CO_2$, demonstrated on an CORE engine at EURO VI compared to an engine at EURO V legislation levels.

Taking into account the recalibration of a EURO V engine to EURO VI emission legislation and combined CORE technologies, vehicle simulations show four different powertrain concepts with $CO_2$ reductions in the target zone of 11-18% compared to current EUROVI engined vehicles. These results show that the CORE project reached its targets and has highlighted achievable path ways for $CO_2$ reduction for long haul commercial vehicle applications.

### *A summary description of project context and objectives*

European wealth, now and in the future, depends on a strong and competitive transport sector. At the same time the transport system of Europe faces significant challenges in order to become sustainable in the long term, and reduce its impact on the environment. With the aim to address these challenges the Collaborative project CORE (CO2 REduction for long distance transport) was started. The consortium consists of 16 partners from truck manufacturers, automotive industries and universities; Volvo, CRF, Chalmers, Daimler, Federal-Mogul, LUH, Honeywell, IAV, Johnson Matthey, JRC, Metatron, POLIMI, POLITO, Rhodia, Ricardo and Umicore.

**<u>Objectives</u>**

The objective is to demonstrate a substantial reduction of $CO_2$ emissions, 15% improved fuel efficiency compared to a EURO V engine and at the same time fulfilling EURO VI emission legislation. By using novel technology combined in flexible engines with a high level of precise control, performance advantages will be achieved with improvements in emissions and fuel consumption. The legislative emission test cycles ETC and the WHTC will serve as the baseline test cycles but, in order to show the improved fuel efficiency and consider the hybrid electric powertrain, specific duty cycles will be used for each application.
The target fuel economy improvement of 15% is based on a EURO V state-of-the-art technology operating at the EURO VI emission standard. It is envisioned to achieve 6 to 9% in the sub-projects (see Figure 1) with different engines, powertrains and fuel approaches. The hybridization of the powertrain will contribute with an estimated 3 to 5% fuel economy improvement dependent on the vehicle test cycle through usage of energy recuperation during deceleration events. An additional 2 to 4% of fuel economy improvement is attributed to friction reduction of the combustion engine and energy efficient exhaust gas aftertreatment systems and operation.

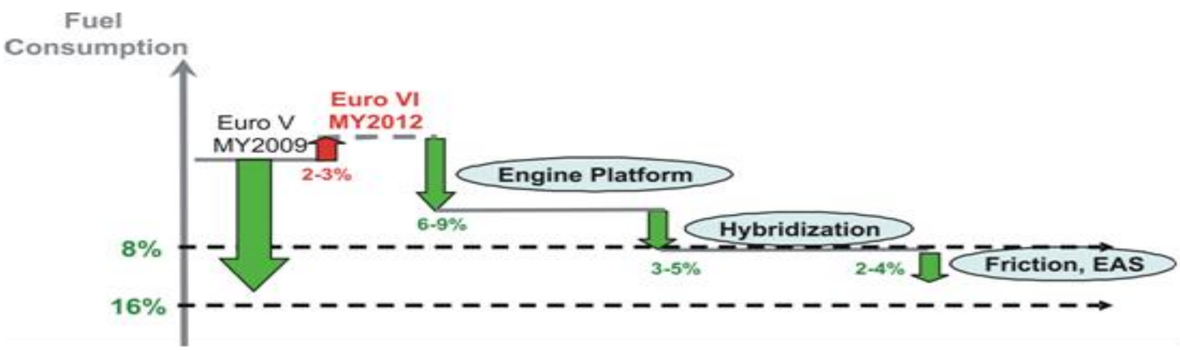



*Figure 1: Roadmap towards fuel consumption reduction.*

## Description of Work

CORE is divided into six sub-projects (see Figure 2), three of which focus on different engine and powertrain technologies. Major areas for these are: optimizing the existing Diesel engine: combustion, air management, aftertreatment and controls, decreasing rated engine speed ( “down-speeding”), optimizing the powertrain layout (hybrid electric components) and using alternative fuels as natural combined with variable valve actuation.
These three sub-projects are supported by two projects (shown horizontally in Figure 2) where friction reduction and improvement of low temperature performance of NOx aftertreatment technologies are studied. Accomplished results are adapted on the three engine and powertrain arrangement. Finally in the last sub-project, to ensure knowledge and technology transfer, all results will be assessed by vehicle simulations for final achievement of the fuel economy target.

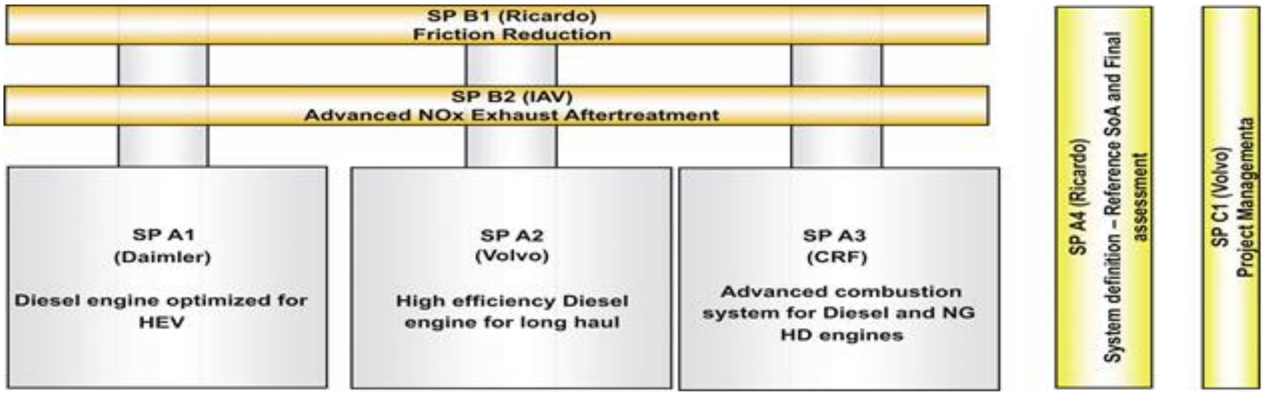



*Figure 2: CORE project organisation.*

## Results

Results show that improved fuel efficiency has been obtained in all sub-projects. The main results are:

- The best measured result was 13% lower fuel consumption on the Daimler CORE engine fulfilling EURO VI emissions legislation compared to a Daimler engine at EURO V emissions.
- In the assessment of CORE technologies the best combination of technologies was simulated to give 18% reduced fuel consumption when compared to the EURO VI vehicle as reference.

An overview and a summary of the results achieved is given here with respect to Figure 1 and results are presented in Figure 3:

*Engine platform (SPA1, SPA2 and SPA3):* Engine application work has been completed. Four different engine systems have been calibrated for transient operation. Thereafter optimisation of the engine and integration of the exhaust aftertreatments system were completed. In order to reach the target all engines have been demonstrated at EURO VI emission regulation, over the transient cycles ETC and WHTC and real life cycles. The achieved results show 2-5 % improved fuel consumption for the Diesel engines compared to the EURO V engines, and 4-7 % improved fuel consumption compared to the EURO VI references.

The natural gas engine was demonstrated on a prototype vehicle (rolling test bench and on-road) with PEMS instrumentation on-board. The CORE CNG engine showed a reduction of 6.5% compared to the EURO VI engine. In second loop of demonstrator testing an LNG tank circuit was installed on the prototype vehicle together with integration of an electronic pressure regulator for the LNG and NG. Additional safety considerations for the LNG operating mode were also implemented. The final results showed improvement of in the range of the vehicle in line with calculation predictions and no impact on the VVA engine behaviour.

*Hybridisation (SP A1):* This work was performed in SPA1. The first task was to development an engine-in-the-loop system (EiL) system including a combined shifting and hybrid operation strategy. This work was completed and EiL has successfully been applied in the test cell together with the engine developed in SPA1. The achieved result from the test cell shows fuel efficiency improvements of 12.9% over a real life operating cycle.

*Friction (SPB1):* Improved design, low friction piston rings and pistons were tested together with modified bearings. Three different oil types were also tested: the production oil, a special blended oil with same viscosity as the production one but with friction modifier additives, and a lower viscosity oil. With the new engine parts and the low viscosity oil, motored friction (FMEP) reductions of up to 9% were measured to a high level of accuracy. Overall, a fuel consumption (BSFC) reduction of about 1% was achieved in some operating points, especially at low loads, with the new engine parts.

*EATS (SPB2):* Integration of EATS to the complete engine system has been completed. This work was supported by a new developed kinetic model of SPAB2 of the SCR catalyst, integrated into the EAT system software, enabling model-based EAT system development. The model was used by SPA1 and SPA3 in their work with integration and optimisation of the SCR system to the respective engine. Injection of ammonium nitrate (AdBlue Additive) has been investigated in detail, and the mechanism of the additive reactions on the Fe-SCR catalyst has been identified.

*Final Assessment (SPA4):* The aim of SPA4, to use a vehicle simulation tool to estimate the CORE technology benefits on vehicle efficiency, has been achieved. The most promising technologies from SP A1, A2, A3, B1 and B2 were grouped together in compatible vehicle packages. Simulation models of the base vehicles were validated through comparison with real vehicle measurements over representative cycles. These models were then extended to include the most promising technologies vehicle packages and further simulations undertaken. The results from these simulations showed that each of these vehicle packages were predicted to achieve the proposed targets of an 11% to 18% fuel consumption reduction from the Euro VI vehicle configuration.

The individual vehicle simulation results show that the relative benefits of each of the CORE technology depends upon the vehicle application and its duty cycle.

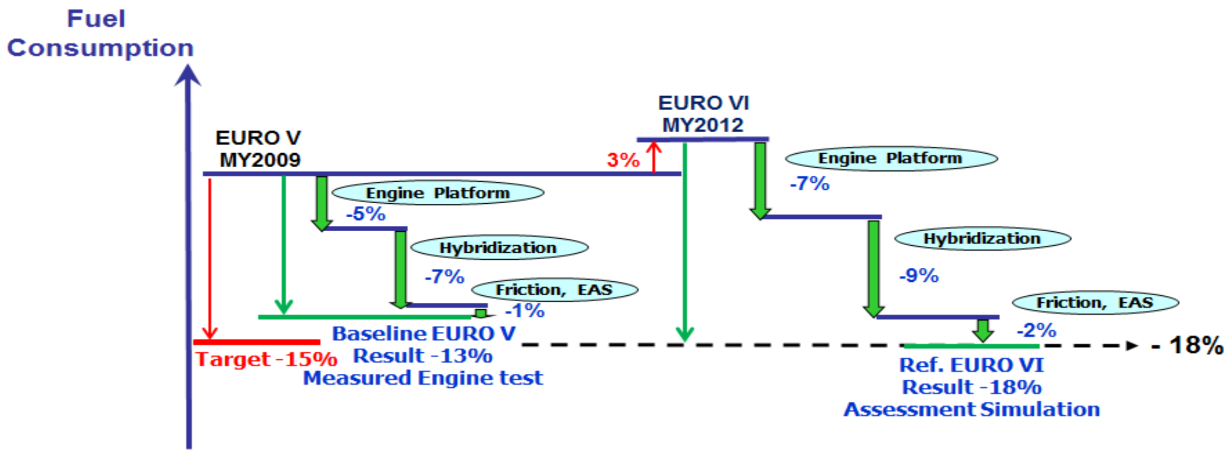



*Figure 3: The diagram shows the achieved CORE results of reduced CO2 by improved powertrain efficiency.*

## Conclusions

- The best experimentally achieved result was 13% reduced $CO_2$, demonstrated on an CORE engine at EURO VI compared to an engine at EURO V legislation levels.
- Taking into account the recalibration of a EURO V engine to EURO VI emission legislation and combined CORE technologies, vehicle simulations show four different powertrain concepts with $CO_2$ reductions in the target zone of 11-18% compared to current EUROVI engined vehicles.
- The results show that the CORE project reached its targets and has highlighted achievable path ways for $CO_2$ reduction for long haul commercial vehicle applications.

## *Description of the main scientific and technological results*

The main results are described per sub-project below.

## *SPA1 Diesel engine optimized for HEV*

The target application of SP A1 was a domestic long distance vehicle in a 4x2 tractor plus trailer configuration. Such vehicles are often equipped with a medium duty engine: in case of EUROV this was an OM926 with 240kW, in case of EUROVI it is an OM936 with 260kW. A typical vehicle weight of 30to including freight was assumed for the subproject. Such a vehicle is shown in Figure 4.


*Figure 4: Domestic long distance vehicle in SP A1*

The following technical approaches and innovations were realized in SP A1:

- Transition from the non-EGR EUROV production engine OM926 to the EGR EUROVI production engine OM936
- Decrease of the engine cruising speed enabled by a significant down-speeding of rated engine speed and low end torque speed to keep engine torque characteristic constant while decreasing engine friction and gas exchange losses
- Significant increase of peak cylinder pressure from 170bar (OM926) to 210 (OM936 EURO VI production engine) respectively 230bar (OM936 “CORE”) to achieve engine down-speeding with further increased engine efficiency
- Layout and design of an innovative two-stage boosting system with interstage cooling and variable asymmetric high-pressure turbine
- Combustion efficiency improvement by injection nozzles with higher hydraulic flow (HD1600 instead of HD1300)
- Take-over of friction optimized pistons and rings from SP B1
- Powertrain hybridization simulated in a real world driving cycle in the engine test cell using an engine in the loop system

These topics had been covered in the six work packages shown below.

