NICE Publishable Final Activity Report

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IP Co-ordinator	Frank Otto, DaimlerChrysler AG
EC project officer	Maurizio Maggiore, European Commission

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Content

1 Section 1 - Project objectives and major achievements

The integrated project NICE ("New Integrated Combustion System for Future Passenger Car Engines") has been part of the framework program 6 (FP6) of the European Commission. It lasted from January 2004 until March 2008. 29 partners have been participating in this project, including 6 OEMs (Daimler, Fiat, Ford, Renault, Volkswagen, Volvo), 5 suppliers, 5 research institutes and 13 universities from 8 countries. Daimler has been the project co-ordinator. The total project budget amounted to 26,3 M€, 14,5 M€ of that have been funding from the EC.

1.1 General project objectives

At the beginning, the vision of the NICE project was one single combustion system at the horizon, to be reached in the subsequent framework programs 8 and 9, and it was expected that a convergence towards this single system would occur in the future. During the project, however, this vision has changed: now, it is mainly assumed, that there will possibly be a convergence concerning several components and technologies like turbocharging or direct injection, but a total fusion within one single concept will not occur. In contrary, future could become even more various. According to this szenario, even the number of different gasoline and diesel engine concepts would increase, depending on local markets incl. local legislation and incentive politics. Furthermore, new fuels get onto the scene, natural gas being only one of them, but also several biogenic fuels could arise.

Therefore, the overall objective of NICE now consists in the development of different integrated combustion systems (now in plural), for different types of fuel (gasoline, diesel, compressed natural gas, synthetic biomass-based fuels), which are able to achieve the excellent fuel conversion efficiency of a cutting-edge DI diesel engine while complying with very low future emission levels (i.e., in the mean time, EU6).
However, the concrete objective has to be specified according to the type of fuel:

- For a gasoline engine, improving fuel economy while keeping low emission levels is the major goal. This may be achieved by introducing new technology components like direct injection, downsizing by turbocharging and variable valve train.
- For diesel engines, an important and challenging task consists in improving the emission levels (towards EU6) with no loss in fuel economy when compared to a current EU4 engine, at affordable cost increase.
- CNG (compressed natural gas) engines already exhibit very low CO_2 emission levels. Besides further reducing fuel consumption, a major task consists in making such engines more attractive by modern engine technologies (e.g. turbocharging) in order to enable an increased market share of such engine concepts.
- Biofuels made from renewable biomass are already an efficient mean for reducing CO_2 emissions. Second generation biofuels, however, offer additional potentials by designing dedicated engines for tailored biofuels. These potentials can be used in order to improve fuel economy as well as to reduce system cost (f.i. aftertreatment), especially when applied for fulfilling EU6 emission standards in a diesel-like combustion process.

In order to address these topics, the NICE project consisted of four sub-projects:

- **A1:** Enlarged HCCI (Homogeneous Charge Compression Ignition) diesel combustion process under transient operation (OEM: Renault)
- **A2**: Compressed / spark ignited variable engines, incl. a new diesel-type combustion system for tailored biomass-based fuels (OEMs: Fiat, VW, Daimler)
- **A3**: Future CNG internal combustion engines (OEMs: Daimler, Ford)
- **B1**: Improved CFD (computational fluid dynamics) tools and modelling (OEMs: Volvo, Daimler, Renault, Volkswagen)

1.2 Summary of Project Results

In sub-project A1, the HCCI combustion process has been extended in the engine map. It uses directly-actuated piezo injection with 2000 bar maximal injection pressure, downsizing (2l => 1,6l), very high EGR (exhaust gas recirculation) rates by low pressure (LP) EGR, high pressure (HP) EGR and internal EGR by variable outlet valve lift actuation and a model based engine control. The increase in injection pressure was a suitable measure against a rise in particle raw emissions at elevated EGR rates. Finally, there was still a soft increase in soot raw emission remaining, but at an acceptable level, which can be handled by the particle filter. The internal EGR proved to be a useful concept for cold start and for limiting HC/CO-emissions at low load conditions.

Target was the demonstration of the compliance with the EU6 emission limits without any expensive NOx aftertreatment devices (like NOx storage catalysts or urea-SCR technology). This can be considered as an important step in order to provide affordable diesel technology (with the very low CO_2 emissions of state-of-the-art diesel engines) for small-size vehicles even under the boundary conditions of the very strict EU6 emission limits. The whole concept has been evaluated not only on the test bench, but also applied in a vehicle validator (Renault Laguna).

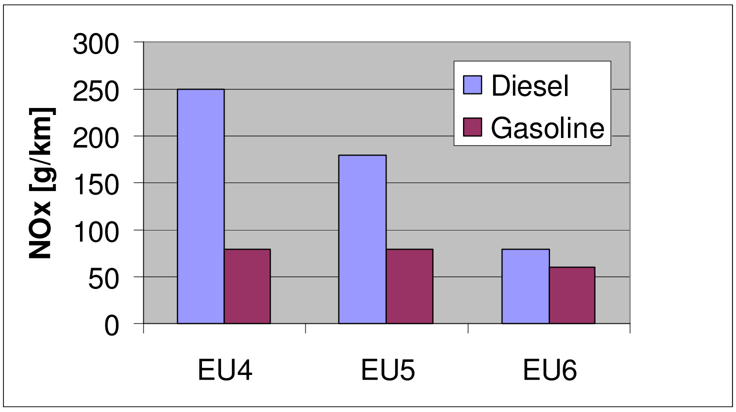


Fig.1: *NOx emission limits in EU legislation. 2014, diesel engines will face the same limit as gasoline engines today. In order to reach this target, strong efforts concerning cost and technology will be required, but also, a deterioration of fuel consumption has to be expected, in general.*

In the vehicle application, some problems with the actuation strategy of the variable valve lift occured for transient engine operation. Therefore, only a preliminary approach was implemented. The vehicle results nevertheless show a good NOx emission reduction (EU6 limit of 0,08g/km in NEDC just reached), this was achieved at an equal fuel consumption as the EU4 baseline engine. And, what is remarkable for HCCI concepts, at low HC emissions.

Only the CO emissions are just over the EU6 limit. Nevertheless, application improvement of the variable valve actuation should solve also this last remaining problem, that is what the test bench results suggest.
In addition, a supporting study of the benefits of 2-stage turbocharging has been performed.

In sub-project A2, a downsized (1.4l swept vol.) turbocharged spark ignited gasoline engine with an variable valve lift concept, achieved by electro-hydraulic valve actuation technology, has been set up ("technology way 2" in the subsequent detailed report). During the project, different variants of cylinder head, ports and piston shapes have been evaluated.
The final engine concept shows an improvement in the fuel economy of more than 20% vs. the baseline engine (2.0l swept vol.), when operated in a compact car.
The electro-hydraulic valve actuation ist mounted on the intake side and offers the option for different strategies like "Early intake valve closing" (EIVC), but also "Late intake valve closing" (LIVO) or combined strategies for fuel consumption issues in low and medium load range, for improving cold start and for an better built-up of low-end torque.
The performance data of the downsized 1,4l engine are 119kW@5500rpm and 210Nm @1800rpm.

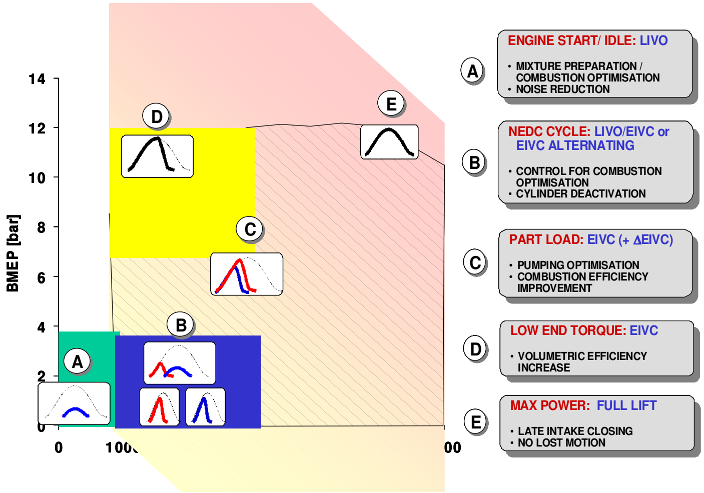


Fig.2: *The electro-hydraulic valve actuation system (NICE A2) can be used for fuel economy issues as well as for low-end torque built-up or an improved cold start behaviour*

As could be seen with the above-mentioned concept, downsizing is an efficient measure for achieving good fuel economy. It should, however, not too simply be realized by combining a large turbocharger and a small engine. This would result in a strong turbo lag, since such a large turbocharger would built up pressure for charge delivery and, therefore, torque with a huge delay when accelerating from low engine speed ranges.
In the previous concept, the downsizing was assisted by suitable valve actuation strategies. A second technology concept addressed in sub-project A2 (within "technology way 1" of the subseq. rep) acts directly at the turbocharger (DOT, "delay optimized turbocharger"): An innovative turbocharger prototype with fast response has been developed. Instead of a throttle, there is an axially variable compressor. During low engine load (when the engine requires throttled operation) the compressor wheel may act as cold air turbine. Then, air is expanded, not compressed. The energy is converted into turbocharger rotation speed. Instead of 10.000 rpm, a turbocharger speed of 60.000 rpm can be achieved for the engine operation point 2 bar bmep/ 1500rpm. Such a turbocharger is able to build up torque much faster when a respective request is transmitted. Therefore, it may be used as an efficient tool for a strong downsizing step.

As a further technology concept within sub-project A2 (also within "technology way 1"), a single-cylinder study of gasoline direct injection and lean homogeneous operation in the whole engine map has been performed. Due to peak pressure restrictions, only 11-12 bar bmep could be realized. The design of the combustion chamber was optimized, tumbling charge motion turned out to be favorable. For direct injection, a centrally mounted piezo-actuated injector was the optimum.
Including the downsizing effect from 65 kW/l to 90 kW/l (this corresponds a downsizing from 2l to 1,44l), a reduction in fuel consumption of -16% (stoichiometric operation) and -25% (lean homogeneous operation) have been found. However, it is evident that these impressive numbers will not survive completely when applying transient operation in a real multi-cyl. engine and NOx aftertreatment with its specific requirements for heat management and regeneration events.
The original idea of fulfilling emission limits without specific NOx aftertreatment devices for lean conditions could not be validated, lean NOx aftertreatment turned out to be necessary. The typical emission level was in the range of the limits for EU4 diesel engines (250 mg/km NOx), i.e. about three times more than the EU4 limit for gasoline engines (80 mg/km NOx), and four times more than the EU5/6 limits (60 mg/km NOx).
The optimal configuration with centrally mounted piezo-actuated injector would also allow stratified operation (spray-guided configuration). This would generate a further 5% benefit in fuel economy, but also imply doubled NOx emissions (i.e. about 500 mg/km).
Finally, in A2, a new combustion system for tailored biomass-based fuel based on a diesel-type engine concept has been designed ("technology way 3"). Various types of fuels have been evaluated. The best one was found to be a synthetic kerosene-type fuel. Potential for EU5 without particulate filter was demonstrated, and also compliance with EU6 without NOx aftertreatment devices is not out of range. In addition, engine control strategies beneficial for such a concept have been pointed out; these are a closed-loop combustion control, lambda control, and a fuel detection resp. a closed-loop torque control (in order to deal also with changing fuel qualities).

In sub-project A3, three innovative turbocharged monovalent (increased compression ratio) CNG engine concepts have been developed, two of them have been applied in a vehicle validator. All concepts are working with stoichiometric and lean combustion.
Concept 1 ("technology way 1" in the subsequent detailed report) applies CNG direct injection, and, therefore, is also able to operate with stratified combustion. Homogeneous stoichiometric, homogeneous lean and stratified lean combustion have been examined for part load conditions. At first, an DMI (direct mixture injection, well-known for gasoline-air mixture injection in the past) injector from AVL as a prototype has applied for testing purposes, later a new piezo injector (double piezo stack, hydraulic stroke transformer), which has also been designed within the NICE project by Siemens CT, was used. Strong benefits in fuel economy could be achieved, for turbocharged/monovalent/stoichiometric operation versus the baseline engine (supercharged/bivalent/stoichiometric) 9% less fuel consumption in the NEDC, for turbocharged/monovalent/stratified charge (lean) additional -16% in fuel consumption (any downsizing effect not yet included). Furthermore, an increase of low-end torque by gas injection after intake valve closing was observed (ca. 8% at 2000rpm). Additionally, direct injection enables scavenging, i.e. a large overlap of intake valve and outlet valve opening phase during gas exchange top dead center, since no combustible mixture reaches (and destroys) the catalyst when gas is injected only after outlet valve closing. Such a scavenging flow, however, is suited to increase strongly the low-end torque.

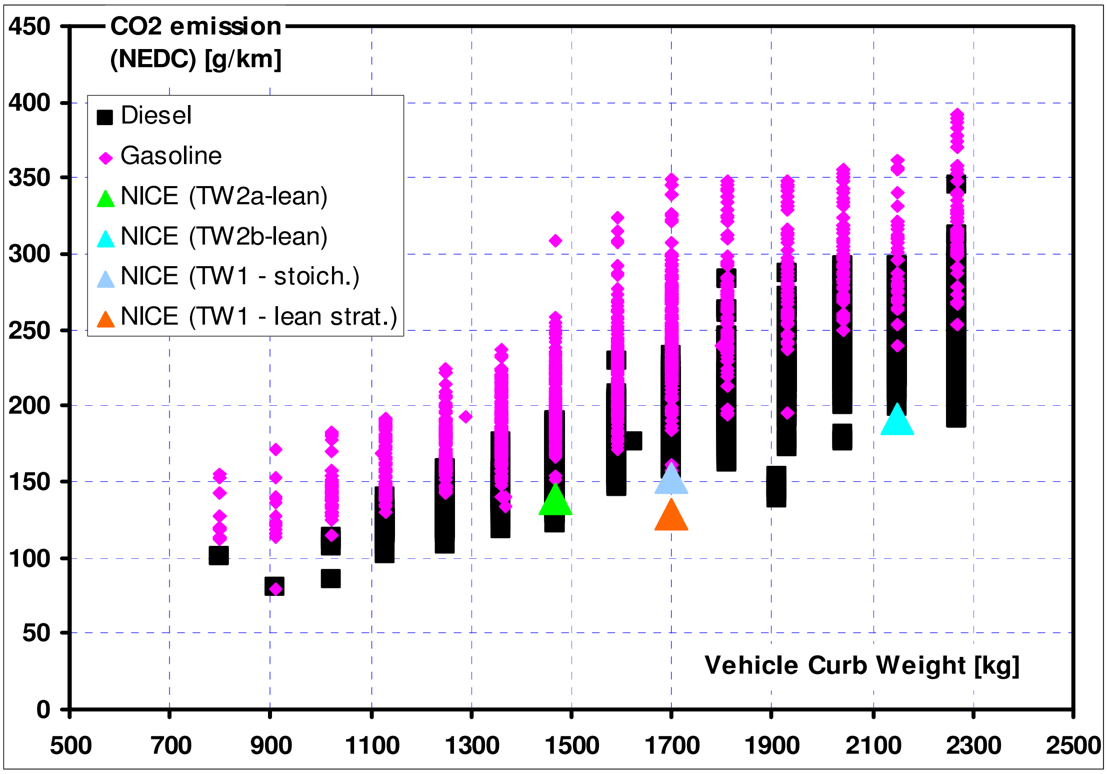


Fig.3: *CO_2 emissions of NICE A3 future CNG engine concepts; all three are at the level or even better than best-of-class diesel engines. In the presented version, the results are, however, not fulfilling hydrocarbon EU emssion limits and not including lean NOx aftertreatment which is required for the lean operation cases.*

Concept 2 ("technology way 2a") is defined by port gas injection and monovalent turbocharged operation. The engine is based on a gasoline engine. In part load, lean as well as stoichiometric operation have been applied. The concept was demonstrated in a Ford Focus C-MAX vehicle validator. Concerning CO_2 emissions, very good results have been found, at best-of-class diesel engine level.

Concept 3 ("technology way 2b") includes port gas injection and monovalent turbocharged operation. In difference to concept 2, however, the engine geometry has been based on a diesel engine. For the whole engine map, lean operation was applied. In order to guarantee a sufficiently high burning rate even for very lean mixtures (onle very little NOx generation!), a specific combustion chamber and piston design was performed (ATAC - advanced turbulence assisted combustion). Because of low exhaust gas temperatures under full load, the VGT turbocharger from the baseline diesel engine could be kept. Again, this concept was demonstrated in a vehicle. The fuel economy of the vehicle was excellent, better then best-of-class diesel engines. The power output was not totally satisfying, but this was due to the not optimally adapted turbocharger size.

For all concepts, it was found, that for use of the full CO_2 reduction potential, lean operation with special NOx aftertreatment devices in order to fulfil emission limits is required. As already mentioned during the discussion of subproject A2, it has to be expected that introduction of lean NOx aftertreatment would cause some deterioration of the CNG consumption figures.

Moreover, all these concepts show difficulties to comply with the European HC (hydrocarbon) emission standards (EU4 as well as EU5 or EU6), since they show quite high methane emissions, the dominant component of natural gas. Methane is a major emission from agriculture and woods, but not a pollutant/poison like other hydrocarbons.

Nevertheless, in European legislation, methane contributes to the HC or THC ("total hydrocarbon", in EU6 standard) emissions. This is different to the US legislation, where methane counts as a green house gas (as it is) but not as a pollutant. With European legislation standards, however, new aftertreatment concepts for future CNG engines are required; otherwise, at least the lean operation concepts cannot be realized.

In total, six new engine concepts have been demonstrated as hardware within NICE. Three of them are integrated in a vehicle. Nearly all of the different technology paths pursued in the NICE project have been proven to be successful.

In subproject B1, advanced simulation tools for diesel and biomass-based diesel-type fuels (like kerosene) have been developed. First, the new combustion concepts investigated in NICE like HCCI or high EGR combustion require special modeling. Second, models have to be extended to the new biogenic fuels, this includes the calculation of adapted libraries, f.i. The models were developed by code-developers and universities, and later transfered and validated by the OEMs.

1.3 Conclusions and outlook

As already mentioned, from the integrated project NICE, it can be concluded that, concerning engine technology, there is not only one single path into future, but several ones.

On the gasoline side, significant improvements concerning fuel economy are possible, especially by concepts based on turbocharging plus downsizing. This combination is the major enabler. String downsizing from 2l => 1,4l may achieve up to 15% reduction in fuel consumption. First downsizing concepts can already seen on the market, further ones will follow soon.

Turbocharging, however, can not only be realized by a combination of a large turbocharger with a small engine, this would generate a strong turbolag. Downsizing has to be moderate, or it has to be supported by special turbocharging agility concepts like DOT ("delay optimized turbocharger", concept in NICE A2). Other (more common) concepts which aim at a fast response turbocharging are the variable turbine or 2-stage turbocharging. Increased agility of the turbocharger may also be supported by other technologies like gasoline direct injection or variable valve actuation (what has been done in NICE A2 by electro-hydraulic valve actuation; a large downsizing step was enabled).

Any further request on progress in fuel economy, however, cannot be fulfilled by moderate downsizing only. Consequently, in NICE, combinations with additional fuel economy techno-logies have been examined: turbocharging/downsizing & variable valve actuation, turbocharging/downsizing & direct injection/lean operation/lean NOx aftertreatment. With such technology packages, fuel economy advantages of 20%, when compared to a state-of-the-art gasoline engine and taking into account losses due to real aftertreatment operation, seem to be reachable. Other options are advanced turbocharging/strong down-sizing.

There are further fuel economy technologies not included in NICE: besides the already mentioned high-agilty turbocharging concepts (variable turbine, 2-stage turbocharging) there have to be mentioned: start-stop (<3% advantage in fuel economy), external EGR (especially interesting for stratified charge operation and high-load performance), and the not yet well-developed concepts of variable compression ratio (interesting for combination with turbo-charging) and combustion-pressure-sensoring-guided engine control (together with variable valve actuation on inlet and outlet valves, the last-mentioned two concepts are also the enabler for controled auto-ignition (CAI), a compression-ignited lean gasoline combustion). Of course, also combinations of more than two technology components are possible, like in the last example (CAI). But all these technology combinations strongly increase cost and complexity, and only slowly increase fuel economy, because the different fuel economy measures act on the same mechanisms, like dethrottling, lean operation and shift of operation point.

For diesel engines, however, the first task is to fulfil the challenging EU6 emission targets without increase in CO_2 emissions. Technology concepts are not as varying as on gasoline side: advanced high-EGR concepts (including low-pressure EGR and residual gas retention), advanced turbocharging concepts like 2-stage turbocharging, downsizing and advanced injection concepts (piezo-actuated, increased injection pressure) It can be concluded from NICE that, using these concepts, it may be possible to fulfill EU6 emission limits without NOx-aftertreatment and without deterioration in fuel consumption, with reference to state-of-the-art EU4 engines, at least for smaller and medium-sized vehicles. This is an important and impressive result, even and especially under CO_2 aspects, since the requirement of NOx aftertreatment would make such vehicles that expensive that their market share would, at least, strongly shrink. This, of course, would be counter-productive in terms of CO_2 emission!
For larger vehicles (SUVs, for example), NOx aftertreatment seems to be indispensible. Combining NOx aftertreatment with the above-mentioned engine technologies (advanced EGR, advanced turbocharging, advanced injection) for medium-sized (and small) premium vehicles, it seems to be possible to get some fuel economy advantage (< 4%), but this has not been examined within NICE.