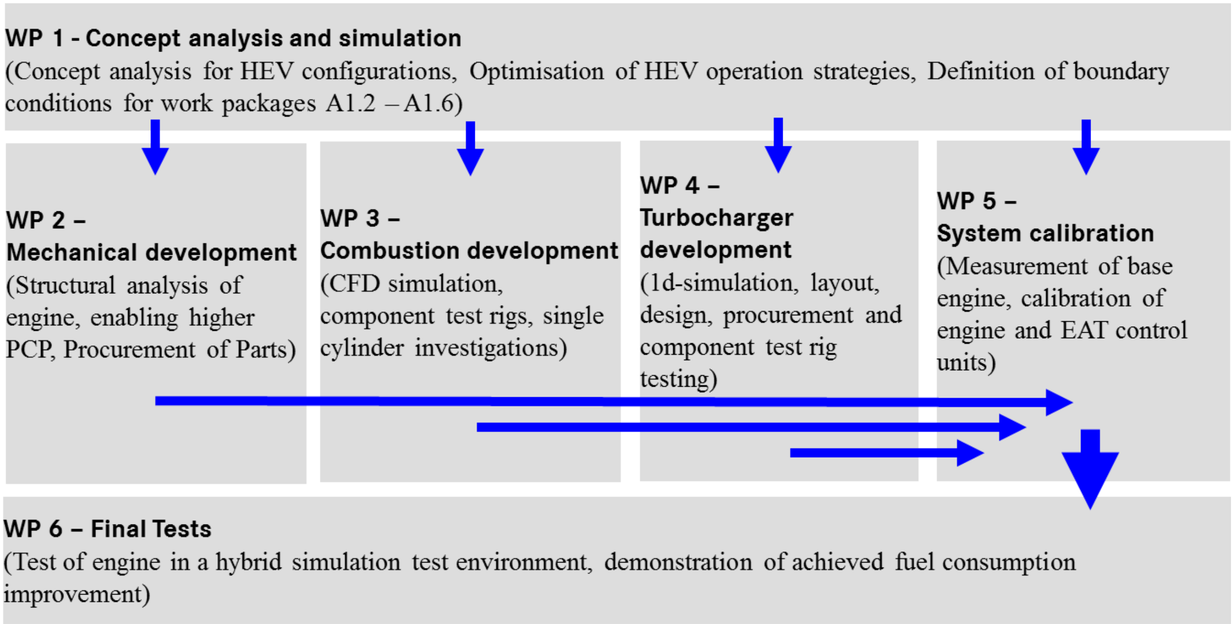



*Figure 5: Work package structure of SP A1*

The torque and power curves of the engines are displayed in Figure 6: The significant down speeding of rated speed and low end torque speed as well as the increased maximum torque is visible.

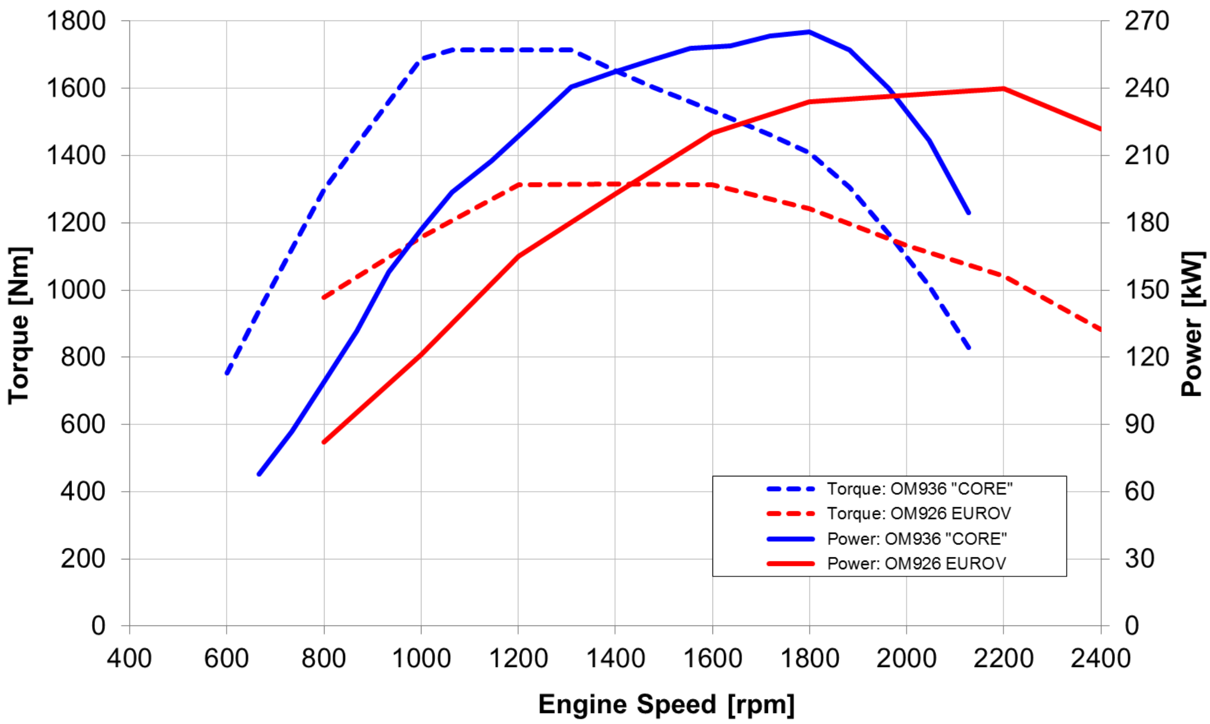



*Figure 6: Torque and power curves of EUROV reference and CORE engine*

While an engine with increased peak cylinder pressure capabilities was available from the internal EURO VI development, the target downspeeding required significant changes at the boosting system to combine efficiency increase with sufficient EGR transport capabilities. Therefore a completely new high pressure turbocharger was laid out and designed. It features a segmented turbine with two volutes, a mechanically simple variability for this turbine and asymmetric flow parameters for the two segments. Additionally a low temperature interstage cooler was installed between the two compressors to lower the required compression work for the desired boost pressure. A section cut through the high pressure turbine with its variability realized by a simple rotating slider is shown in the following figure. The turbine is shown with slider position for smallest flow parameter.

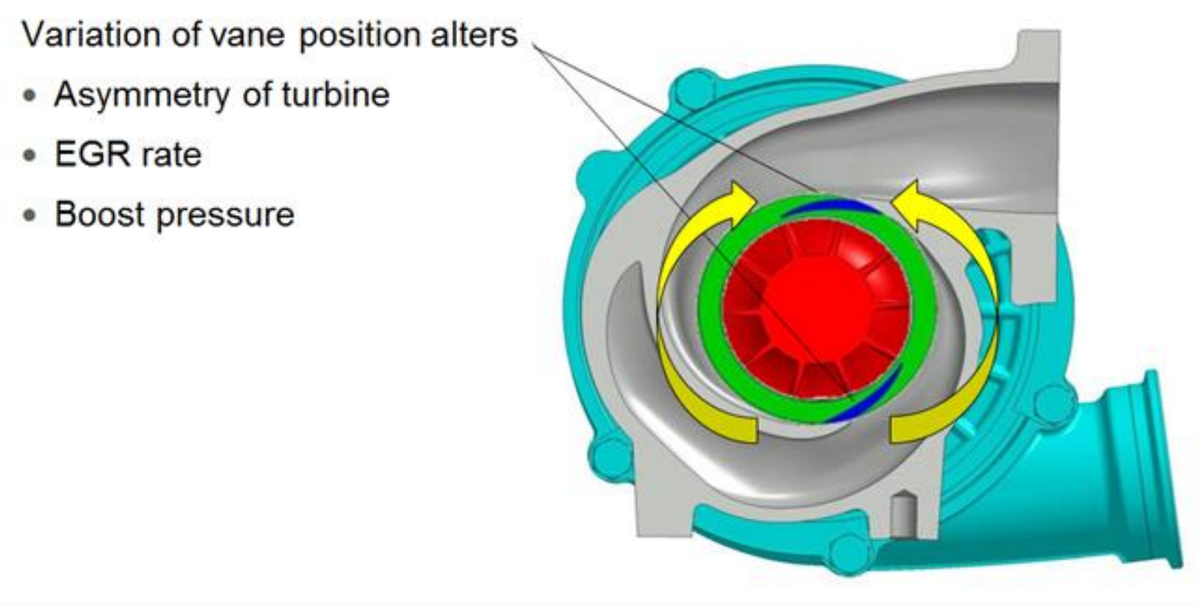
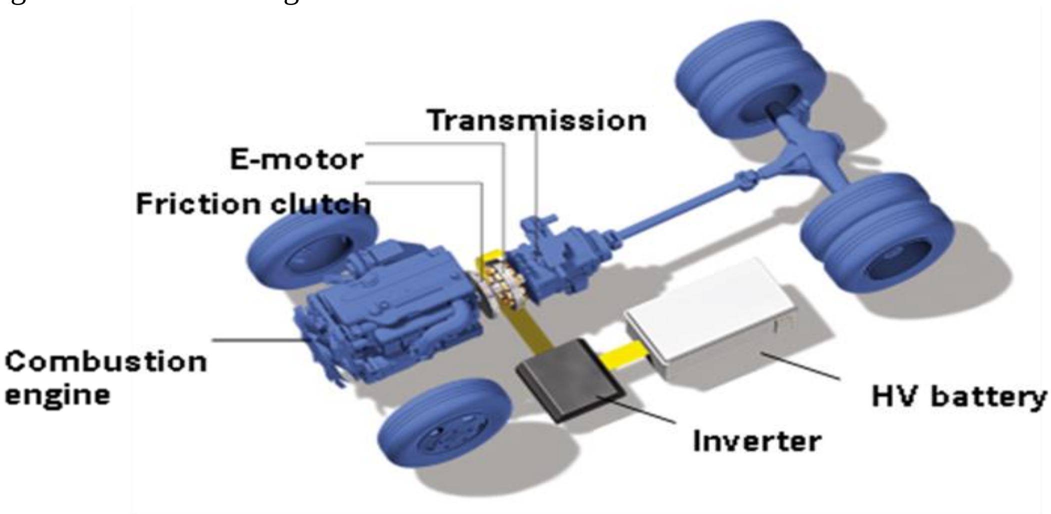



*Figure 7: Segmented asymmetric and variable high pressure turbine*

The engine and boosting system modifications had been complemented by hybridization of the powertrain to reach the target fuel efficiency improvement. The hybrid components were modelled in an engine-in-the-loop system which included a defined route, vehicle and powertrain system simulation. The chosen hybrid concept was a so called P2 hybrid which is a parallel hybrid with an electrical machine connected to the input shaft of the gearbox. The clutch can separate combustion engine and electrical engine.



The final result of SP A1 was 12.9% improvement in fuel efficiency in a real world road cycle for a domestic long-distance truck measured in the engine test cell. This result splits up into 5.4% improved fuel efficiency measured in the test cell for the conducted changes on engine and final drive ratio (FDR) without hybrid contribution and additional 7.9% improvement by the hybridisation like shown in the following figure.

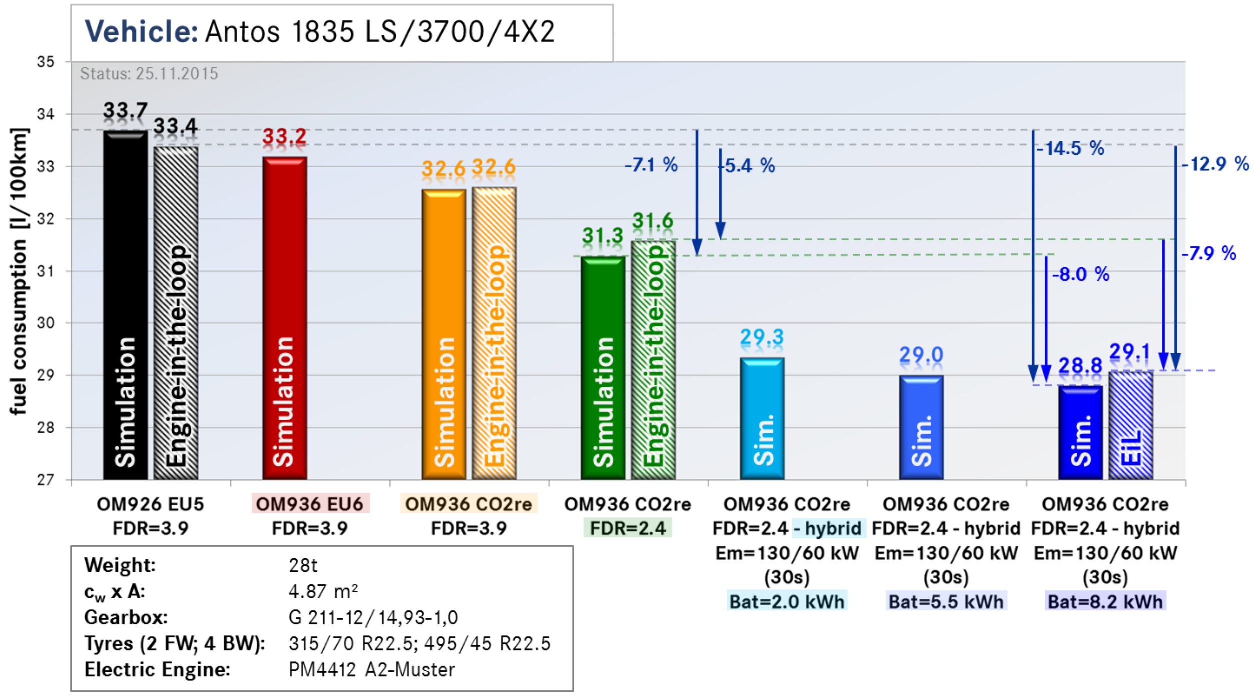



*Figure 8: Fuel consumption walk in SP A1*

## SPA2 High efficiency Diesel engine for long haul

Sub-project A2 was carried out by Volvo, Honeywell, Johnson Matthey and Chalmers. The target application was an international long distance truck with gross vehicle weights of 40 ton. The objective was to improve the engine efficiency and demonstrate this over a transient cycle.