For CNG engines, monovalent concepts plus turbocharging are very attractive, and generate an excellent CO_2 emission level. Turbocharging offers not only the option for downsizing, but also the chance to increase torque and power, which are the typical deficits of an CNG engine. Therefore, this means a large progress towards attractivated CNG engines, an important step for increasing the market share. When applying stoichiometric operation, CO_2 emissions of the level of best-of-class-diesel are possible, with lean operation even better ones. Full potential can only be achieved with stratified lean operation. However, NOx aftertreatment should be considered when applying lean operation; otherwise, fuel economy advantages cannot be realized, or are, at least, very limited.
In all cases, HC emissions (mainly methane) are most critical. Methane is a stable molecule, the catalyst lightoff occurs at a temperature > 400°C. Typically, all fuel economy measures reduce the exhaust gas temperature: the combination turbocharging & increased compression ratio seems already to be very critical (even for high-load-of-precious-metal catalysts), lean operation may offer no chance to fulfill the limits. A progress in aftertreatment is strongly required, or, alternatively, a change in legislation (no counting of THC (total hydrocarbons) any longer, only NMHC (non-methane hydrocarbons, like in US). Otherwise, realizing lean operation seems to be very difficult!

As impressive as the NICE results are, it has to be concluded that these concepts are not sufficient to fulfill the currently discussed CO_2 emission demands in total.
Let us assume that

- all gasoline engines would get a "NICE" package, i.e. one of the following technology packages:
    - turbocharging/downsizing & variable valve actuation (phasing + lift!)
    - turbocharging/downsizing & direct injection & lean NOx-aftertreatment
    - advanced turbocharging/strong downsizing

- this would lead to an average CO_2 advantage of about -20%, relatively to a state-of-the-art gasoline engine (incl. cam phasing)
- all diesel engines would get a "NICE" package, i.e. a combination of advanced EGR, advanced turbocharging/downsizing and advanced injection technologies, without any NOx aftertreatment
- this would be the enabler for fulfilling EU6 without deterioration in fuel economy (±

It should be clear that these are very strong, optimistic propositions! Starting from an average CO_2 emission of 160g/km, and estimating the gasoline:diesel distribution as roughly 50:50, we would get an average CO_2 reduction rate of 10%, resulting in an average CO_2 emission of 160*0,9 g/km = 144 g/km. This, by far, does not meet current CO_2 requirements of the European Commission (120 -130 g/km in 2012/2015) and, at all, not the requirements beyond.

Further measures seem to be necessary. As far as engine technology is concerned, the addition of further fuel economy components like variable compression ratio or NOx aftertreatment for diesel engines or the creation of larger technology packages may result in a few additional percents of gain of fuel economy, at strongly increased cost. Since cost of different components do not only add up, even the increasing complexity of interaction will cause additional cost. On the other hand, as already explained, fuel economy increases at a much smaller rate, due to the fact that many fuel economy measures act in the same or at least a similiar manner (one engine can be dethrottled only once).

Therefore, a strong further increase in engine efficiency may only be achieved by an extremely expensive overall hybridisation roll-out.

2 Section 2 – Objectives, work and results of the Subprojects

The following section should include a description of subproject objectives, contractors involved, work performed and end results, elaborating on the degree to which the objectives were reached. The section briefly describes the methodologies and approaches employed and it relates the achievements of the subproject to the state-of-the-art. It should explain the impact of the project on its industry or research sector. It includes, if available, diagrams or photos illustrating the work of the project, a project logo and a reference to the project website.

2.1 Subproject A1

2.1.1. Objectives

Subproject A1 addresses enlarged Homogeneous Charge Compression Ignition Diesel combustion. The purpose is to improve the emission levels of a diesel engine toward EURO6 with no loss in fuel economy compared to a EURO4 current engine. Cost increase must stay reasonable hence the technical solutions have been chosen to avoid using costly NOx after treatment. A wide range of work has been carried out from better understanding the combustion with numerical, optical and dedicated testing facilities to the building and calibration of a demonstrator vehicle. As the final product, the vehicle is equipped with the selected technologies integrated in a multi-cylinder engine using HCCI combustion principle on a wide range of operation (at least NEDC cycle) and fully capable of being driven.

2.1.2. Contractors Involved

BU (Brunel University)	Visualisation of air / fuel mixture formation in HCCI
Delphi	Fuel injection system and engine management system design, engine and vehicle calibration
IFP (Institut Français du Pétrole)	Optimisation of injection parameters to HCCI
Mechadyne	Variable valve actuation system
Renault	Design of single & multi-cylinder engines, vehicle hardware integration
UPVLC (CMT)	Cold start and turbocharger

2.1.3. Work Performed

- **Concept Specifications to Overcome HCCI Technical Barriers**

Renault and IFP have analyzed the HCCI know-how & barriers based on previous results, the analysis of state of the art and the use of 0D simulation.

The output is the definition of preliminary multi-cylinder HCCI specifications, especially concerning VVA, air loop circuit and EMS features.

The NADI (Narrow Angle Direct Injection) combustion system has been selected to start several investigations concerning mixture formation on HCCI and full load performances using CFD calculations. They were performed to understand the effects of multi-injections with high cooled EGR rate and give some orientations not only based on quantitative results but also on physical analysis along the injection-combustion and expansion phases. In addition to the classical NADI concept with a bowl tip angle of 70°, a range of bowl tip angle from 90° to 110° as well as the bowl aspect ratio and the spray angle influence were considered.

Tests on single-cylinder engine have been compared to the calculations results and showed quite good matching: the CFD calculation offered good support to perform engine tests and to understand phenomena due to high cooled EGR rates used with multi injection strategy.

The NADI combustion chamber was characterized at UPVLC and compared with a more classical chamber geometry. Due to its design, there's an early spray/wall interaction whose consequences on the mixture formation and combustion process development are interesting to be explored. On the one hand, it was observed that:

- The effect of injection pressure is the same as the one observed in a free spray: the higher the injection pressure, the farther (along the spray path) the ignition takes place (this is viewed looking at the region containing CH-radical). On the other hand, the higher the injection pressure, the shorter the ignition delay (this result is already "classic").
- The effect of nozzle size is observed to be also the same as for free sprays: the greater the nozzle diameter, the nearer to the nozzle the ignition takes place. On the other hand, the ignition delay increases significantly, which can be due to a higher evaporation rate, which reduces local temperature.

On the other hand it was observed that the wall cooling effect seems to be responsible for the greater ignition delay and the displacement downstream of the ignition zone (region containing CH-radical, as shown in Figure 1). Both results were obtained when comparing the NADI chamber geometry to a classic one. This result will surely have consequences on the pollutant produced during the combustion process.

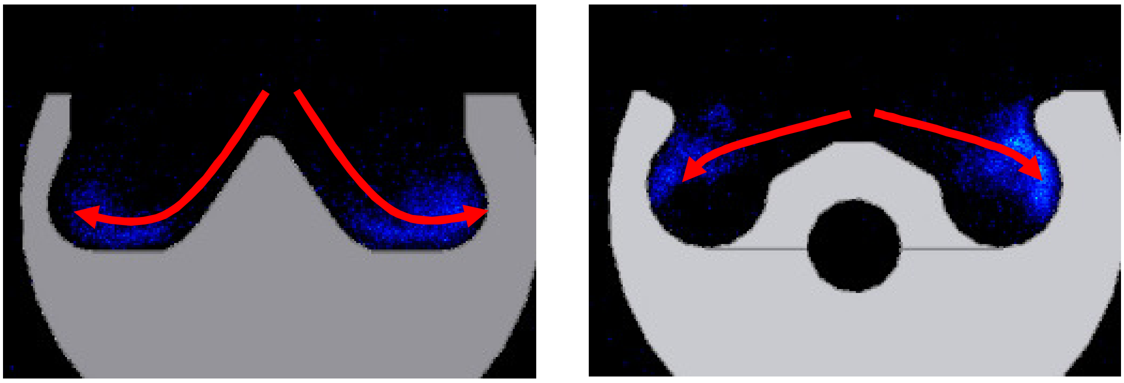


Figure A1.1: CH-radical images taken at 835 μs after the start of the electrical pulse for the 1200 bar and 264 cc/min case. Left – NADI chamber. Right - Classic chamber.

An optical engine was used at Brunel University to study the mixing and combustion process for HCCI combustion using the NADI system. As early injections are required for the formation of a homogenous mixture, multiple injection strategies were utilised to reduce wall wetting and improve mixing. Eight different injection strategies were formulated consisting of two three-injection strategies and six four-injection strategies.

The use of three-injection strategies resulted in excessive surface wetting leading to poor fuel/air mixing and subsequent combustion. Further investigation of these strategies was thus not carried out.

Results with four-injection strategies were more varied, ranging from very poor combustion to achieving near-HCCI combustion. In many cases a modified combustion process emerged consisting of four discernible phases, a mixture of pre-reactions, premixed and diffusion combustion.

The difficulty of creating a homogenous mixture is made more difficult in an optical engine by the lack of the ability to optimise injection strategies. The use of a flat piston window rather than a NADI geometry window further compromised the mixing and combustion process, nevertheless combustion approaching HCCI was achieved with some strategies.

On the single-cylinder engine, first evaluations with a 120° bowl tip angle and a 95° spray angle combined to the Delphi innovative fuel injection system, with piezo-direct injector, have shown very interesting results in terms of output power reached at 1500 and 4000 rpm full load. The engine testing phase on single cylinder was continued with a new piston bowl geometry designed by Renault, named H-WAB for Homogeneous Wide Angle Bowl. This combustion chamber configuration allows to keep high full load performance targets at 1500 and 4000 rpm with a significant reduction of the injector flow rate; it leads to better results at part load in terms of pollutant emission levels with a short time separation in a double event injection strategy.

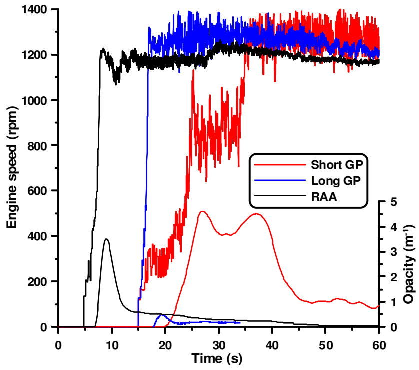
At last, very low engine loads were investigated with the Delphi injectors in order to reduce the HC and CO emissions, taking into account the very low exhaust temperature level on these working points. Moreover, high engine loads operated in HCCI were also investigated in order to improve their fuel consumption levels, and thus to enlarge the engine operating range usable with very low NOx.

A work was operated to evaluate the influence of a very high intake pressure increased from 1.9 bar to 2.5 bar at 1500 rpm, 8 bar IMEP. On the one hand, with higher intake pressure, ignition delay is reduced thanks to better in-cylinder conditions of pressure and temperature. The SOI could be optimized to get best combustion timing and the cycle efficiency is improved: ISFC decreases by 8 % at the limit of HCCI zone with the same level and NOx criteria (0.1 g/kWh). On the other hand, it allows to estimate the potential on HCCI zone extension : for a same ISFC criteria (230 g/kWh), IMEP could reach 9 bar instead of 8 bar and this limit could not be overtaken because of high smoke level due to important equivalence ratio obtained by EGR adaptation.