Work was focus on an optimum combustion and aftertreatment system supported by a very efficient air management system. In order to achieve improved combustion and increased engine efficiency the developed engine concept used variable valve actuation (VVA) and a dual state turbo system (DST). The VVA system enables both advanced combustion strategies as well as novel heat management strategies for more efficient exhaust aftertreatment.
The primary of the efficient breathing system of the engine concept was the turbo charger. By the use of a two-stage turbo the residual energy in the exhaust can be very well utilised and restored to the cylinder by means of a higher charge pressure and increased air flow, giving higher thermal efficiency in the combustion cycle.

Further, the turbo has been well matched with VVA system to utilise operation in the Miller cycle for additional increased engine efficiency. The Miller cycle is obtained by the VVA system, with late closing of the inlet valves resulting in an over expanded thermodynamic cycle. When the intake valve closure (IVC) is delayed part of the inlet air is pushed back into the inlet manifold before the valves are closed, resulting in less trapped mass of air in the combustion chamber. The volumetric efficiency is thereby decreased and the compression stroke reduced. The reduced compression stroke is compensated for by the high efficient turbo charging system, i.e. part of the compression is moved from the piston to the turbines, so that enough air is available for a complete combustion and soot oxidation process. Further, since part of the compression is performed by the turbo charger system including two charge air coolers, the total compression work is more efficient and the temperature of the charge at top dead center (TDC) is reduced. The improved efficiency of the compression work increases the overall engine efficiency and the reduced temperatures reduces the engine out NOx emissions while keeping the engine out soot emissions at a low level as long as the delay of IVC is not exaggerated. A too late IVC will cause a lack of air, and both engine-out soot emissions as well as fuel consumption will increase significantly.

The engine concept also includes engine downspeeding (narrow band) application. The downspeeded approach increase engine efficiency by reduced engine friction losses, gas exchange losses and the potential for further sub-system optimisation. To keep the same engine power in this downspeeded concept the torque curve has been adjusted with increased torque, which also requires the capability of the engine to operate at a PCP of 220 bar or more.

The engine concept with VVA gives opportunities to use heat modes for optimum performance of the diesel particulate filter (DPF) as part of the complete system. The scope was to minimize the fuel penalty and $CO_2$ emissions from DPF implementation. The target was expressed as a reduction of exhaust back pressure at nominal ash/soot loading and a minimization of active DPF regeneration.

The turbo system was developed from scratch with the aim to meet the target application and the compact installation demands. In order to meet the tough efficiency targets state of the art technologies were to be used which included ball bearings, nozzled turbines, fine-tuned gas paths, generous compressor inlets, axial/radial layout, in addition to clearance reduction and gas friction loss technology, see figure 9.

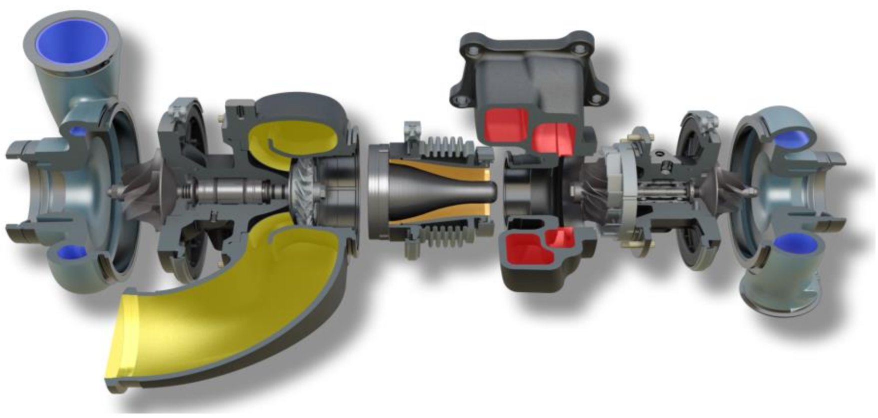


*Figure 9: 3D rendering of the turbocharger system*

Applying a design of experiments approach, gas stand testing of many turbo hardware variants was completed to enable down-selection of the optimum configuration suited to the engine requirements

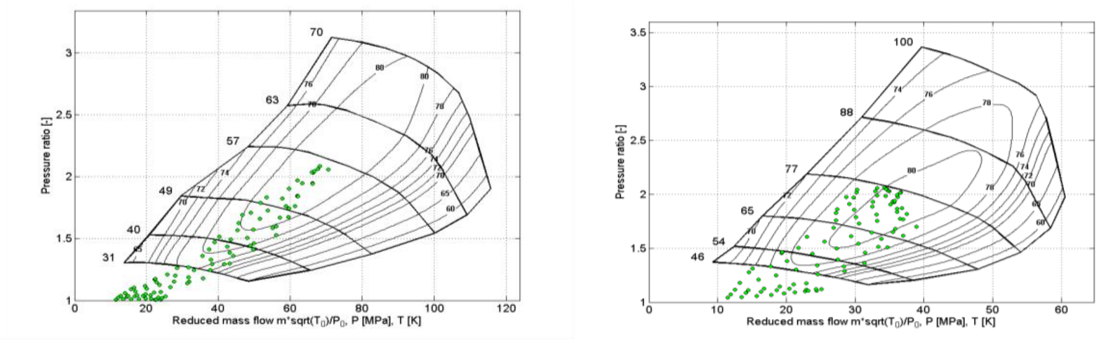


*Figure 10: Overlay of engine running points on to low and high pressure compressor maps*

In gas stand turbo component performance is measured. The result is typically presented in what is called compressor maps, which show how flow and pressure ratio varies going from surge to choke conditions at constant speed. Efficiency islands are then added to show how efficient the compressor operates in different areas. Figure 10 show compressor maps with nominal geometries for both the LP and HP compressors. Engine operating points have been added to show the very good matching that was achieved, i.e. close to the peak efficiency island.

The work with diesel particulate filter (DPF) was performed in a parallel work-package with the aim to development and delivery a DPF with improved soot oxidation efficiency and lower back pressure in order to support the $CO_2$RE project target.

Performance tests with the new CORE DPF and reference filter were conducted with full size filters and engine operating in WHTC. The PN emissions were measured over five consecutive WHTC cycles starting with cleaned filters. The CORE filter shows 30% higher soot burn compared to the reference. The PN emissions were the same, well below the Euro VI legal limit, for the reference and the CORE filter even though the CORE filter has a higher porosity. The back pressure was lower, see figure 11, and the net $NO_2$ make is higher for the CORE filter compared to the reference. The difference is estimated to give approximately 0.1-0,2 % lower BSFC with the CORE filter.

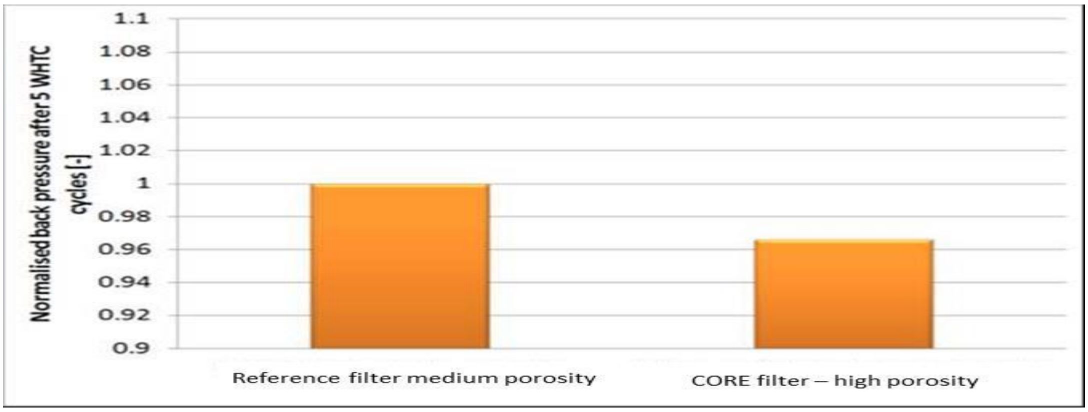



*Figure 11: Normalised back pressure over the tested filters after five consecutive WHTC cycles*

The final result of SP A2 was demonstrated in a Volvo fuel cycle, Borås-Landevtter-Borås (BLB). The new SPA2 CORE is a high efficient engine with improve fuel consumption, see figure 12 presenting the engine efficiency map.

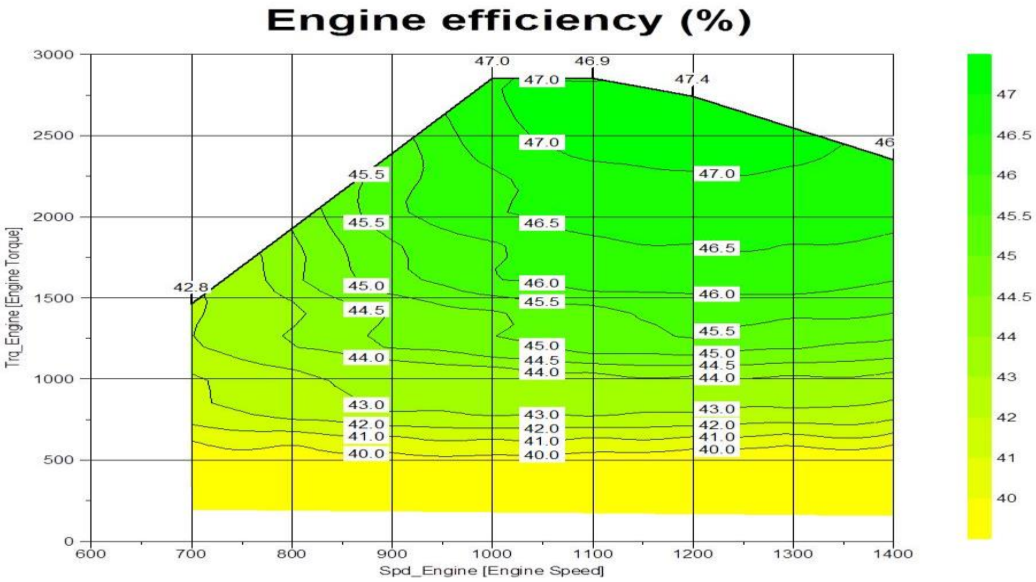



*Figure 12: SPA2 CORE engine efficiency map*

BLB cycle results comparison in EURO VI legislation between the CORE SPA2 engine and EURO VI reference, are presented in table below. The CORE engine fulfils the EURO VI legislation for NOx and PM for both WHSC and WHTC. For the WHTC the result was from the combined cold/warm test. The reduced fuel consumption was 6%, which was in the target zone for the project.

| | EURO VI reference | SPA2 CORE | |
|---|---|---|---|
| **WHSC Results** | | | |
| NOx [mg/kWh] | 152 | 23 | |
| PM [mg/kWh] | 1,3 | 1,6 | |
| BSFC [kWh] | 201,4 | 196,6 | |
| **WHTC Results (cold & warm)** | | | |
| NOx [mg/kWh] | 259 | 193 | |
| PM [mg/kWh] | 2,5 | 2,3 | |
| BSFC [g/kWh] | 209,1 | 201,1 | |
| **Fuel Ref Cycle** | | | |
| BSFC [g/kWh] | 199,7 | 188,5 | 6% |

## SPA3 Advanced combustion system for Diesel and NG HD engines

The first part of the project consisted in the integration of the Variable Valve Actuation technology on HD engine platform to realize HD Diesel and NG prototype to support experimental evaluation. The goal was to realize a common cylinder head equipped of Variable Valve Actuation. The system provides on intake side a fully flexible and continuous variation of valve lift and timing. The activity has been performed on the Cursor family; Cursor 9 Diesel engine and Cursor 8 NG engine.
To apply VVA technology to the intake valve lift, it was necessary to include in the kinematic chain an hydraulic control volume. The hydraulic fluid is the lubrication oil and a solenoid valve controlled by dedicated electronics units manages the valve lift strategy. The solution was to adopt a single unit for each cylinder, the bricks of adjacent cylinders have been coupled in a single one, with a total amount of three independent elements. VVA system was installed on the engines and the necessary adjustments were performed. The engines were mounted on test benches with all necessary measuring devices (fig.13).

*Figure 13: Diesel and NG prototypes on test bench*

The aim of the second part of the project consisted in performing experimental tests with innovative combustion approaches, allowed by VVA system, in order to verify the potential of internal EGR in term of NOx emission and fuel consumption for Diesel engine and to measure the fuel consumption saving due to pumping friction reduction and the impact on engine thermal state for NG one. A modelling activity developed by POLITO was used as a guideline all along the development.
At the end of the activity period, the advanced combustion model results were successfully verified to make it optimized for further investigations.One of the most interesting output of the first test bench activity was the CO2 saving on NG engine that results in 2% at high load and high engine revolution but becomes 10% at lower load and engine revolution. The different combustion obtained using Miller tuning with a resulting post-expansion of fresh charge and low starting temperatures means that a more anticipated spark advance can be used than traditional combustion consequently obtaining lower temperatures of the exhaust manifold (fig.14)

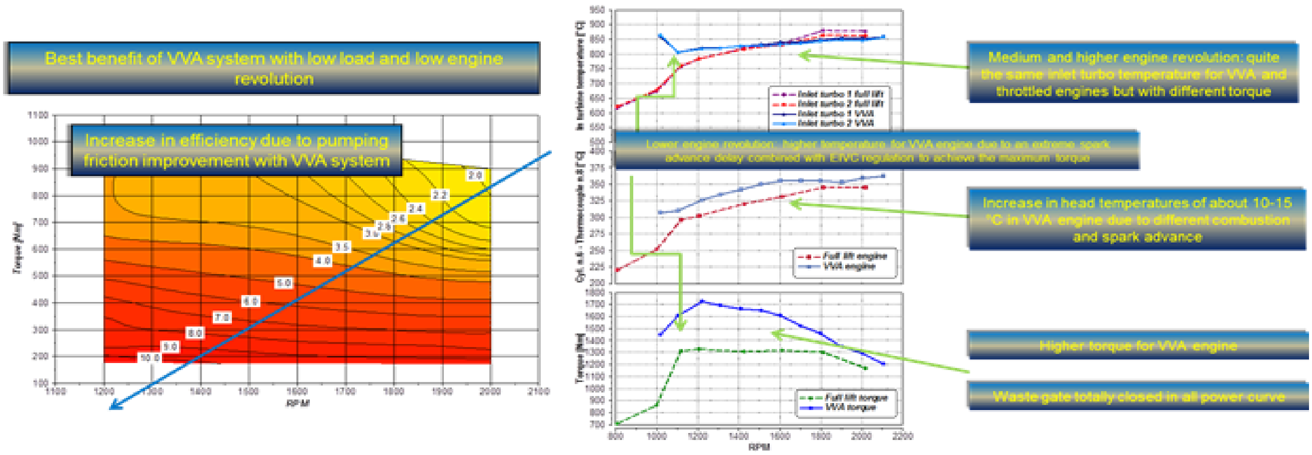



*Figure 14: BSFC reduction [%] (left) - Power curve, inlet turbine & head temperature (right) – VVA vs throttled engine*

In addition, it was assessed that VVA affects exhaust pollutants amount, so compromise between THC emission, performance and fuel consumption had to be found in successive calibration phase.

**For Diesel engine** the engine behavior, with internal and external EGR was, at first, simulated, then a full test bench activity was performed adopting different strategies to control engine raw NOx emissions: 1)Retarded strategy, 2) External Cooled EGR strategy, 3) Internal EGR (uncooled) strategy and 4) Internal EGR and Early Intake Valve Closing.

The first is representative of Euro VI production engine and it is the "reference" case. Test results, according with simulations, show that external (cooled) EGR is the best solution to control NOx emissions while iEGR strategy results are not always aligned to expectations due to a considerable BSFC penalization for higher charge temperature. To reduce the average charge temperature is necessary to combine iEGR with Early Intake Valve Closing to cool down the charge temperature with the cylinder expansion phase. The increasing in BSFC with iEGR can be mainly ascribed to the higher heat transfer across the combustion chamber, compared to eEGR mode, as predicted by GT-POWER.

A specific activity consisted in a deeply investigation of VVA technology impact on emissions level on both prototype engines (Diesel and CNG) with a particular focus on after treatment systems optimization was successively performed.

POLITO had carried out simulations, under both steady-state and transient conditions to obtain the best compromise between fuel consumption reduction and good emission level exploring all potential given by VVA device to improve efficiency of aftertreatment systems.

About Cursor 8 NG, different combustion and air management strategies were obtained by properly combining spark timing, boost level and throttle position or EIVC angle.

In the Cursor 9 Diesel engine, a full definition of working strategies required a specific calibration of injection pressure, injection timing of the main pulse, boost pressure, as well as electric angles of EIVC and/or iEGR valve lift profiles.

Third part of the project was focused on ECU strategies calibration with the purpose to do the assessment of the final prototype engines configurations in according to homologation tests at the rolling chassis dyno, comparing new VVA engines with reference ones, as actual state of the art.

In addition, calibration data were used as input to verify, in cooperation with No-Waste project, the potential in term of energy saving of Rankine cycle installed after NG catalyst or Diesel ATS.

**<u>Diesel engine</u>:** the comparison between reference EuVI BSFC map and CORE VVA shows that VVA strategies have a positive effect on BSFC (at constant NOx) especially at High Load and Speed including the full load curve. iEGR and EIVC allow a more efficient combustion (more advanced MBF) at same NOx level. Boost pressure was calibrated in order to have the same air mass flow to balance the effect of early intake valve closing.

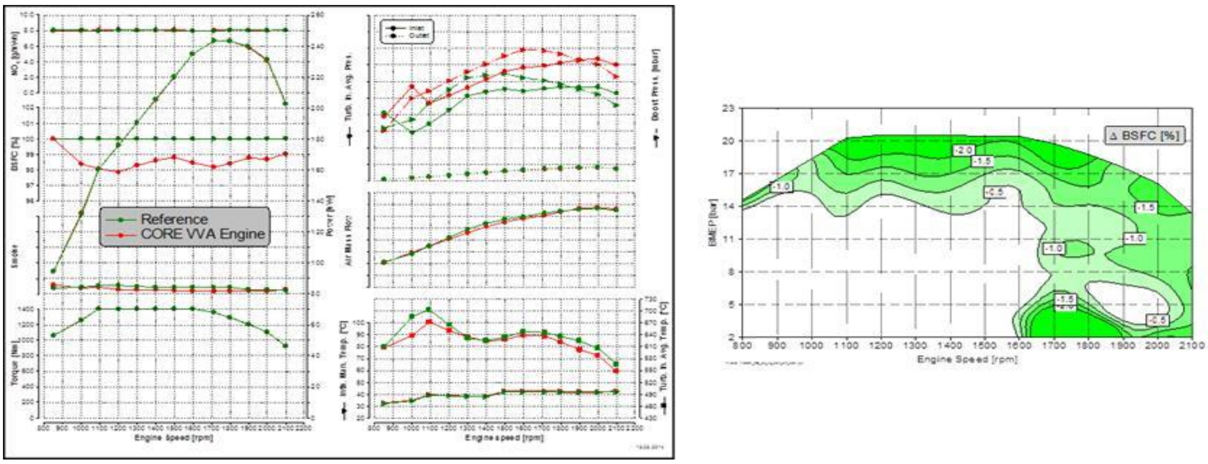



Figure 15: Full Load Curve (left) & BSFC differences (VVA vs base engine) (right) on Diesel engine

CNG engine: benefits achievable with a Miller-type adjustment (early intake valve closing) are especially evident at low and medium loads. Increasing performance, this advantage tends to decrease where even traditional engines work practically with the throttled completely open. Fuel reduction in this area can be obtained because of different tuning of other engine parameters, as spark advance.

The first calibration step was, consequently, to adopt in partial load the EIVC tuning. The second was to achieve the best compromise between EIVC strategy and other fundamental engine parameters: A/F ratio, spark advance, injection phase in principle.In fig. 16 it is possible to see (left) the power curve and BSFC corresponding reduction (from 0 to 4% max.) obtained operating on spark advance tuning. The map of EIVC strategy adopted to eliminate differences between boost and intake manifold pressure, responsible of pumping losses is also shown (right).

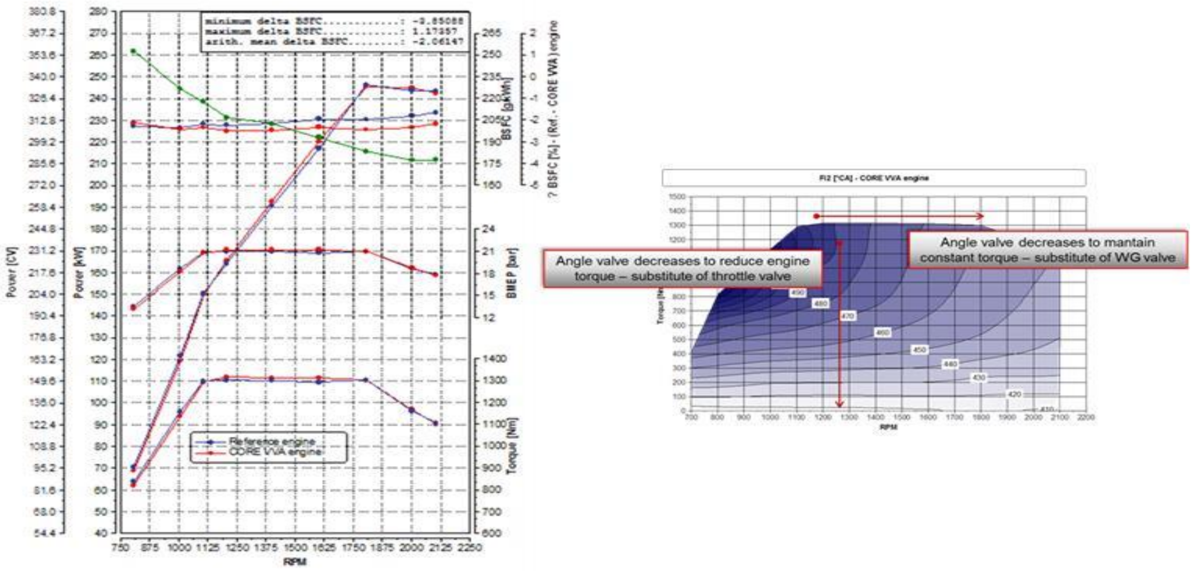



*Fig. 16: Power curve and BSFC (left), EIVC map (right) on NG engine*

After engine mapping phase, real WHTC cycles at dyno bench were performed on Diesel engine. Results show a lower NOx level at the same FC. Following steps show a reduction on fuel consumption at same NOx level, with a proper calibration adjustment.

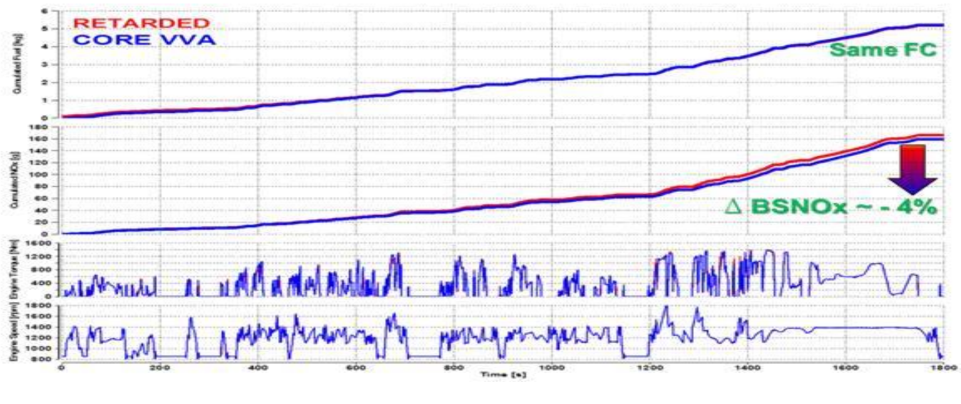



*Fig.17: Compare of WHTC with Retarded engine and CORE engine*

After engine calibration a catalyst solutions evaluation via simulation was performed, due to the CORE project internal collaboration, evaluating the conversion efficiency of the SCR developed in SP B2 in comparison with the “state of the art” technology. The simulations demonstrated a good potentialities of the “Gen3” technology in both warm and cold cycles with and without iEGR and good potentialities of iEGR to enhance both “old and new technologies” SCR efficiency in cold cycles.

A series of ETC and WHTC cycles were performed also on NG engine, in CRF. A CO2 reduction between 5% and 7.5% and emissions level generally lower than reference engine, except THC, were recorded.
After test bench cycles, an extended testing activity on a demonstrator NG truck was planned. At first a reference vehicle equipped with normal production NG engine was tested. After installation of VVA engine on the same vehicle, same cycles were done to compare results.
All test campaign was held at VELA facilities in JRC (Ispra). $CO_2$ and other main emissions of the demonstrator NG truck over the ETC and WHVC cycles were determined. The same pollutants were also examined with PEMS under real-world conditions on road and results were analyzed in comparison to the bench tests.
In the following chart (fig. 18), CO2 consumption evolution along the ETC cycle is described. A CO2 reduction with CORE VVA engine prototype in comparison with reference engine is obtained all along the three cycle phases. Similar results were obtained on WHTC and on road cycle.

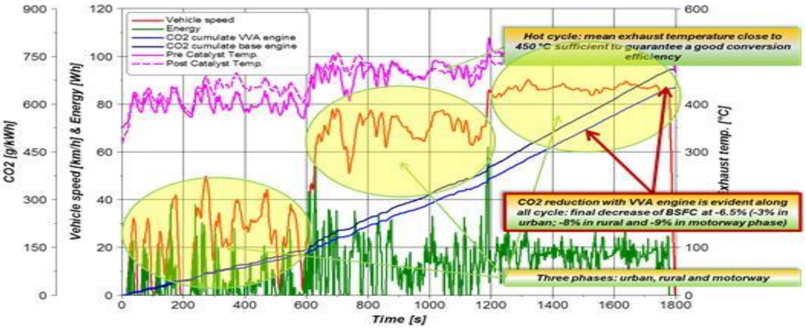



*Fig. 18: ETC cycle results: CO2, catalyst temperatures*

In the table, average values for every pollutant are reported for each cycle performed. A comparison with official European homologation cycles limits (EUROV and EURO VI targets) are also mentioned.

| ETC (European Transient Cycle) [g/kWh] | VVA engine | Reference engine | Difference (%) | Limit (EEV) |
|---|---|---|---|---|
| BSFC / CO2 | 661 | 706 | -6.5 | - |
| CO | 0.24 | 0.33 | -27 | 3 |
| THC/CH4 | 0.53 | 0.34 | +56 | 0.65 |
| NOx | 0.67 | 1.07 | -37 | 2 |

| WHVC (World Harmonized Vehicle Cycle) [g/kWh] | VVA engine | Reference engine | Difference (%) | Limit (Euro VI) |
|---|---|---|---|---|
| BSFC / CO2 | 715 | 751 | -4.8 | - |
| CO | 0.10 | 0.35 | -70 | 4 |
| THC/CH4 | 0.3 | 0.21 | +43 | 0.5 |
| NOx | 0.97 | 2.50 | -61 | 0.46 |

| Road cycle (PEMS) [g/kWh] | VVA engine | Reference engine | Difference (%) | Limit (Euro VI) |
|---|---|---|---|---|
| BSFC / CO2 | 688 | 751 | -8.4 | - |
| CO | 0.52 | 1.23 | -58 | 4 |
| THC/CH4 | 0.36 | 0.43 | -16 | 0.5 |
| NOx | 0.63 | 1.25 | -50 | 0.46 |

CORE target achieved in ETC cycle
Reference engine is compliant with EEV emission level; it isn't tuned for EURO VI level
Satisfying reduction for all pollutants except for THC that are, hovewer, under EEV limit
Fuel reduction performance very close to CORE target in WHTC cycle
Reference engine is not calibrated for EURO VI level; infact NOx level is too high
Satisfying reduction for all pollutants except for THC (same increase than in ETC cycle)
CORE target achieved in road test
Reference engine is fully into EEV limits and partially into EUROVI limits (except NOx)
VVA engine is fully into EEV limits and partially into EUROVI limits (except NOx)
Due to CO very low value, a slight richer tuning could fully achieve EURO VI target

*Fig. 19 : CO2, THC, NOx and CO level for ETC, WHVC and PEMS cycles; JRC facilities*

In conclusion, average CO2 reduction recorded with VVA device (versus reference configuration) during ETC cycles resulted close to 6.5%. In WHVC this difference was about 5%; on road it was possible to obtain more than 8%.
About main pollutants, generally the state of the art was better in VVA configuration except for THC that will need a specific activity in term of catalyst efficiency or lay-out and/or in term of combustion behavior.