Cold starting is a key issue of HCCI engines. Assessment has been performed at UPVLC with the aim of establishing the compression ratio for cold starting, the definition of air heating and injection strategies, and to validate these strategies through engine tests in climatic chamber.

The compression ratio specification was carried out through the estimation of the thermal power required in intake air to achieve the threshold temperature of fuel self-ignition. The threshold temperature estimated by the application of a methodology developed at UPVLC was about 410÷420ºC. For the calculation of the air thermal power requirements, the estimated threshold temperature was assumed as the minimum temperature to start the fuel ignition during the cranking phase of the engine at any ambient temperature. To fulfill these requirements, an electrical air heater of ribbon resistances with very low thermal inertia was designed. The resistances were arranged so that the air flows through a parallel plates heat exchanger (see Fig. 2). The maximum heat power capability of the heater is about 1200 W at 11 V. The heat energy dissipated by the heater is controlled by a dedicated electronic control unit, which regulates the demanded energy as a function of the ambient temperature, the battery voltage and the speed of the engine (at post-heating time).
The injection and air heating strategies for proper cold starting by means of the air heating technology has been defined in base of the results obtained in the theoretical study performed during the first year of the project. These predefined strategies were refined according to the results were obtained during the validation tests.
Validation was done on 16:1 and 14:1 engine configuration at different temperatures up to -27ºC. In both engine configurations, intake air heating technology has allowed appropriating cold start at all tested temperatures, while comparable results have been obtained only with high protrusion glow plugs (see Fig. 3). Classical glow plugs (short tip length) were suitable to start only the reference engine (c.r. 16:1) at temperatures higher or equal than -23ºC. Regarding the cold start performance of the engine, engine stability after starting can be remarked as the highest benefit of air heating technology while long glow plugs seems to be more suitable for shorter starting times. Therefore, the best cold start performance of lower compression ratio HCCI engines should be expected with the optimum combination of intake air heating and glow plugs technology.

Figure A1.2 Prototype of the electrical air heater used at the inlet of the intake manifold of the engine.



	GP		Heater
	S	L	RAA
Preheating (s) (J) (A)	15 8700 88,3	15 8750 90	4,7 3000 70
Starting (s)	11	2	3,1
Postheating (W) (A)	450 44,2	439 45	298 26
Stability (rpm)	±63	±26	±14
Opacity (m^{-1})	4,62	0,45	3,5

Figure A1.3 Cold starting of 16:1 c.r. engine at –23ºC with glow plugs (short and long) and air heater

- **Multi-cylinder Hardware Design and Integration**

The multi-cylinder engine has been designed following specifications issued from single cylinder tests.
It had to bear a combustion chamber of H-WAB type with compression ratio of 16:1, a global displacement of 1.6litre and the cylinder head had to be capable of receiving the Delphi piezo

injectors and be as versatile as possible to switch from standard to variable valve actuation with minor modifications.

VLD Cylinderhead Design

The objective was to design and manufacture a prototype variable valve actuation system to facilitate a significantly expanded operating envelope for HCCI and to assist with increasing diesel engine power density. The resulting system was to be used for testing in HCCI single- and multi-cylinder engines.

Mechadyne's specific responsibility was to produce designs and drawings, based on Mechadyne's pre-existing, patented, VLD system, to allow the hardware of the VVA system to be manufactured.

Valve lift characteristics for the single cylinder engine

This part of Mechadyne's input was a contribution to the design of the VVA hardware required for Renault and IFP to complete the single cylinder engine testing.

However, it soon became clear that there was considerably more work involved in the development of the multi-cylinder VVA system required, than had initially been estimated, and it was agreed by the consortium that the single cylinder engines should be built to utilize a number of fixed camshafts that would be made to replicate the valve motions intended from the VVA system. Consequently Mechadyne produced valve motion data for Renault to produce these fixed cams.

Renault and IFP defined the VVA functional requirements thus: variable intake valve closing, and exhaust valve re-opening. The resulting valve lift characteristics are shown below in *figure 4*.

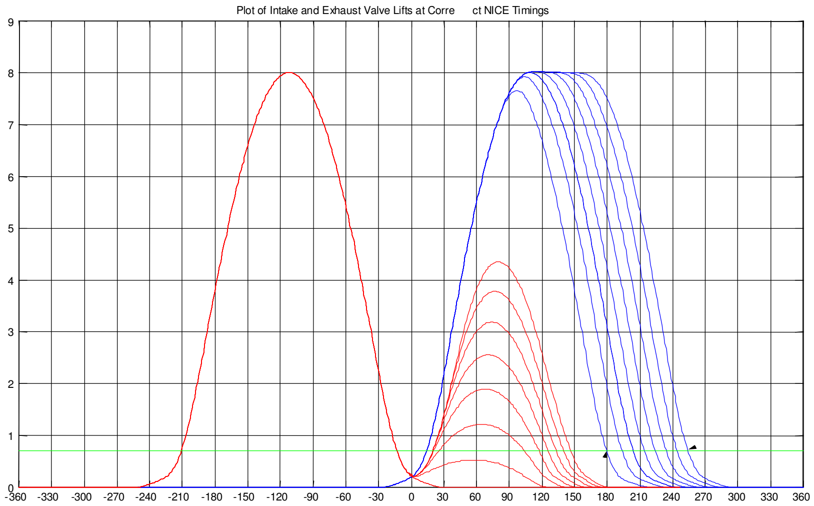


Figure A1.4: Valve lift characteristics generated by the VVA system as used in the single and multi-cylinder engines

Operation of the VVA system

The Variable Lift and Duration, "VLD," system uses a rocker system to combine the motion of 2 cam profiles, where the 2 cam profiles are on ***concentric cam.*** *Figure 5* shows the rocker system and part of the concentric camshaft for the VLD system as applied to the NICE project

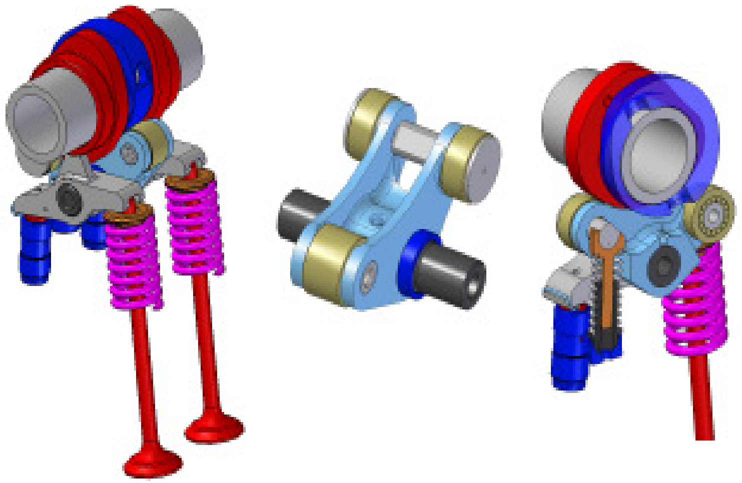


Figure A1.5 : Summing rocker system and concentric camshaft

Mechadyne's design responsibilities for the multi-cylinder engine

Mechadyne was responsible for the detailed design and component drafting of all non-standard valve train parts, (camshafts, summing rocker assemblies,) the structural cam cover, (which included the cam bearings, valve train lubrication and hydraulic control systems,) and the rotary actuators used to set the VLD position.

It should be noted that the head and valve train interfaces were also designed to be built with standard camshafts and type 2 rockers on both intake and exhaust sides.

Renault designed the cylinder head from the fire face up to the oil deck and Mechadyne and Renault jointly designed the side walls of the cylinder head which formed the interface to the structural cover and valve train.

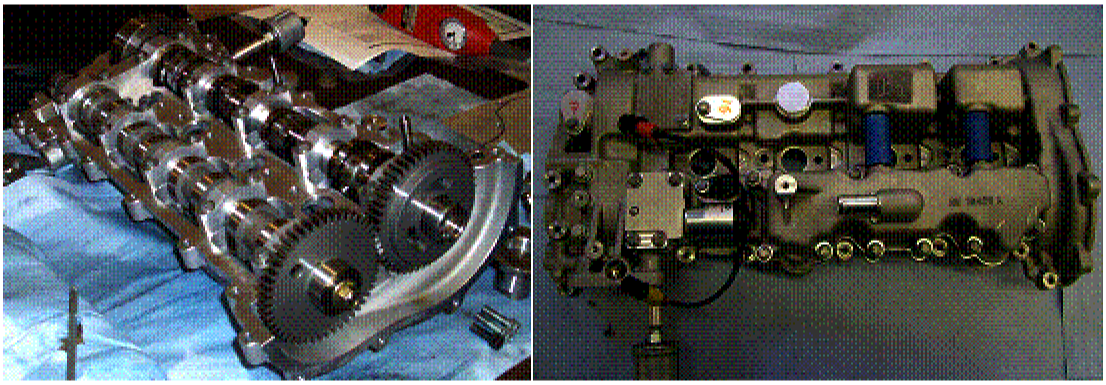


Figure A1.6 Views of the structural cam cover assembly

Figure 7 shows the rocker systems installed in the cylinder head and *figure 8* shows the complete assembly on the Mechadyne laser valve motion measuring system.