Last activity concerning Diesel platform was the analysis in order to define the best compromise between BSFC and Urea (AdBlue) consumptions with the aim to minimize the operating cost for both ”on – Road” and ”off – road” Diesel applications. The operating cost was evaluated in ”euro per hour” and it was the sum of fuel and AdBlue costs. A separate investigation between “on – Road” and “off – Road” applications was necessary due to their different mission profiles. To perform this analysis were used fuel consumption measurements at test bench applying VVA calibration while the AdBlue consumption was estimated through a calculation model. The final operating cost was improved in some engine certification modes thanks to VVA technology that reduces BSFC and / or Urea consumptions for each mode.

In the meanwhile, to realize the final LNG vehicle prototype, an advanced feeding system was developed by Metatron. The activity objective was the design, realization and testing of an electronic gas pressure regulator able to work with NG and LNG, properly tuning injection pressure for both fuels and in every engine map condition. These features can be achieved only by means of a mechanical system managed by an electronic control unit connected with the engine control unit. In parallel an LNG fuel storage system was installed on NG vehicle prototype to perform range tests: in fact VVA device allows NG engines to become efficiency competitive in comparison with Diesel engine; but range of these vehicles remains too short due to lower density of gas energy compared with liquid fuel. Adopting LNG fuel part of this gap could be eliminated.
The electronic pressure regulator was added to the common line, in order to work with different pressure set-up (9 bar with NG and 7 bar in LNG mode).
Additional safety procedures had to be taken into account during LNG operations.
Rolling bench tests were performed to verify if engine performances, fuel consumption or emissions could be affected by LNG fuel while extensive road tests were done to verify increase of vehicle range.
At the end of the activity, it was possible to conclude that LNG storage technology has practically no effect on engine behavior because liquid fuel, before injection, is transformed in gaseous form (NG); after pressure regulator, injection parameters (temperature, pressure) are not precisely the same among LNG and NG but differences can be well-compensated by ECU control injection model. It was assessed that LNG system improves twice the vehicle range and reduces the vehicle weight.
Final pressure regulator and vehicle prototype lay-out are illustrated in the following figures.

*Fig. 20: Electronic Pressure Regulator (Proto C) and LNG + NG vehicle lay-out*

## SPB1 Friction Reduction

Sub-project B1 was carried out by Ricardo, Federal-Mogul (F-M) and Daimler: with the push to reduce $CO_2$ emissions, friction was in focus. The objective was to achieve a 10% reduction in frictional mean effective pressure (FMEP) by changes to the engine reciprocating and rotating components combined with downspeeding and an alternative lubricant. The major focus was on the reciprocating components, which typically contribute almost 40% of the total engine friction. Federal-Mogul had estimated that, within the piston ring pack, the oil ring has the biggest share of around 13% of engine friction, followed by the first compression ring (top ring) with 9%; the friction contribution of the second ring is relatively small (3%). Furthermore, the total share of piston ring friction in the total fuel energy use is around 4%. Therefore, in order to reach 1% of fuel consumption, the piston ring friction must be reduced by around 25 %.

The organisation of the sub-project is given in Figure 21. As a basis for the work in SP B1, the Daimler OM936 engine was used (see figure 22). In the following paragraphs the activities inside SP B1 will be described in a little more detail.

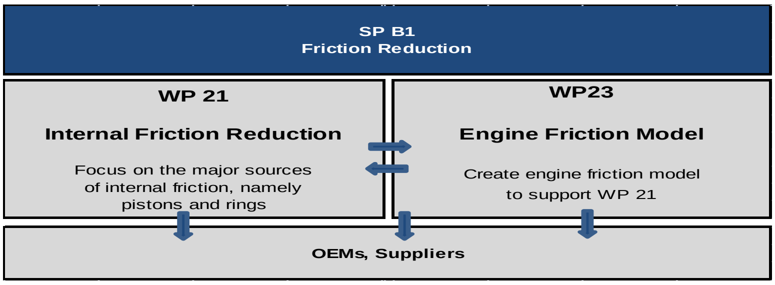



*Figure 21: CORE SP B1 Structure*

*Figure 22: Daimler OM936LA engine*

In order to manage the risks of changing a piston/ring/cylinder combination, which has been developed over years to have excellent durability, it was decided to carry out the SP B1 project in two Phases:

- Phase 1: the first set of engine tests incorporated changes to pistons and rings to enable friction reduction to be measured whilst keeping the risk of failure at an acceptable level at the maximum cylinder pressure of the then current OM936 level. An oil with reduced viscosity was included as part of the test matrix.
- Phase 2: In the second set of engine tests, more radical changes were considered consistent with the plan to downspeed the engine and increase the maximum cylinder pressure limit. In addition to the standard and reduced viscosity oils, an oil with standard viscosity but a friction modifying additive was included as part of the test matrix.

Prior to an experimental engine based investigation, a detailed model of the engine friction was created using Ricardo analysis tools:

- The RINGPAK software was used to make mathematical models of the piston rings. This program has fully coupled and integrated models for axial, radial and twist dynamics of the ring, inter-ring gas dynamics and lubrication at the ring/cylinder interface. It also calculates oil consumption, blow-by and wear. RINGPAK was used to calculate the oil film thickness and friction power loss at each piston ring through one engine cycle of 720 degrees at a range of engine loads and speeds. Calculations were also made under motoring conditions because the results could be validated against measured data from a motored teardown test, where the boundary conditions are less complex than for firing conditions. The modelled surface roughness of the cylinders was based on measurements made in a worn engine. Typical roughness data for the other surfaces on the rings, piston and pin were used in the calculations.
- Friction between the piston skirt and the liner and between the piston pin and piston pin bore was calculated using the Ricardo PISDYN software. PISDYN was used to calculate the oil film thickness and friction power loss on both sides of the piston skirt at one degree intervals over the engine cycle of 720 degrees.
- Finite element models of the piston and cylinder block and head assembly were made in order to calculate the running shape of the surfaces under operating conditions.
- Viscous friction in the crankshaft bearings was estimated by using the Ricardo ENGDYN and VALDYN software.

The model was used to calculate friction, oil consumption, blow-by and wear at key points corresponding to the operation of the engine in a typical regional long distance truck. In the following section, results are shown for three cases:

- Baseline engine
- Revised design of pistons and rings (called ‘Phase 1’, Build 1)
- ‘Phase 1’ with Low Viscosity (LV) Oil.

In Figure 23 the differences between the baseline and the Phase 1 components are listed. The Phase 1 components were designed by F-M to demonstrate a reduction in friction whilst minimising the risk of failure and retaining acceptable oil consumption. The Low Viscosity oil corresponded to a 25% reduction in viscosity from the baseline 5W30 oil.

| | Baseline | Phase 1 |
|---|---|---|
| Top ring maximum width | Reference | - 1mm |
| Top ring mean tangential load | Reference | - 40% |
| Second ring maximum width | Reference | - 0.5mm |
| Second ring mean tangential load | Reference | - 30% |
| OC ring maximum width | Reference | - 1mm |
| OC ring mean tangential load | Reference | - 40% |
| Piston skirt clearance | Reference | + 20micron |

*Figure 23: Baseline and Phase 1 in-cylinder components (OC: Oil Control ring)*

Selected results from the simulation are given in Figure 24. The model showed that the FMEP of the top ring under firing conditions is highly dependent on the maximum cylinder pressure. Maximum FMEP occurs at peak torque where maximum cylinder pressure is highest. By contrast, motoring FMEP is at a low level and increases with engine speed.

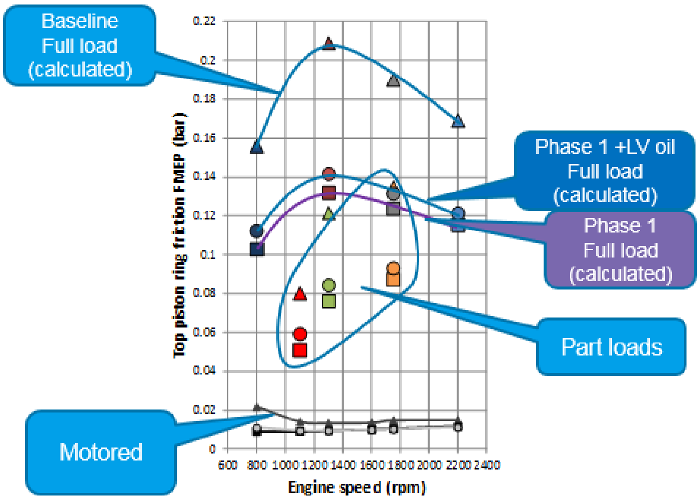



*Figure24: Baseline and Phase 1 top ring FMEP simulation results*

Compared with the baseline, the Phase 1 build was predicted to reduce top ring FMEP by about one third. Reducing oil viscosity was predicted to reduced motoring FMEP but increase firing FMEP.

The friction model was used to calculate oil consumption, blow-by and wear. The results indicated that the Phase 1 components would enable these parameters to be maintained at levels similar to the baseline condition.

For the Phase 2 components the partners discussed the various options for further reductions in friction, based on analysis by both Ricardo and F-M, and tests on the Floating Liner Engine at F-M. The trade-off between friction and functionality (oil consumption, blow-by and wear) was considered. The Phase 2 components were selected to give reduced friction by means of coatings. A further reduction in oil control ring tension was accepted at the possible expense of an increase in oil consumption. In summary, Phase 2 components (Build 2) and oil changes included:

- Low friction coating on top ring face and oil ring faces
- Low friction, scuffing resistant coating on the piston pin
- Improved oil flow plain bearings
- Oil with increased friction modifier additives and viscosity similar to the production one.

During the engine testing considerable care was needed to enable small changes in fuel consumption to be measured. Above all, the control of engine temperatures was critical. By attention to detail, it was possible to maintain key temperatures in a narrow range:

- Coolant out target 90±0.1°C
- Oil sump target 90±0.2°C
- Charge cooler out target 55±0.2°C
- Cell air temperature target 27±0.5°C
- Fuel supply temperature target 40±0.1°C
- Intake air temperature target 25±0.5°C.

Fuel temperature was accurately controlled by a fuel meter that controlled both the temperature of the fuel supplied to the engine and the temperature of the fuel returned from the rail. This ensured more accurate readings at the measuring head. In addition, the Ricardo RADAR software was built into the test bed control, which ensured that measurements were taken only when the engine was running in a stable condition and data were within pre-determined limits. In order to enable calculation of FMEP under firing conditions, six cylinder pressure transducers were installed, one in each cylinder. The FMEP was calculated from: *FMEP = Net IMEP – BMEP*.

A range of tests was carried out to evaluate the effect of the different components and oils. Measurements were made in the following conditions (see Figure 25):

| *Engine Build, firing or motored* | | *Key Measurement* |
|---|---|---|
| 1 | Full engine, firing | Fuel consumption, firing FMEP |
| 2 | Full engine, motored | Motored FMEP |
| 3 | Cylinder head removed, replaced by plate and cover, motored. Oil pump removed and driven externally. | Motored FMEP excluding pumping losses and valve train losses |

*Figure 25: Engine Test Conditions*

Compared to the baseline build, the Phase 1 build gave a consistent reduction of between 4% and 6% in the motored friction of the whole engine and in the crank train motored friction. The change in FMEP calculated from cylinder pressure measurements in the whole engine tests was consistent with the values measured from the torque flange in the crank train configuration.

In Figure 26 the comparison of baseline and Phase 1 builds in terms of fuel consumption difference at a range of steady-state key points is shown. The repeatability of fuel consumption measurement was generally excellent and enabled small differences to be identified.

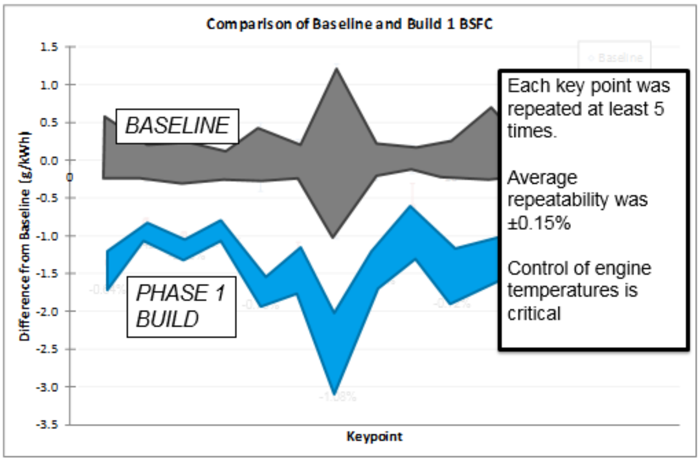



*Figure 26: Baseline and Phase 1 Build Fuel Consumption Differences over a range of Key Points*

In Phase 1, in summary the conclusions were:

- Within Phase 1 of the project, the new components (Build 1) were seen to reduce the engine friction (FMEP reduced by 4 to 5%) and bring a BSFC benefit (between 0.4 to 1.1% over the steady-state key points), when using the production oil (see Figure 27).
- The low viscosity oil was seen to bring a motoring friction reduction (FMEP reduced by 3 to 4%) but no significant BSFC change (±0.3%).
- Initial measurements over a short period indicated that oil consumption with the Phase 1 components was largely unchanged compared with the baseline. Blow-by was increased but still at an acceptable level.

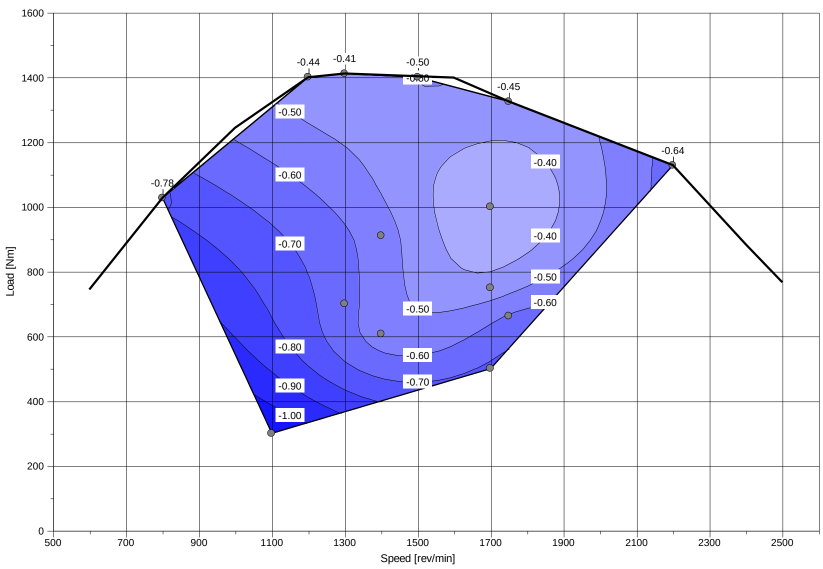



*Figure 27: Phase 1 Build Percentage Fuel Consumption Improvement Compared with Baseline*

In Phase 2, in summary, the findings were:

- With the production oil, Build 2 was seen to bring a further reduction in cranktrain motoring friction and a very slight reduction in engine BSFC (<0.5%) under some conditions, compared to Build 1.
- With the low viscosity oil with Build 2, a reduction in cranktrain and whole engine motoring friction was seen but a slight increase in engine BSFC (up to 1%) measured, compared to the production oil.

In discussing these results the following points were identified:

- The effects of the low viscosity oil and the friction modified oil appeared inconsistent between Builds and testing type: it was suspected that other effects confounded the test results.
- From a methodology point of view it was recommended to use an external oil pump when testing to ensure that oil flow rates can be carefully controlled when testing components or oils, such that changes in the demanded oil flow from the oil pump do no confound other friction reductions and fuel consumption improvements.

In conclusion, the optimal friction reduction and fuel consumption improvements possible for this engine within the constraints of the activity were measured repeatedly, to a high degree of accuracy as between a 4% to 9% reduction in FMEP (the higher values include the additional effects of low viscosity oil) and a BSFC reduction of more than 1%. These results (as engine maps) used within the overall assessment of the potential for fuel consumption or $CO_2$ reduction for truck engines, in Sub Project A4. The results were consistent with other measurements made independently by partners using similar components. The target of a 10% FMEP reduction with a consistent fuel consumption improvement was not seen, through the changes in tribological components applied within this Sub Project, even when those changes and investigations went beyond that originally planned and included some higher risk modifications. Further research work was recommended into: the effects of oil viscosity and additive formulations with these and other engines and components; and some engine testing procedural improvements, e.g. relating to the oil lubrication circuit.

## SPB2 Advanced NOx Exhaust Aftertreatment

Implementation of the advanced powertrain technologies creates a challenge for the exhaust aftertreatment (EAT) system, as it is required to reduce higher NOx concentrations down to the levels required by Euro VI standard at constantly decreasing engine exhaust gas temperatures. Low exhaust gas temperatures lead to an overall reduced catalytic activity of the SCR catalyst and makes the conversion of AdBlue into ammonia difficult, leading to formation of deposits of urea and by-products of its decomposition.

The SP B2 addressed the challenges by executing an integrated effort that included investigation and development of several innovative technical solutions:

- Advanced SCR catalysts based on both mixed metal oxides and Cu-zeolite materials.
- Integration of the advanced SCR catalyst materials onto a diesel particulate filter substrate (SCR/DPF)
- Selection of optimal substrates for SCR and SCR/DPF catalyst components
- An electrically heated device for complete vaporization and hydrolysis of the urea-water mixture in a small by-pass flow (AdBlue processor)
- Ammonium nitrate addition to AdBlue to improve low-temperature performance of the SCR catalysts through optimization of operating conditions.
- SCR system solutions, evaluated using a simulation platform incorporating models of new EAT components, performance and emissions of a medium-duty engine, and vehicle driving cycles
- Advanced control algorithms to support integration of new SCR technology solutions.

Development of integration approaches for the new technologies, evaluation of their potential impact on the exhaust emissions, and potential synergies have been conducted using EAT system simulation based on boundary conditions provided by SP A1 and A2.

As a reference for evaluation of new technologies, a model of an EAT system comprising DOC, cDPF, SCR and ASC catalyst models and AdBlue injection control algorithm was built and. The reference SCR system showed that high exhaust temperatures in PEMS cycles provided by SP A1 and A2 result in almost complete NOx reduction. To benchmark new technologies under more challenging real driving conditions, models for engine emissions and operation of several vehicles have been developed and used in the project.

Several new formulations of SCR catalyst materials have been developed, coated on various substrates, both flow-through and filter, and evaluated in synthetic gas and engine test benches. As a results of extensive benchmarking, the 3rd generation Cu-SCR catalyst (Gen3) technology was selected. Compared to commercial reference catalysts, the Gen3 technology demonstrated improvements in:

- NOx conversion over the low-temperature range
- dynamic response to $NH_3$ storage
- performance at high space velocities
- sulfation resistance
- desulfation behaviour

Figure 28 illustrates the improved NOx conversion of a hydrothermally aged Gen 3 SCR over the reference technology, as measured in a synthetic gas bench. Drastically improved sulphur tolerance and full regeneration of Gen 3 SCR catalyst, as compared with reference technology on the engine test bench, is shown in Figure 29.

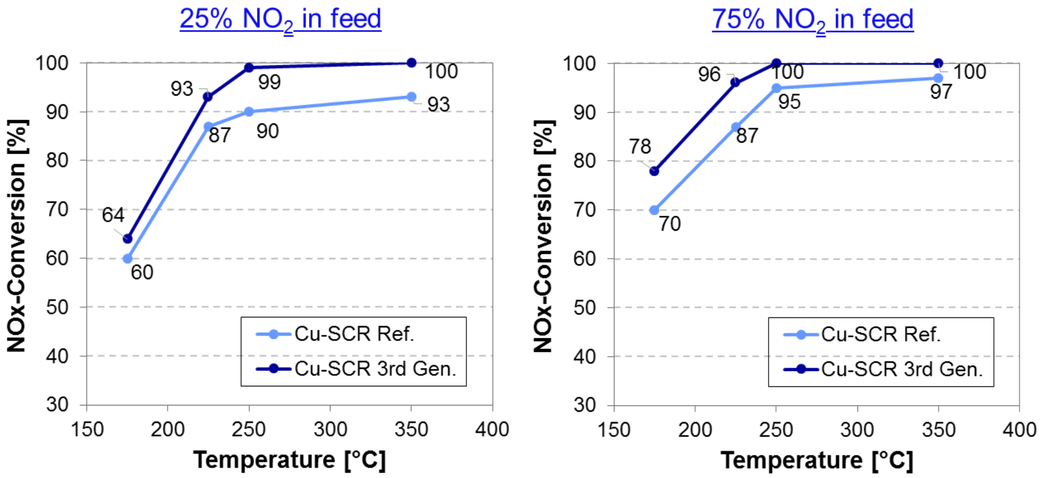



*Figure 28. NOx conversion of Gen3 vs. reference Cu-SCR catalyst, aged at 750°C.*

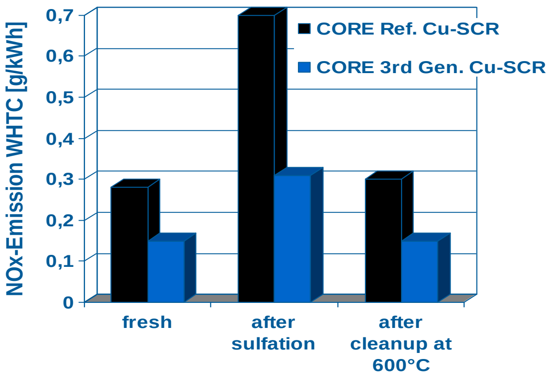



***Figure 29.*** *Comparison of NOx emissions, WHTC test at the engine bench fresh*

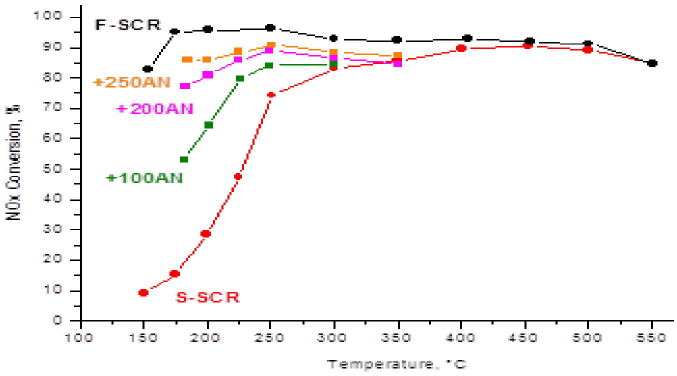



***Figure 30****: Effect of AN addition to the standard SCR reaction on Fe-SCR catalyst.*

Test samples of the Gen3 catalyst have been evaluated in synthetic gas and engine test benches. Results of extensive laboratory tests were used for the development and calibration of a kinetic model of SCR reactions on the hydrothermally aged Gen3 SCR. The model has been provided as a black box to SP A1 and A3. In SP B2, the EAT system model has been updated with the Gen3 SCR model, and the control strategy parameters have been recalibrated to account for $NH_3$ storage and activity of the new catalyst. Simulation showed that implementation of the new SCR catalyst can reduce tailpipe NOx emissions by up to 30 %, depending on engine exhaust parameters.

Several flow-through substrates have been coated with the reference SCR catalyst to investigate the influence of substrate structure on the $NH_3$ storage, NOx conversion and pressure drop. Higher cell density was found to increase NOx conversion and observed storage capacity, while the substrate wall thickness did not affect the performance. No significant effect of substrate parameters have been found in simulated WHTC.

Several SCR/DPF coating technologies have been investigated and optimized, and the most promising samples have been delivered for the assessment in a laboratory test rig. In the tests, the Gen3 Cu-SCR/DPF sample showed the most improved NOx conversion.

Four different substrates have been compared in the tests of performance and pressure drop of SCR/DPF component. Significant substrate effect was found, and a substrate providing the best combination of $NH_3$ storage, NOx conversion and pressure drop has been identified.

An EAT system model incorporating SCR/DPF technology has been created, along with corresponding AdBlue injection algorithm. The SCR/DPF system showed reduced NOx emissions in the WHTC, while the SCR washcoat loading was kept the same as in reference system, and precious metal loading has been reduced. The improvement resulted from higher temperatures of the SCR washcoat giving rise to earlier AdBlue injection start and higher reaction rates (Figure 30).

An often discussed subject of passive regeneration of soot in the SCR/DPF has been investigated using system simulation representing vehicle driving conditions. It was found that increased NOx concentration in engine exhaust has significant positive impact on passive oxidation of soot. This indicates promising synergy between advanced engine technologies and the SCR/DPF concept. The tailpipe emissions remain within the boundaries set for in-use conformity.

The development of the concept of ammonium nitrate addition to AdBlue was based on a systematic experimental investigation of several SCR catalysts in fresh and aged state in a laboratory test bench over a wide range of operating conditions. As a result, the potential for the NOx conversion improvement on a commercial Fe-SCR catalyst has been quantified (Figure 3). AN addition was shown to significantly increase NO conversion on Fe-SCR catalyst in the low-temperature range without undesired secondary emissions (e.g. $N_2O$). The improvement was the result of *in situ* increase in the $NO_2$/NOx ratio towards the optimum value of 1:1. For the Cu-SCR catalysts, AN addition brought no benefits.

The following reaction mechanism has been proposed and confirmed:

$$NO + NH_4NO_3 \rightarrow NO_2 + N_2 + 2H_2O \quad (1)$$
$$NO + NO_2 + 2\,NH_3 \rightarrow 2\,N_2 + 3\,H_2O \quad (2)$$
$$NO + NH_3 + \tfrac{1}{4}\,O_2 \rightarrow N_2 + 3/2\,H_2O, \quad (3)$$

with the reaction (1) being regarded as the rate determining step of the mechanism.

The NO oxidation by $O_2$ has been also analysed over the same catalyst for comparison purposes and was found to be insignificant at low temperatures.

The global kinetic model of reactions (1-3) has been developed and calibrated. Further investigation showed that ammonium nitrate can be stored on the Fe-SCR catalyst without inhibition of SCR reactions. Parameters of AN storage have been determined experimentally and included in the kinetic model.