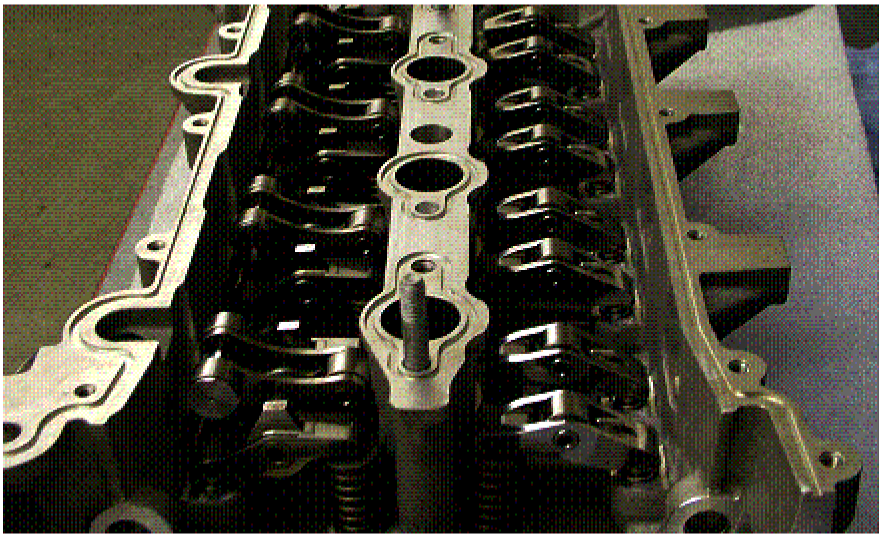


Figure A1.7 Rockers installed in the cylinder head (std valve train on intake side)

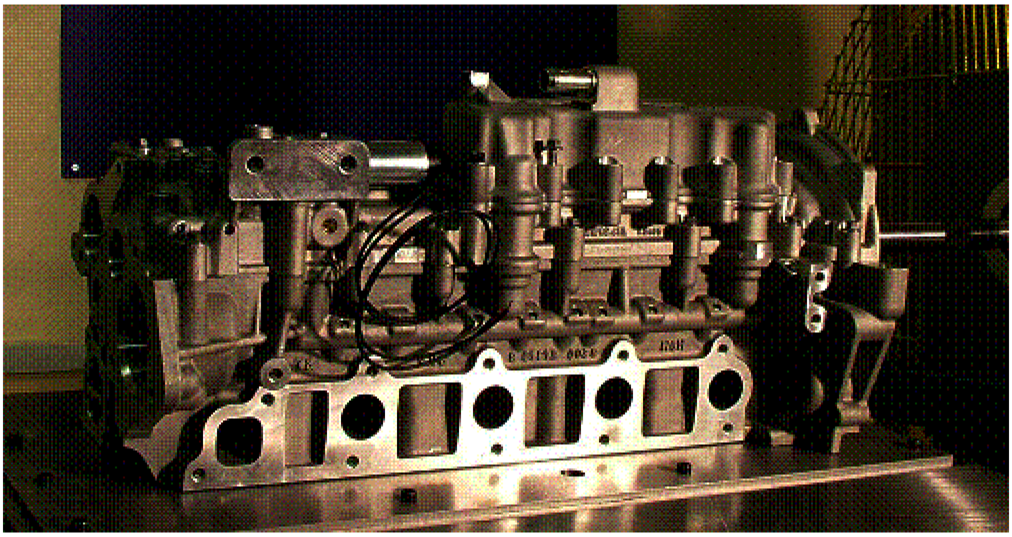


Figure A1.8 Complete cylinder head assembly on Mechadyne's test rig

Several sets of components have been procured and engines successfully run at Renault, Delphi and IFP.

FIE Hardware : DELPHI Advanced Direct Acting Common Rail System

The injection system used is a Delphi Direct Acting System technology which relies on a novel injector operating principle, where the nozzle needle is directly driven by a piezo actuator. The direct acting injector can both be very fast in needle speed, and at the same time deliver small pilot quantities in good accuracy with very low shot to shot variation.
Injection rate literally approaches a square wave and leads to an excellent multiple injection behavior whereas having the capability of operating at very high pressures up to 2000bar.

The other advanced common rail system components used are DFP3.x pump and DFR3 rail with high pressure discharging valve. A key feature of the pump family is the adaptable faceplate concept which allows all the connections (electric and hydraulic) to be optimally placed to fit the small engine packaging environment. The hydraulic components have been designed to be capable of continuous operation up to 2000 bar for the NICE Program.

DELPHI, then performed hardware integration of the fuel injection Systems, fuel injection system pre-calibration on test rig, integration on the engine & engine definition as well as ECU and wiring harness delivery to the partners testing a multi-cylinder engine.

Final Multi-cylinder Engine

Named H9M, the engine features the technologies required for exploiting the HCCI combustion with the planned parameters of variability **(see Fig. 9)**.

- ✓ Bore x Stroke : 79 x 81,5 mm (1598 cm3)
- ✓ 4 valves / cyl-Std or VVA
- ✓ Single turbo charging (TARGET 60 kW/L)
- ✓ Fuel Injection System:
  - Piézo Delphi APZ 2000 bar
  - 6 holes / spray angle 155 °
  - Hydraulic flow 320 cm3 / 30s / 100bar
- ✓ Continuous variable swirl
- ✓ HP EGR + LP EGR + particulate filter

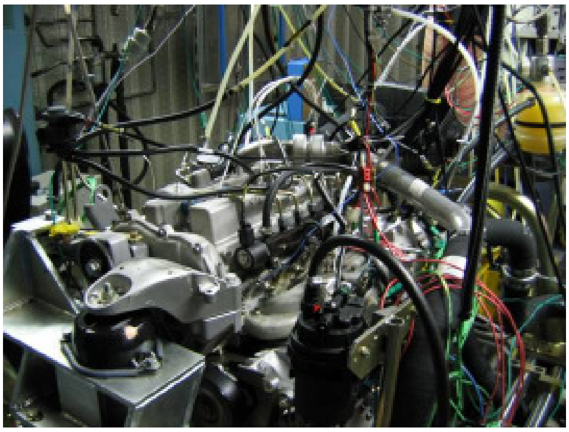
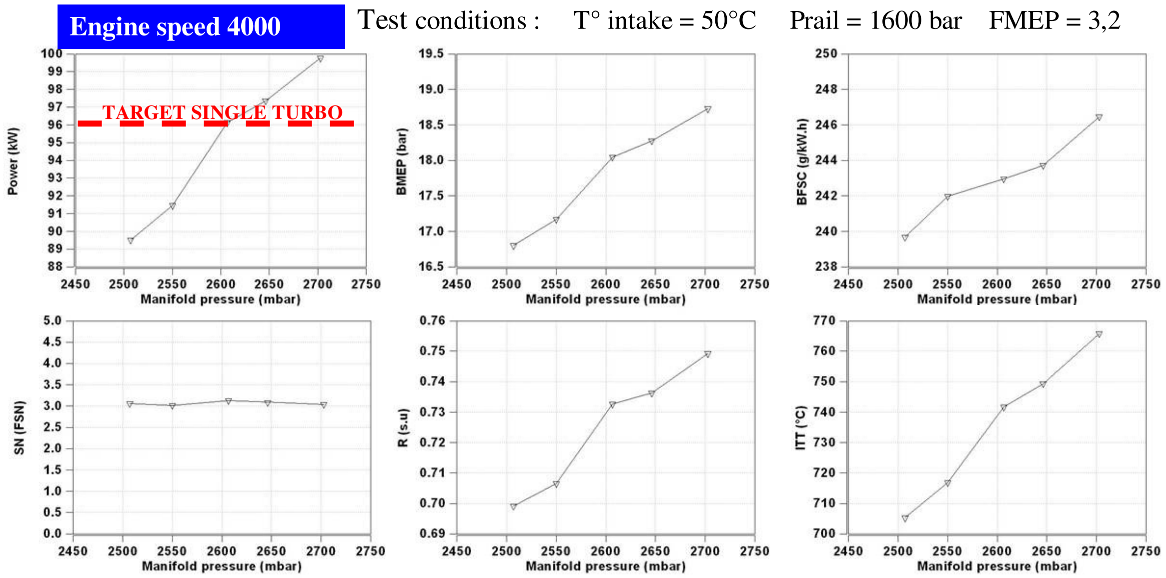


Figure A1.9 Characteristics of H9M engine

- ### Multi-cylinder Engine Test Bench Results

It has been possible to qualify the performances capacities of the multi-cylinder completely integrated which fulfilled the targets (see Fig. 10).



The max power is reached → 96 kW at 4000 rpm (1/λ = 0,735 – 3 FSN)

Figure A1.10 Performances characteristics of H9M

After full load testing, however, the first prototype manufacturing of cylinder head proved to be not reliable. The following prototypes required modifications which induced delays.

After the cylinder head problem-solving by Renault, the multi-cylinder engine received the integrated exhaust VVL cylinder head provided by Mechadyne at the end of Month 36.

- The good control of the exhaust VVA cylinder head allowed IFP to examine the potential of Internal Gas Residual (IGR) by reopening the exhaust valve during the intake phase. As global burnt gases temperature inside the combustion chamber increases, HC and CO emissions could be reduced by 40 % at low load. In order to respect the same noise level, IGR being warmer than EGR, it is necessary to raise the global burnt gases with an air/fuel ratio rise: NOx emissions could be so divided by 2. Exhaust temperature before the catalyst bed is increased of 30°C; it a good benefit for aftertreatment light off. At last, the exhaust valve reopening during the intake phase balances the intake and the exhaust pressure and improves the permeability. As result, IMEP low pressure is reduced and BSFC decreases by 4 % due to the improvement of the low pressure loop and the combustion efficiency.

- Due to a low combustion temperature in HCCI, HC and CO emissions rise strongly especially at very low load. To overcome this barrier, the optimization of multiple injection strategies in HCCI combustion completes the use of IGR. Thanks to a controlled noise level, the EGR rate could be reduced whereas the extra local temperature is profitable for HC-CO emissions oxidation while keeping a low NOx level. Thus multistage injections were investigated by phasing in a second injection very close to the main one. This injection splitting up moderates the heat release and so the noise. Due to the impact on the second injection auto ignition delay, it is important to adjust the repartition and the separation between each injected quantity to define the best trade-off between noise and particulates. The minimum separation is suitable to achieve the best results in particulates with lower HC-CO emissions and an acceptable noise level.

  The combination of multiple injections and IGR in HCCI is a good way to keep engine out HC and CO close to reference Euro-4 levels. In comparison to standard HCCI with a single injection strategy, multiple injection developments on this study have the best efficiency at 3 bar BMEP with a 60 % decrease on HC-CO emissions, whereas IGR has a more distinct influence at lower load with a 50 % reduction on these pollutants. These significant results highlight a new direction between conventional and homogeneous combustion: the different resultant balance maintains HCCI advantages on NOx with a reduction by 90 % compared to reference, whilst grappling with low combustion temperature drawbacks.

- These strategies, using the exhaust VVL system, are especially interesting in cold conditions when the oxidation catalyst is not lit off. The temperature increase of the burnt gas has always a positive impact on HC and CO emissions and involves benefits on the IMEP stability in those conditions as well as on the exhaust temperature with 40°C higher at 2000 rpm, 1 bar BMEP. Engine temperature impact on pollutants at idle speed is similar to the low load point.

- Although efficient, the VLD system has to be compared to other solutions from a cost-to-value point of view. Thus, the double lift exhaust system was compared with a short route high-pressure EGR loop without cooler by quantifying their respective gains on steady state points of the NEDC cycle: the potential in HC-CO emission reduction remains significant on a large scale of engine temperatures.

However, the VLD system allows to achieve an advantageous higher burnt gas temperature at idle speed (HC-CO emissions reduced by 35 %) and at low engine temperature. Even if the results on the steady-state points seem to be very close except specific points, the estimated response time is four times better with the VLD system: it could be very interesting to get a fast control of the global burnt gas inside the cylinder.

- On the limit load range in HCCI, particulates emission is a main problem. In order to improve the homogenization of the mixture, the influence of two parameters was studied: injection rail pressure and swirl ratio. Until 1800 bar, there is a benefit on particulates emissions with an injection pressure increase, with no effect on fuel consumption and on combustion noise. Increasing the swirl ratio enhances the homogenization without rising the EGR rate: thanks to the associated increase of the auto ignition delay, particulates emissions could be reduced. Nonetheless, the benefit becomes lower when the load is higher. Indeed, the required permeability at high load balances the possible benefit link to the auto ignition delay.

- A work was then operated to define the multiple injections strategies adapted to different load ranges and combustion modes used in the European drive cycle. In the same way, VVL exhaust settings were optimized to find the limit of its potential. The calibration work is operated on 13 representative NEDC points for the vehicle application Renault Laguna. Global results show that :
    - at low load under 3 bar BMEP, it is possible to achieve the Euro6 targets defined by Renault on pollutants, emissions and consumption
    - at the HCCI range limit, there is some difficulties on particulates, consumption
    - on the EUDC part, it is difficult to reach the NOx level objectives

  In conclusion of this work, it is noted that the HC and CO emissions barrier in HCCI could be resolved thanks Internal Gas Residual coupled with adapted injection strategies and we could expect particulates emissions to be more reduced with a two-stage turbocharging system.

- **Vehicle Preparation**

The main objective of the HCCI demo vehicle is to validate under transient conditions the results obtained on steady state test bench.

After vehicle hardware delivery by Renault, including the prototype multi-cylinder engine integration in the vehicle, DELPHI, developed the software including:

- Control strategies and Advanced Engine management system development.
- System integration & calibrations on multi-cylinder engine

Control Strategies: Model Based Control Strategies Adapted to HCCI, LP EGR & VLD

DELPHI applied a structured engine principle and model based approach to the control software. This structure is compatible with advanced combustion. A specific work was done to adapt the generic software structure to the NICE multi-cylinder engine and vehicle.

The features of the generic structured engine software are (Figure 11) are:
- Structured engine control architecture
- Modules based on physical subsystems
- Interfaces clearly defined by physical parameters
- Emissions and fuel efficiency related scheduling variables
- Management of the transition between several combustion modes

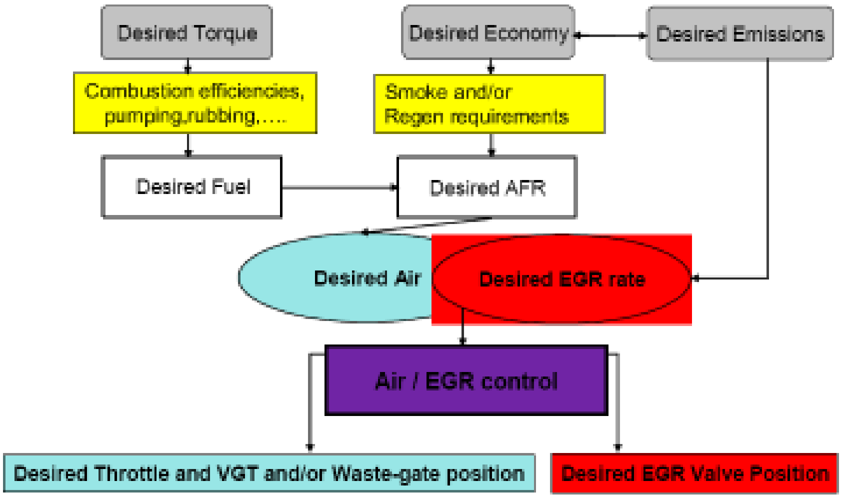


Figure A1.11 : Structured engine control architecture

EGR Systems Control

At the beginning of the project, only the low pressure EGR circuit was considered. During the first vehicle tests, HC and CO emissions were very high due to the cold exhaust temperature and low oxidation catalyst efficiency. To sort out this cold starting issue, it was decided to integrate an additional high pressure EGR.

Low pressure cooled EGR, High pressure hot EGR, and internal hot gas recirculation (using Mechadyne^{TM} VLD) are presented in Figure 12.

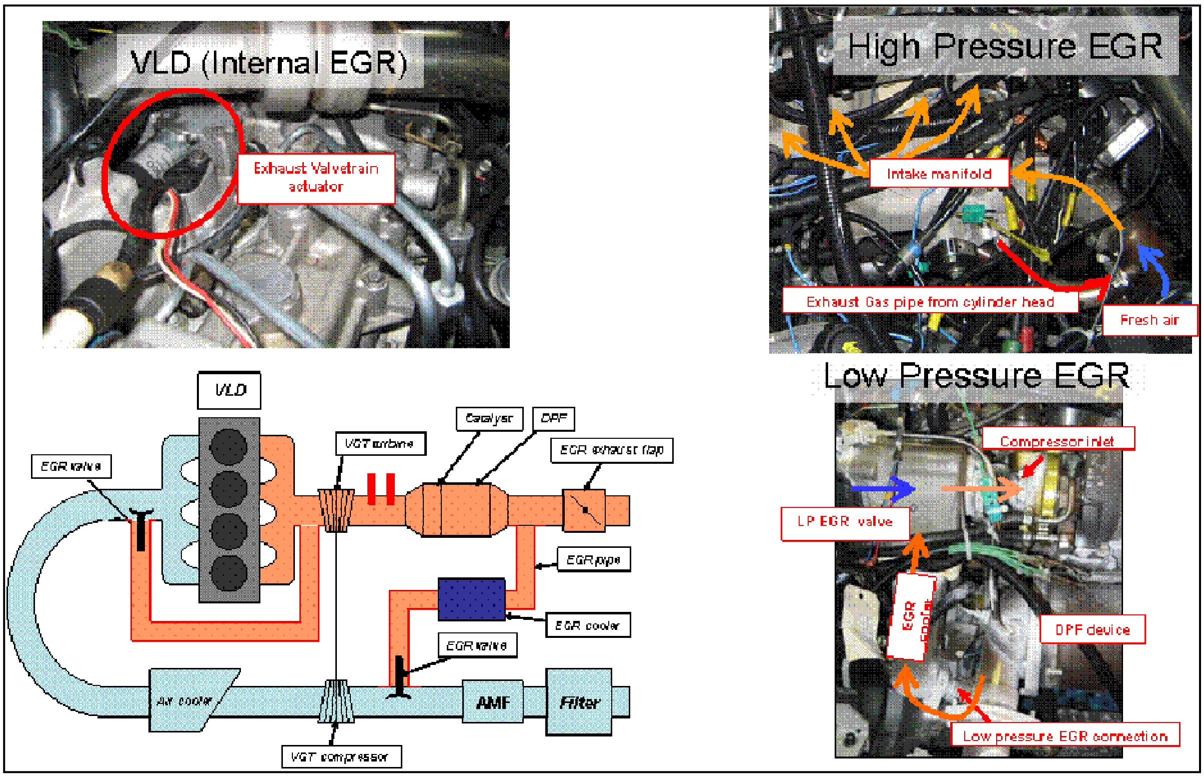


Figure A1.12 : EGR systems

A specific development was done to allow the control of the new EGR low pressure circuit. The first step was to enable the valve and exhaust flap actuator control and to modify the ECU pin-out to adapt the command to the actuator specifications. Then a model based strategy was developed to finally have an optimized calibration between exhaust flap position, EGR valve flow, …

A dual EGR mode was also developed to manage the transition between Low Pressure and High Pressure EGR (or IGR via Mechadyne VLD) modes. It enables to possibility to run simultaneously the 2 EGR circuits.

VLD System Control Adaptation

The multi-cylinder & vehicle was equipped with Mechadyne VLD system. The initial delivered VLD system has got its own ECU which is controlled via dedicated laptop.

To integrate the Mechadyne VLD on the multi-cylinder and vehicle, DELPHI proposed the solution of DELPHI ECU taking in charge the demand algorithm and the Mechadyne control Box was used as a smart actuator (integrated closed loop on the engine exhaust valves position).

DELPHI EMS Interface with Vehicle CAN Network

Many information such as fan management, coolant temperature, engine revs, vehicle speed, engine state (stopped, cranking, started, stalled, …), dashboard displays, … are passing through the can network mandatory input or output variables for the engine or vehicle control units then for the global vehicle behavior.

The demo vehicle base is a RENAULT Laguna II which is a new development base for DELPHI. Thus, CAN network specifications were transcribed and integrated into DELPHI software.

The integration of hardware and software lead to the multi-cylinder engines and the demonstrator car being fully functional.

- **Accompanying studies**

Alternative and Renewable Fuels for HCCI

The main objectives of this task are to improve the knowledge on the fuel formulation effect on HCCI combustion in terms of operating range, CO_2 and pollutant emissions performance, and to check the compatibility and synergy between the enlarged HCCI hardware and technologies developed in this project with alternative and renewable fuels from "RENEW". Three alternative fuels were tested, two being biomass-to-liquid fuels, and compared to commercially available pump diesel.
The means have involved simultaneously the transparent engine from Brunel University with the NADI combustion chamber and the single cylinder at IFP.

On the transparent engine, a test plan consisting of selected four-injection strategies as well as three conventional pilot-main injection strategies was formulated. The same injection timings were employed between fuels, the injection quantities varying slightly to compensate for differing calorific values and densities.

With the pilot-main injection strategies improvements, in terms of IMEP and emissions, were encountered with the use of the alternative fuels. In some cases, the faster, more active combustion may present noise issues, although this was not a measured.

The different chemical properties of the alternative fuels presented difficulties when combined with multiple injection strategies, excessive charge cooling impacting upon the level of pre-reactions and thus affecting the following combustion. For one of the tested fuels this factor, exacerbated by a lower cetane number, resulted in no practical combustion. These results have to be considered within the view that the engine definition and injection system is not representative of what is used even on the single cylinder engine.

However, one injection strategy with the remaining alternative fuels resulted in improved charge homogenisation and combustion than achieved with the baseline diesel. Strategy optimisation between fuels would result in significant improvements.

Three fuels were tested on single cylinder HCCI engine at IFP : one fuel from Renew consortium with high cetane number (75), a second one from Renew consortium with low cetane number (36) and a last one formulated at IFP with low cetane number (35.5). Besides their cetane number, their characteristics were quite different: LHV, density/volatility, composition (naphtenes, aromatics). Four items were studied:

- 1.8 bar IMEP at 1500 rpm for the HC and CO emissions problematic associated to low exhaust gas temperature / working of the oxidation catalyst,
- 8 bar IMEP at 1500 rpm to look at the behavior of the alternative fuels at limit load of HCCI area of reference fuel,
- Research of the maximum HCCI load at 1500 rpm to evaluate the potential of the fuels for the enlargement of the HCCI combustion area,
- Full load at 1500 and 4000 rpm to check performances are conserved with alternative fuels.

Low cetan number fuels and high volatility (ex. Renew CN 36 / IFP CN 35 fuels) show:

- positive influence on HCCI combustion mode
- at low load, few NOx emissions are obtained with little EGR rate
- HCCI zone extension of 1 bar IMEP

Coupling high turbocharging and alternative low cetane number fuels show promising results for HCCI zone extension at the same ISFC (230 g/kWh): 11 bar IMEP reached.