The model has been further integrated with the SCR system model for the evaluation of the AdBlue additive performance in WHTC. Several system architectures incorporating control algorithms for AN injection, both separately from AdBlue and as a single urea-AN-water mixture, have been evaluated. Addition of ammonium nitrate has been shown to help significantly reduce NOx emissions (Figure 4). Further, the results confirmed the opportunity for the reduction of precious metal content, currently required for oxidation of NO into $NO_2$ in the upstream DOC.

The concept is at an early development stage, and significant further research and development is necessary. The effect of AN on the performance of SCR/DPF seems to be particularly interesting.

Two concepts for the AdBlue processor have been selected for detailed investigation in the project. The first concept involved pre-heating of the AdBlue solution prior to injection into the exhaust line. Optical spray investigation showed favourable change of an AdBlue spray into a dispersed cloud with very fine droplets that facilitate evaporation of the liquid. However, initial results indicated that the concept development to a prototype stage would require much greater time and budget than was planned in the CORE project.

A prototype of another concept, a by-pass reactor that evaporated liquid spray using electrically heated hydrolysis catalysts was found to be available from a third party on the market.

In parallel, several system architecture options of the AdBlue processor integration has been evaluated using system simulation that included corresponding reductant injection control modifications. Simulations included both WHTC (Figure 31) and vehicle driving cycles. The results showed no benefits from injection of gaseous $NH_3$ for long distance transport applications, while consuming electrical energy for AdBlue conversion.

As a result of discussions with OEM partners in SP A1 and A2, the decision was made to discontinue the development of the AdBlue processor in CORE project. Nevertheless, the technology can be of interest to other applications, such as city buses and delivery trucks.

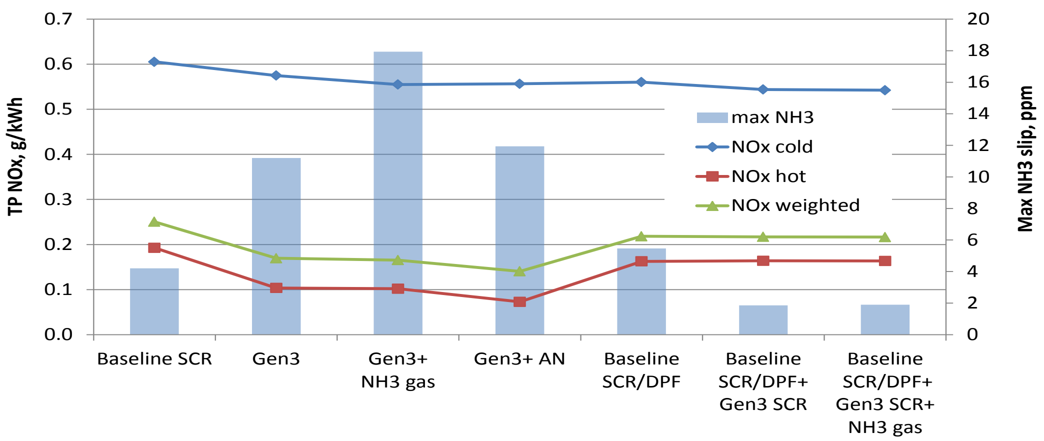



***Figure 31.** WHTC simulation results, SP A1 boundary conditions*

To summarize, the work completed in the SP B2 resulted in several new technical solutions developed to various stages of maturity. The technologies such as Gen3 Cu-SCR catalyst, corresponding kinetic model, system simulation platform, and key control strategy components are suitable for commercial product development in the near term. The metal oxide SCR catalysts, SCR/DPF, and by-pass AdBlue processor concept need further development, and could be of greater interest to markets other than long-haul transport. The AN additive and pre-heated AdBlue injection are essentially at the research stage and require significant long-term development effort.

EAT system simulation results show that all system variants are able to comply with Euro VI emission limits. Of new technologies investigated, the Gen3 SCR catalyst, AN addition and SCR/DPF showed highest potential for further emission reduction. The trends in Figure 4 are similar for boundary conditions both of the SP A1 and of the SP A2.

## SPA4 System definition - Reference SoA and Final assessment

The aim of SPA4 was to use a vehicle simulation tool to estimate the combined CORE technology benefits for commercial vehicle efficiency. The most promising technologies from the different sub-projects SP A1, A2, A3, B1 and B2 were grouped together in compatible vehicle packages. Simulation models of the base vehicles were validated through comparison with real vehicle measurements over representative cycles. These models were then extended to include the most promising technologies vehicle packages and further simulations undertaken. The results from these simulations showed that each of these vehicle packages are predicted to achieve the proposed CORE project targets of an 11 to 18 percent fuel consumption reduction from the Euro VI vehicle configuration. In the following paragraphs the activities inside SP A4 will be described in a little more detail.

The sub-project was split into three tasks as described briefly here:

- Task A4.1.1 - Definition of vehicles and routes. The first activity was to define the scope of the simulation and the input data. The transport missions and the related vehicle classes determined the drive cycle to be used in simulation. A mapping of which technology improvements made in the CORE project were to be attributed to which mission and vehicle class was established to ensure that all technologies were covered.
- Task A4.1.2 - Selection of Technology Packages. The most promising technologies investigated in SP A1, A2, A3, B1 and B2 were reviewed and grouped together into compatible technology packages, for example, a high efficiency heavy duty Diesel engines for long distance trucks, a medium duty Diesel engine with electric hybridisation or a medium duty LNG engine.
- Task A4.1.3 - Validation of driveline enhancements using the simulation tool. Firstly, the simulation models were parameterized for the vehicles defined in Task A4.1.1. Data required for this purpose was obtained from the measurements in the experimental setups or from detailed component simulation in the other SPs. Secondly, the current models, which were available from the standard vehicle simulation library, were assessed. Where required, the models were upgraded to enable the simulation of selected technology packages. Finally, confirmation of project targets and, in particular, estimation of fuel consumption benefits expected from technology improvements were carried out using the parameterised and upgraded models.

At Ricardo, vehicle simulation activities have been generally conducted using the commercially available “Ricardo V-SIM” tool. V-SIM is a library of individual vehicle components, including engines, transmissions, electrical motors, energy recovery systems, vehicle platforms etc. (see a representation in Figure 32), coded in the MATLAB graphical interface Simulink. The library of components allows the construction of models of various vehicle architectures, from conventional to hybrid to full electric, and of various complexity levels. V-SIM vehicle models are ultimately used to provide accurate predictions of vehicle fuel consumption, $CO_2$, emissions and performance over any drive cycle or road condition.

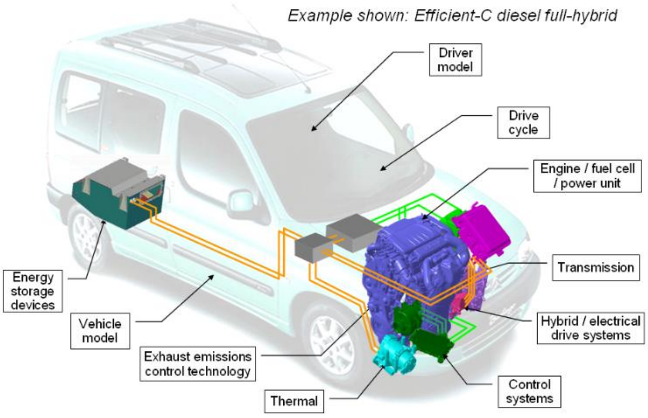



*Figure 32: Example Features included in V-SIM*

V-SIM models are forward looking models and operate as per the following computation process: a drive cycle or any other vehicle cycle is entered into the driver model; the driver model returns a torque demand from the powertrain; torque propagation is then performed between the engine - acting as the power source - and the vehicle wheels, using vehicle energy balance equations accounting for vehicle systems friction and efficiency, aerodynamic drag and road gradient. Predicted engine speed and torque are, in turn, used to calculate fuel consumption and engine-out emissions.

A common lay-out characterises each system model dealing with power generation or power transfer, i.e. all models except the driver and controller models, see Figure 33. The suite of system models allows the construction of any type of vehicle architectures, see for example Figure 34.

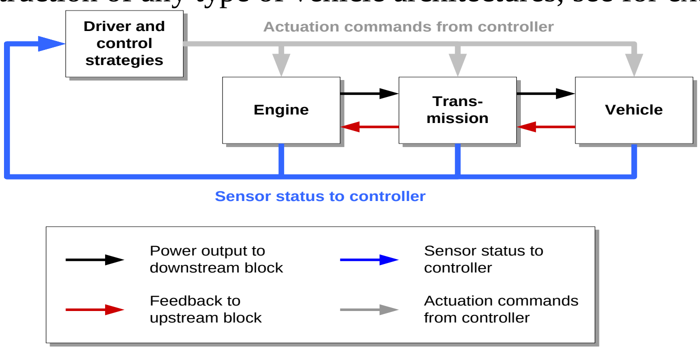



*Figure 33: Power Transfer Models in V-SIM*

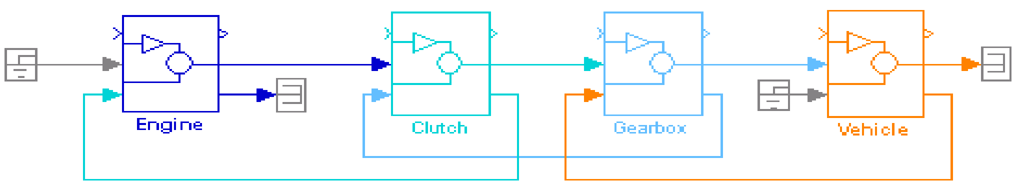



*Figure 34: Examples of Vehicle Architectures in V-SIM (Conventional Vehicle)*

Ricardo have conducted many vehicle simulation programmes, covering Diesel, gasoline, conventional, hybrid, light and heavy duty vehicles. The fuel consumption prediction methodology has been extensively validated and is extremely reliable. Any errors are found to be normally distributed, such that a standard deviation of 1.8% error is calculated, giving a 95% confidence interval for any individual simulation of ±3.5% error.

A Simulink model of each of the three partner vehicles was created using standard V-SIM component blocks. The vehicle system data included all the main vehicle components as provided by the partners. Drive cycle data,was also provided by each partner to assess the vehicle efficiency over appropriate driving conditions. Simulations were performed and the results correlated with the partner's own measurements: this ensured that the models were set up correctly and behaved as expected. In each case, there was considered to be an acceptable correlation of model output with the partner's own data.

Following validation of the baseline vehicle models, the partners discussed and agreed an exploitation plan, defining which technologies should be assessed on each vehicle, using the simulation models. The agreed combinations of technologies for each vehicle is shown in Figure.

**Matrix of technology packages for investigation in CORE (SP A4)**

| | SP A1 | SP A2 | SP A3 |
|---|---|---|---|
| | Diesel engine optimised for HEV | High efficiency diesel for long haul | Advanced combustion system for diesel and NG HD engines |
| | Daimler | Volvo | CRF |
| | Domestic long distance | International long distance | Domestic medium range |
| | 7.7 litre | 13 litre | 9 litre diesel, 8 litre NG |
| Technology explored in CORE | Downspeeding | VVA & Miller | VVA & Miller for NG SI |
| | Downsizing | Advanced combustion | VVA EGR for diesel |
| | Variable 2 stage TC (and EGR) | 2 stage TC | Advanced TC management |
| | Hybridisation | Efficient DPF | LNG technology |
| Additional technology from other SPs | Efficient DPF (from SP A1 analytical work) | | Efficient DPF (from A2) |
| | Friction reduction (from B1) | Friction reduction (from B1) | Friction reduction (from B1) |
| | High SCR efficiency (from B2) | | High SCR efficiency (from B2) |
| | | Hybridisation | Hybridisation |
| | Effects of WHR | Effects of WHR | Effects of WHR |

**KEY**

- (blue) Included in CORE engines as tested by partners in respective sub-projects
- (green) To be analysed in SPA4 with V-SIM simulations

*Figure 35: The Technology Combination Packages Considered*

A series of analyses was carried out for each vehicle, considering all the technologies of interest as defined by the partners. This led to the production of waterfall diagrams, $CO_2$ walks, for each of the four vehicles under consideration and, ultimately, to the summary waterfall diagram giving in the overall project summary above, figure 3. The individual vehicle simulation results showed that the relative benefits of each of the CORE technology depends upon the vehicle application and its duty cycle. Engine downspeeding coupled with boosting system improvements and friction reduction was seen to be beneficial in all cases. Aftertreatment technology improvement was also consistently beneficial but at a relatively small rate. The significance of the benefits of hybridisation and whether the application of VVA was beneficial was seen to be clearly engine type, vehicle and duty cycle dependent. More benefits for VVA were seen for the gas engine and when combined with the Miller Cycle for heavy duty, high load operation. Hybridisation was seen to be more beneficial for medium duty operation. The series application of the various technologies will, however, necessarily be dependent on their cost versus benefit ratio, rather than efficiency alone.

## *Potential Impact and the main dissemination activities and exploration of results*

Improvement in the engine efficiency, reduced emissions and in aftertreatment performance affect and will continue to affect air quality and consequently the health of most of European population. Economic impact of innovations in this field is always important repercussion on engine manufacturers, on truck powertrain manufacturers, and in general on the entire European manufacturing industry.

The CORE project was designed to have a direct impact on the next generation of heavy duty transport vehicles enabling them to run more energy efficiently whilst meeting future emissions standards. By developing three advanced heavy duty engine systems adapted to the OEM´s widely used vehicle configurations, and providing these on an industrial scale and commercial basis, the CORE project will have an impact on the rate of emissions from the next generation of European long distance surface transport.

The presented CORE results show a substantial reduction in $CO_2$ emissions by improved fuel efficiency in the powertrain. The different developed and analysed concepts will support the new products for introduction on the market in 2020 in long haul applications. Some of the demonstrated sub-systems or complete powertrains may be fully introduced in the future. In others applications parts of CORE technologies will be integrated into products for market introduction.