Flexible Air & EGR Charging and Boosting

The overall objectives of this work are to develop & deliver air & EGR charging & boosting technologies to be integrated and controlled in the multi-cylinder engine.
After state of the art analysis, a double stage turbocharging architecture has been chosen then simulation was carried out to specify the associated turbochargers characteristics **(see fig 13).**

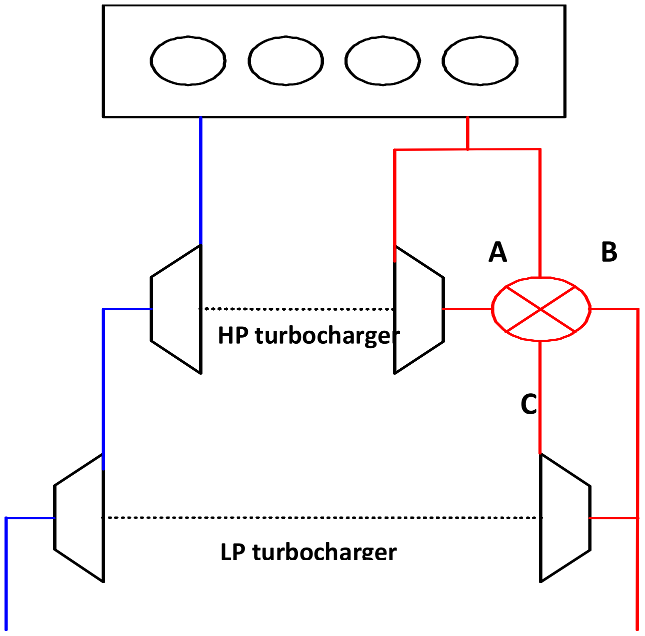


Figure A1.13 Double turbocharging architecture

The target was to obtain a system capable of supplying 120kW at 4000rpm together with rapid transients.

In the mean time engine tests were carried out by Renault with the two different turbochargers composing the system, a simulation was ran and crosschecked with the tests to firstly validate the computer model. The simulation was then used to analyze the effects of intake valve closing, secondary exhaust valve lift strategies and the double stage turbo charging operating strategies. The simulation proved to be coherent with the multi-cylinder engine test results.

- Two-stage turbocharging increases air availability via boost pressure increase. This can be used to either achieve higher EGR rates or reduce equivalent ratio, which is considerably high due high EGR rate at this engine running conditions.
- With the final turbochargers matching, the best strategy regarding air management is to avoid by-passing the high pressure and low pressure turbines.
- When using a high pressure loop EGR system, in-cylinder exhaust gases composition remains constant if the secondary exhaust valve lift is activated. Instead, if this strategy is employed, internal gases recirculation is increased but external gases recirculation decreases due to the reduction on exhaust/intake pressure difference. As a result, although the gases composition do not change, the ratio external/internal EGR is modified and so the in-cylinder temperature.
- With a low pressure loop EGR system and performing simulations with constant equivalent ratio, EGR rate is reduced when applying the intake valve closing strategy. Obviously, the in-cylinder temperature decreases and this effect can be used for HCCI control purposes.

From a testing point of view, when increasing the boost pressure, the benefit in particulates emissions is important up to 2000 rpm which constitutes the upper limit of use of the high pressure turbocharger matched. It should then be switched to the use of both high pressure and low pressure turbocharger to avoid the low pressure turbocharger back pressure increase, which tends to increase consumption.

The use of variable IVC with HP turbocharger relies on the reduction of effective compression ratio to decrease end of compression temperature. This has a positive effect on NOx emission allowing the reduction of EGR rates to keep NOx constant. The reduction of EGR rates leads to particulates emission reduction.

As a conclusion the use of a double turbocharging system with a H9M of a 1.6litre displacement allows reaching 120 kW power (see figure 14), while respecting NOx emission targets, keeping the same fuel consumption as a single turbocharger equipped H9M and bringing DPF regeneration interval in a more reasonable range as shown in table 15.

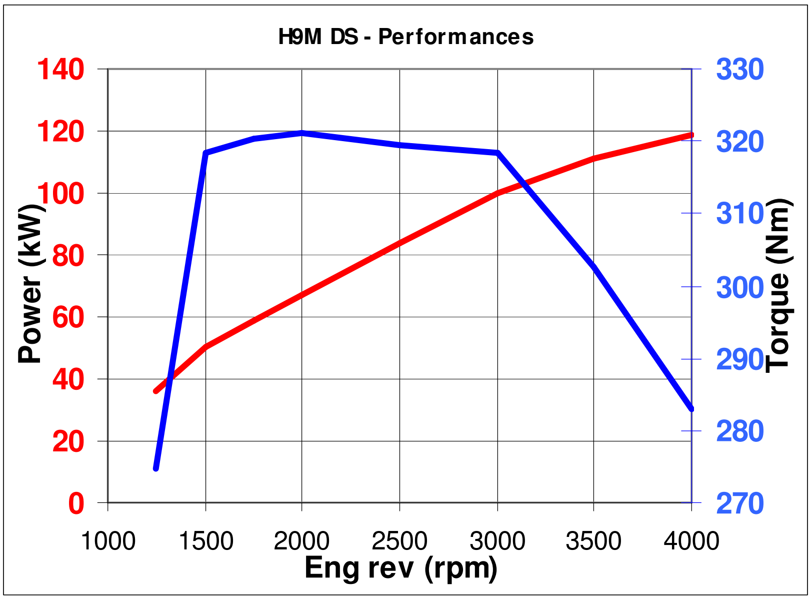


Figure A1.14 Double turbocharged H9M performances capabilities

Values given relative to reference targets	NO_x	BSFC	HC	CO	DPF load
Standard calibration // standard turbo // Prail opti	+ 3 %	+1.8 %	- 37 %	- 9 %	**+ 70 %**
Small turbo // Prail opti // swirl ratio // variable IVC	**+ 4.2%** **<EURO6**	**+1.8%**	**- 37 %** **<EURO6**	**- 9 %** **<EURO6**	**+ 45%**

Table A1.15 Double turbocharged H9M depollution capabilities (simulation from test bench results)

2.1.4. Final Results

- **Final Results**

The calibrations issued from test bench have been supplied by IFP then implemented on the vehicle.
The first tests carried out on the vehicle with HCCI and the new Low Pressure EGR system, showed a very low exhaust temperature inducing very high CO and HC emission. The internal EGR using VLD has been applied to the vehicle in order to sort out this issue of high HC and CO at low load observed also at the IFP. Due to the complexity of the system, it was not possible to obtain an optimized calibration within the time allowed to this task. The HP hot EGR was therefore implemented in parallel to LP cooled EGR to sort out the HC and CO problem at cold phases.

Finally, compared to production EURO4 car, a reduction of 30 % for NOx emissions is demonstrated on EUDC Extra urban cycle without consumption increase (Figure 16). On a full cold NEDC cycle, more than 50 % HC and 30 % CO emission reduction is demonstrated within NICE A1 project by keeping the large advantage in NOx emissions reduction with HCCI (Figure 17).

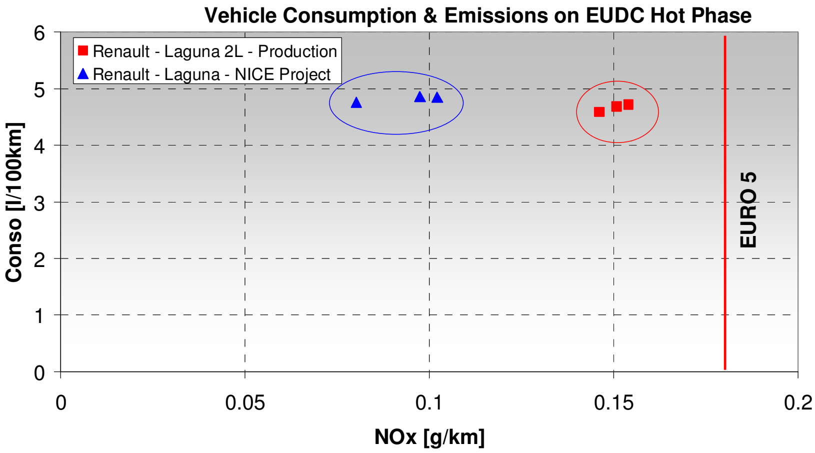


Figure A1.16: Emission comparison on EUDC 'hot phase'

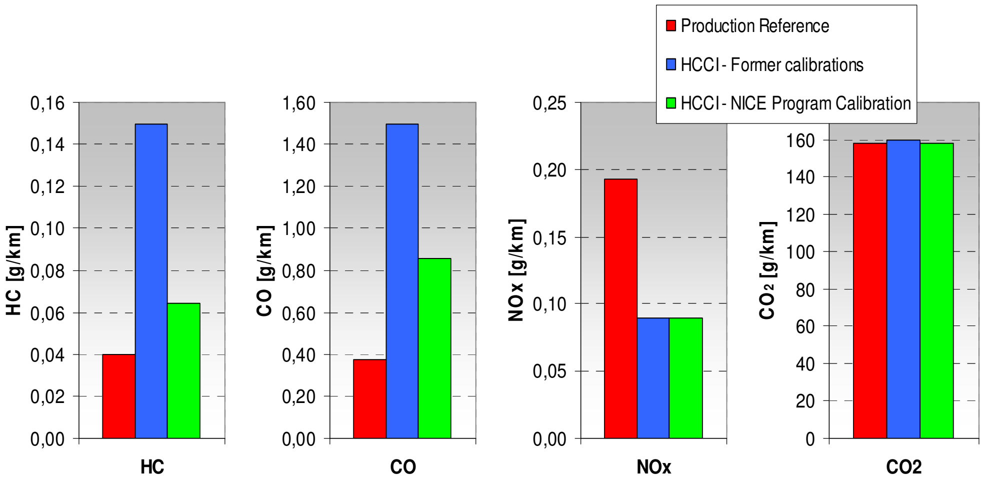


Figure A1.17 : Full cold NEDC cycle emission results

- The re-use of IFP NICE HCCI based calibrations is made at hot conditions on emission cycle from ECE4 to EUDC except for idle & 100→120 km/h acceleration. The problem of high CO and HC at low load on the vehicle, was solved by adding HP hot EGR in parallel to LP cooled EGR. The VLD has been applied to the NICE demonstration vehicle, but due to the complexity of the system, it was not possible to obtain an optimized calibration on time.

- Potential 50 % NOx emissions reduction is demonstrated on European cold NEDC compared to production vehicle.

- This calibration compared to ‘known HCCI calibration results confirms the high reduction of HC/CO emission by keeping the large benefit in NO_x.