Outcome of the project revealed valuable results in the assessed hardware, component optimization in a system comprising engine, air management, aftertreatment and hybrid electric vehicle powertrain, and also in the applied methodology.

The concept of turbocharging used in CORE revealed significant improvements and shall be further investigated in other applications. The stretched mechanical limits of the engine will be investigated further through sorrow inspection of the components.

Integration of the VVA system is innovative and its main interest is related to the management of a "fast responsive" system to realize Miller cycle and internal EGR (iEGR) with very fast response during transient operations and precise dosing. This innovative system can be further optimized in future with hardware and software refinements. The potentialities of the VVA system in increasing the fuel economy were also demonstrated without throttled control to avoid pumping friction (SI engine) and in controlling the exhaust gas temperature to the EATS, which will be further enhanced in future. Nevertheless, CORE also showed that more develop work in reliability and long term operation is required for the VVA applications.

The hybrid potential exceeded the expectations in most of the investigated applications. However, as pointed out the relative benefits of each of hybridisation depends upon the vehicle application and its duty cycle. Furthermore in the cost analysis the results showed that the business case may not yet appeared in the investigated applications for long haul hybridisations. Federal incentives could accelerate the process of converting trucks to hybrid vehicles. Such incentive programs are established in other countries and known to boost the penetration of innovative but expensive technologies. Nevertheless, additional simulation studies have shown that the CORE project technologies have potential for application in other areas, such as city buses and delivery vehicles, or off-road machinery.

The developments of engine testing and simulation methods are other important outcomes from CORE. New developed simulation models applied and verified in different sub-project have been delivered. These models are already in use by partners for tomorrow's research and product development. Some of the new developed software will also progress to commercialisation and be available on the market.

Other positive outcome of CORE is the developed and applied methodology of engine-in-the-loop (EiL) techniques. The models of the powertrain components are a very useful supplement to existing simulation and emulation tools. Some challenges were found in the simulation of details of the truck operation, for example accessory power or start-stop mode, and need further investigations. It is noteworthy that such issues were also found during the development of VECTO (Vehicle Energy consumption Calculation Tool) to be used in future CO2 emission regulations. The methodology of EiL showed that a significant complexity is necessary when appropriate results are targeted. This supports the fact that the approach used in VECTO was well chosen.

In the end, the participation in the CORE project enabled beneficiaries to gain further experience, improved practices and validation information in relation to its on-going business, in particular the development of engines and vehicle powertrains for low $CO_2$ emissions. Furthermore, findings from the project helped identify some of the limits of application of those tools and the necessity for further research. By that results and knowledge from CORE will contribute to selection of technologies that later will be developed by differ OEMs as production solutions for reaching future demands.

Below a prediction where the CORE project has or will contribute in engine system efficiency :

In the short-term <2020, where steps to market introduction are taken continuously:

- Newly developed mechanical capability for higher peak cylinder pressures;
- Friction reduction associated with novel piston and ring technology.
- Improved SCR performance
- Improved DPF performance
- Turbo system improved performance
- EGR strategies
- SW for system optimisation

In the mid to long term >2020, for sub-technologies where the CORE results have shown improved fuel efficiency:

- High efficiency turbocharging systems, VTT and DST;
- Improved exhaust aftertretment giving the potential for higher raw NOx emission;
- The use of variable valves, to allow further optimisation of the engine system and enable novel application strategies.
- Hybridisation for long haul application

## *Project public website and contact details*

Website: http://co2re.eu

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## 4.2 Use and dissemination of foreground

***Section A - Public***

Table A1 below lists the scientific (peer reviewed) publications and table A2 lists other dissemination activities performed by the partners to promote the CORE project and its results.

| TEMPLATE A1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| NO. | Title | Main author | Title of the periodical or the series | Number, date or frequency | Publisher | Place of publication | Year of publication | Relevant pages | Permanent identifiers[2] (if available) | Is/Will open access[3] provided to this publication? |
| 1 | Use of an Innovative Predictive Heat Release Model Combined to a 1D Fluid-Dynamic Model for the Simulation of a Heavy Duty | M. Baratta | *SAE Paper* | 2013-24-0012 | SAE Int. J. Engines 6: doi:10.4271 | *USA* | *2013* | | | no |

[2] A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication (link to article in repository).
[3] Open Access is defined as free of charge access for anyone via Internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Diesel Engine | | | | | | | | | |
| 2 | *Model Based Exhaust Aftertreatment System Integration for the Development and Calibration of Ultra-Low Emission Concepts* | *S. Adelberg* | *SAE Paper* | *2014-01-1554* | SAE | USA | 2014 | | | no |
| 3 | *Potential Of The Variable Valve Actuation (VVA) Strategy On A Heavy Duty Cng Engine* | M. Baratta | | *ASME Paper No. ESDA2014-20217* | ASME | Europe | 2014 | | | no |
| 4 | Combined Effects of Late IVC and EGR on Low-load Diesel Combustion | J.Sjöblom | *SAE Paper* | 2014-01-2878 | SAE<br><br>Fuels & Lubricants | Europe | 2014 | *SAE Int. J. Engines* 8(1):60-67 | | no |
| 5 | *Enhancing the Low-T NH3-SCR Activity of a Commercial Fe-Zeolite Catalyst by NH4NO3 Dosing: an Experimental and Modeling Study", Emission Control Science and Technology* | *E.Tronconi* | Springer | *Volume 2, Issue 1* | Springer | Worldwide | 2016 | *p1-9,* | | no |
| 6 | *A system simulation study of the Enhanced-SCR reaction* | V.Storts | submitted for publication | | | | 2016 | | | |

| TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| NO. | Type of activities[4] | Main leader | Title | Date/Period | Place | Type of audience[5] | Size of audience | Countries addressed |
| 1 | Publication | V.Storts IAV | Internal newspaper at IAV | March 2012 | IAV internal | Industry | 5000 | Worldwide |
| 2 | Workshop | J.Engström Volvo | EUCAR Fuel and Powertrain Board meeting, oral presentation | June 2012 | EUCAR, Brussels, Belgium | Industry, automotive OEM | 25 | Europe |
| 3 | Workshop | J.Engström Volvo | Ulysses meeting, oral presentation | September 2012 | JRC, ISPRA, Italy | Industry, automotive, Policy makers | 30 | Europe |
| 4 | Conference | J.Engström Volvo | EUCAR, Poster presentation, | November 2012 | Brussels, Belgium | Industry, automotive, Policy makers | 100 | Europe |
| 5 | Publication (Magazine) | J.Engström Volvo | Government Pan European Networks, issue 4 | November 2012 | Europe | Industry, Scientific Community, Policy Makers | 2000 | Europe |
| 6 | Conference | V.Storts IAV | Int. Forum on Measurements & | May 2013 | Varese, Italy | Scientific Community, | 50 | Italy, Europe |

[4] A drop down list allows choosing the dissemination activity: publications, conferences, workshops, web, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters, Other.

[5] A drop down list allows choosing the type of public: Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias, Other ('multiple choices' is possible).

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Monitoring CO2 emissions HDV, oral presentation | | | Industry | | |
| 7 | Publication (Magazine): | J.Engström Volvo | Government Pan European Networks, issue 6 | May 2013 | Europe | Industry, Scientific Community, Policy Makers | 2000 | Europe |
| 8 | Conference | E.Tronconi POLIMI | 3rd International Symposium on Modeling of Exhaust-Gas After-Treatment<br><br>MODEGAT III | September 2013 | Bad Herrenalb/ Karlsruhe, Germany | Industry, Scientific Community, | 200 | Europe, (Worldwide) |
| 9 | Conference | C. Such Ricardo | ATZ Live conf.-HD on and off highway engines, oral presentation | November 2013 | Ludwigsburg, Germany | Industry | 500 | Europe, (Worldwide) |
| 10 | Conference | J.Engström Volvo | EUCAR, Poster presentation, | November 2013 | Brussels, Belgium | Industry, automotive, Policy makers | 100 | Europe |
| 11 | Workshop | J.Engström Volvo | Ulysses final meeting, oral presentation | November 2013 | Brussels, Belgium | Industry, automotive, Policy makers | 30 | Europe |
| 12 | Ph.D. Thesis | F.Marchitti POLIMI | Study of new NH3-SCR deNOx technologies for long haul applications | March 2014 | Milan Italy | Scientific Community, | 20 | Europe |
| 13 | Conference | S. Adelberg Umicore | SAE World Congress | April 2014 | Detroit USA | Industry, Scientific Community | 200 | Worldwide |
| 14 | Conference | J.Engström Volvo | 5th TRA, poster | April 2014 | Paris, France | Industry, Scientific Community, Policy Makers | 2000 | Europe |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 15 | Conference | C. Such Ricardo | 5th TRA, oral presentation | April 2014 | Paris, France | Industry, Scientific Community, Policy Makers | 100 | Europe |
| 16 | Workshop | E.Tronconi POLIMI | CLEERS, oral presentation | May 2014 | Dearborn, USA | Industry, Scientific Community, | 100 | USA |
| 17 | Conference | V. Storts IAV | JSAE Annual Congress, oral presentation | May 2014 | Yokohama, Japan | Industry, Scientific Community, Policy Makers | 500 | Japan (Worldwide) |
| 18 | Conference | M.Baratta POLITO | 12th Biennial Conference on Engine system Design & Analysis, oral presentation | June 2014 | Copenhagen, Denmark | Scientific Community, | 200 | Europe |
| 19 | Conference | V. Storts IAV | 5th MinNox, oral presentation | June 2014 | Berlin, Germany | Industry, Scientific Community, | 200 | Europe |
| 20 | Conference | V. Storts IAV | 5th MinNOx, poster | June 2014 | Berlin, Germany | Industry, Scientific Community, | 200 | Europe |
| 21 | Conference | I. Nova POLIMI | Int. Conf. on Environmental Catalysis, oral presentation | August 2014 | Asheville, USA | Industry, Scientific Community | 300 | Worldwide |
| 22 | Conference | V. Storts IAV | SAE HD Emissions Control | September 2014 | Goteborg, Sweden | Industry, Scientific Community, Policy Makers | 300 | Europe |
| 23 | Conference | E.Tronconi POLIMI | Int. Symposium on Chemical Reaction Engineering, oral presentation | September 2014 | Bangkok, Thailand | Industry, Scientific Community | 300 | Asia |
| 24 | Conference | F.Marchitti POLIMI | SCI 2014 | September 2014 | Rende, Italy | Scientific Community, | 500 | Italy |
| 25 | Workshop | J.Engström | EUCAR Fuel and | September 2014 | EUCAR, | Industry, | 25 | Europe |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Volvo | Powertrain Board meeting, oral presentation | | Brussels, Belgium | automotive OEM | | |
| 26 | Conference | J.Sjöblom Chalmers | SAE, Fuels and Lubricants, oral presentation | October, 2014 | Birmingham, United Kingdom | Industry, automotive OEM | 400 | Europe (Global) |
| 27 | Conference | J.Engström Volvo | EUCAR, Poster presentation, | November 2014 | Brussels, Belgium | Industry, automotive, Policy makers | 100 | Europe |
| 28 | Conference | C.Such Ricardo | ATZ Live conf.-HD on and off highway engines, oral presentation | November 2014 | Saarbrucken, Germany | Industry | 500 | Europe, (Global) |
| 29 | Workshop | J.Engström Volvo | ERTRAC meeting | June 2015 | Brussels, Belgium | Industry, Scientific Community, Policy Makers | 50 | Europe |
| 30 | Conference | A.Noble Ricardo | Delphi Int. Conf. and Exhibition - Commercial Vehicles | April, 2015 | Gillingham, United Kingdom | Industry, Scientific Community, | 100 | Europe |
| 31 | Conference | E.Tronconi POLIMI | 4th International Symposium on Modeling of Exhaust-Gas After-Treatment<br><br>MODEGAT IV, oral presentation | September 2015 | Bad Herrenalb/ Karlsruhe, Germany | Scientific Community, | 100 | Worldwide |
| 32 | Conference | E.Tronconi POLIMI | XII European Congress on Catalysis, oral presentation | September 2015 | Kazan, Russia | Scientific Community, | 200 | Worldwide |
| 33 | Workshop | J.Engström Volvo | EUCAR Fuel and Powertrain Board meeting, oral | September 2015 | EUCAR, Brussels, Belgium | Industry, automotive OEM | 25 | Europe |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | presentation | | | | | |
| 34 | Conference | A.Banks Ricardo | IRTE | September 2015 | Nottinghamshire United Kingdom | Industry, Scientific Community, Policy Makers | 250 | United Kingdom |
| 35 | Conference | T. Grigoratos JRC | SAE, ICE | September 2015 | Naples, Italy | Industry, Scientific Community, Policy Makers | 200 | Europe |
| 36 | Conference | M. Baratta POLITO | SAE, ICE | September 2015 | Naples, Italy | Industry, Scientific Community, Policy Makers | 200 | Europe |
| 37 | Conference | V.Storts IAV | CAPoC, oral presentation | October 2015 | Brussels, Belgium | Industry, Scientific Community, | 200 | Worldwide |
| 38 | Master Theses | D. Brambilla A.Donadel POLIMI | Experimental study of the SCR reactions with co-feed of a NH4NO3 solution over Cu and Fe-zeolite commercial catalysts | October 2015 | Milano, Italy | Scientific Community, | 50 | Europe |
| 39 | Conference | J.Engström Volvo | EUCAR, Poster presentation, | November 2015 | Brussels, Belgium | Industry, automotive, Policy makers | 100 | Europe |
| 40 | Conference | S.Edwards Ricardo | $6^{th}$ TRA, poster | April 2016 | Warsaw, Poland | Industry, Scientific Community, Policy Makers | 2000 | Europe |
| 41 | Conference | J.Engström Volvo | $6^{th}$ TRA, oral presentation | April 2016 | Warsaw, Poland | Industry, Scientific Community, Policy Makers | 100 | Europe |