- **Degrees to which the Results Have Been Reached and Discussion**

The NICE subproject A1 enlarged HCCI diesel combustion has involved several innovative technologies to overcome HCCI barriers and achieve **for different types of fuels** the **excellent fuel conversion efficiency** of a cutting-edge **DI Diesel** engine while complying with very low **future emission levels** (i.e. EURO6).
The potential of these technologies had been explored from simulation to single cylinder before application on a multi-cylinder engine.
Amongst the list : low pressure EGR, variable valve actuation, variable swirl, double turbocharging, new generation engine management and fuel injection system, all have been implemented on a multi-cylinder engine on steady state bench and up to the demonstrator vehicle (except double turbocharging).
The result is a vehicle that would be capable of up to 120 kW power with a 1.6 litre engine, what already has the same fuel consumption of a EURO4 110 kW power 2 litre engine and fulfils EURO6 NOx emission requirements.
Further work needs to improve the NEDC cold phases HC and CO emissions as well as noise, which has been demonstrated on the test bench but remains to work on a vehicle.

Furthermore the technologies remain to be validated before on road application but HCCI combustion has been used on the whole NEDC driving cycle.

2.1.5. A1-List of Acronyms

EGR: Exhaust gases recycling
IGR: internal gases recycling
VLD: variable lift distribution
TC: Turbocharger
HCCI: Homogeneous charge compressed ignition
CO: Carbon monoxide
NEDC: New European Driving Cycle
VVL: Variable valve lift
HC: Hydrocarbons
VVA: Variable valve actuation
NOx: Nitrogen oxides
IMEP: indicated mean effective pressure
BSFC: brake specific fuel consumption
CH4: Methane
BMEP: Brake mean effective pressure
HP EGR: High pressure loop exhaust gases recycling
LP EGR: Low pressure loop exhaust gases recycling
ECU: Engine control unit
CAN: control area network
EMS: Engine management system
DI: Direct Injection

2.2 Subproject A2

2.2.1. Objectives

The main general objectives of sub-project A2 have been:

- the development of subsystems of integrated flexed low cost components with the goal of a variable ICE structure;
- the definition of a combustion system able to run also on tailored bio/bio-blend fuels (to this purpose, liquid fuel specs have been investigated and proper recommendations for renewable fuels have been released);
- the increase of the fuel conversion efficiency of about 10% with particular regard of engines running on diesel fuel and gasoline that have the main impact on the environment in the next 20 – 30 years.

Sub-project A2 considers different approaches for different combustion processes:

a) spark ignited combustion process

The general approach on spark-ignited engine took into account that highly boosted downsized gasoline engines will represent one of the best ways for gasoline engines to improve the fuel consumption and emissions.
Two complementary Technology Ways have been explored:

Technological way A2.1 – *New combustion chamber and intake duct geometry for high turbo-charging pressure, together with BMEP > 2.3 MPa, high compression ratio and high EGR.*

Technological way A2.2 - *Mixture preparation with electro-hydraulic VVA (Variable Valve Actuation) and multiple injections.*

b) compression ignited combustion process.

The approach on compression-ignited combustion takes into account that the process must preserve the advantages of the Diesel-process, mainly consisting of low fuel consumption, while preventing the NOx and soot production. One of the key points of this combustion process is a synthetic fuel made of biomass – renewable fuel – with a different evaporation and ignition delay behaviour with respect to a diesel fuel. The basic way consists in a modified turbo-charged Diesel engine with direct injection and reduced compression ratio lower than 19 adjusted for use of alternative, renewable fuels.

Technological way A2.3 - *A new combustion system using tailored fuels, high EGR, optimised mixture handling and advanced subsystems*

2.2.2. Contractors involved

- AVL List GmbH [AVL]
- Centro Ricerche Fiat SCpA [CRF]
- Daimler AG (formerly DaimlerChrysler AG) – [DAI]
- FEV Motorentechnik GmbH– [FEV]
- Istituto Motori Consiglio Nazionale delle Ricerche [IM-CNR]
- Czech Technical University in Prague [JBRC]
- Università degli Studi di Genova [UNI-GE]
- RWTH Aachen – VKA (Institute for Combustion Engines) – [VKA]
- Volkswagen AG [VW]

2.2.3. SPA2 – Technology Way 1

2.2.3.1 Objectives

- Main Objectives of Technology Way 1 (TW1) have been:
    - Significant CO_2-emission reductions in passenger cars were achieved through highly efficient Diesel engines. For further improvements also the spark ignition (SI) engine must be taken into account.
      On the basis of thermodynamic considerations (Fig. A2.1), lean burn operation with simultaneously increased compression ratio is an appropriate approach for the SI combustion process. Compared with conventional stoichiometric SI engine (CR = 10), approx. 10 % efficiency can principally be achieved through lean operation ($\lambda = 1.5$) and approx. 7 % through increased CR=13.
      The expansion of the lean burn operation towards higher part load and full load requires boosting to compensate for the lower mixture calorific value.
      Furthermore, such a homogeneous lean burn combustion system shall emit low NOx such that Lean-NO_x-aftertreatment can either be omitted or at least minimized.
    - Thus, it is focus of this subproject to research and develop a homogeneous lean boost SI engine combustion system, focusing on high lean burn capability and low knock sensitivity with main parameters charge motion and mixture formation.
    - A known problem of turbocharged spark-ignition engines is their delayed response to sudden load increases from lower partial load and low engine speed conditions. An option for improving transient operating behavior is to be investigated.

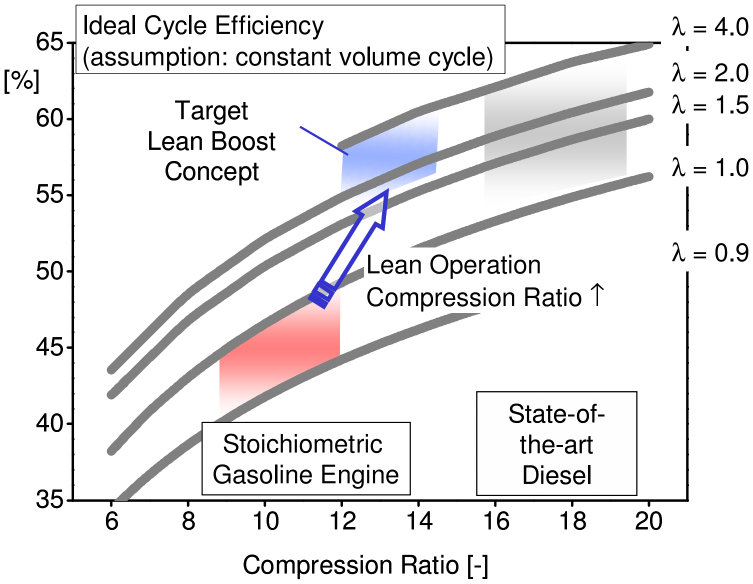


Fig. A2.1 Homogeneous lean burn combustion objective:
Lean burn operation with high compression ratio and high boost

- Relation of the objectives to the strategic goals
    - In this regard, the objective of TW1 correlates well to the main strategic goal of NICE that is "to develop a new integrated combustion system that,(…), is able to achieve the today highest fuel conversion efficiency of the DI diesel engine (43 %), while complying with a zero-impact emission level."

2.2.3.2 Contractors involved

- Daimler AG (formerly DaimlerChrysler AG) – [DAI]
- FEV Motorentechnik GmbH– [FEV]
- RWTH Aachen – VKA (Institute for Combustion Engines) – [VKA]

2.2.3.3 Work Performed & Final Results

2.2.3.3.a Combustion System

- Work performed
    - Layout, design and setup of a new spark ignition combustion system within single-cylinder engine
    - 3D CFD-analysis of air flow and fuel mixing based on pre-defined engine geometry
    - Thermodynamic single-cylinder engine testing
    - Benchmark assessment of the combustion system configuration with state-of-the-art SI technology

- Final Results and Recommendations for the layout of a homogeneous lean-burn combustion system:
    - With regard to injection system configuration, central injector position with outward opening piezo injector has shown the highest potential with regard to fuel consumption and stability vs. NOx-emission. See Fig. A2.2

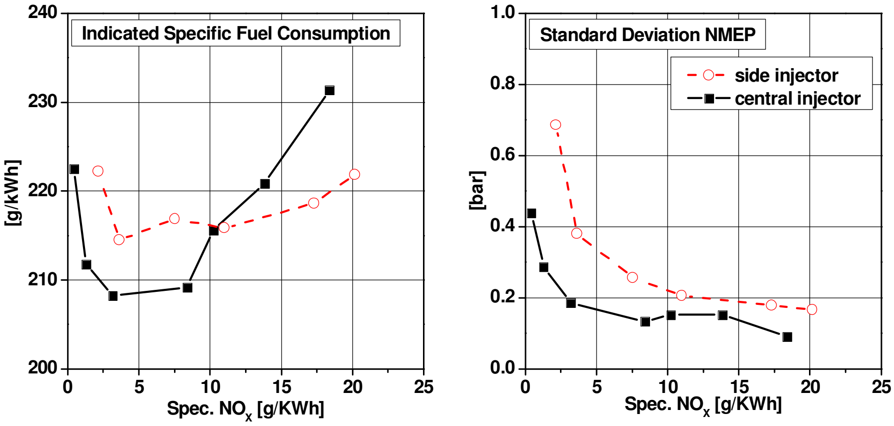


Fig. A2.2 Assessment of new lean burn combustion system
Variation of relative Air/Fuel-Ratio, n = 2000 rpm, NMEP = 10 bar

    - Injection mode: Both CFD, as well as experimental results indicate a strong influence of chronological sequence of the injection. Especially, split injection helps to reduce wall impingement and to improve homogenization. Fig. A2.3

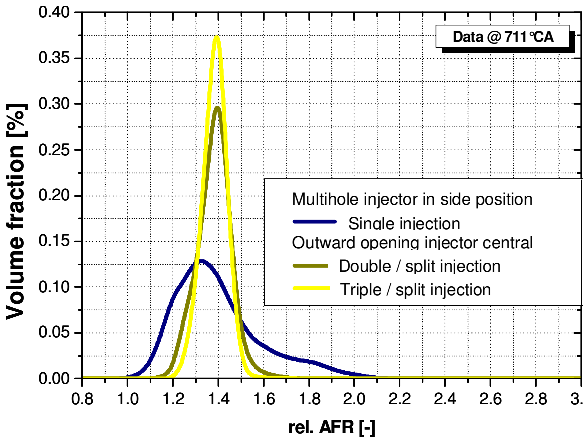


Fig. A2.3 3D CFD simulation of homogeneity distribution for different injection modes

    - With regard to the combustion system layout for highly diluted mixtures with deteriorated combustion conditions, enhanced charge motion (swirl, tumble) and compact combustion chamber layout have proven beneficial. High compression ratio (CR > 12) represents a good compromise for both limits, lean burn stability and knocking.
    - Full-size engine gas exchange simulations for lean boost full load operation indicate achievable mean effective pressure of more than 20 bar with excellent low break specific fuel consumption of less than 220 g/kWh and specific power of more than 70 kW/l with further potential through multi-stage boosting, Fig. A2.4.

➔ Full load limitation by the combustion process, not by boosting system!
However, homogeneous lean burn combustion principally yields high cylinder pressures that will require a more robust mechanical engine design!

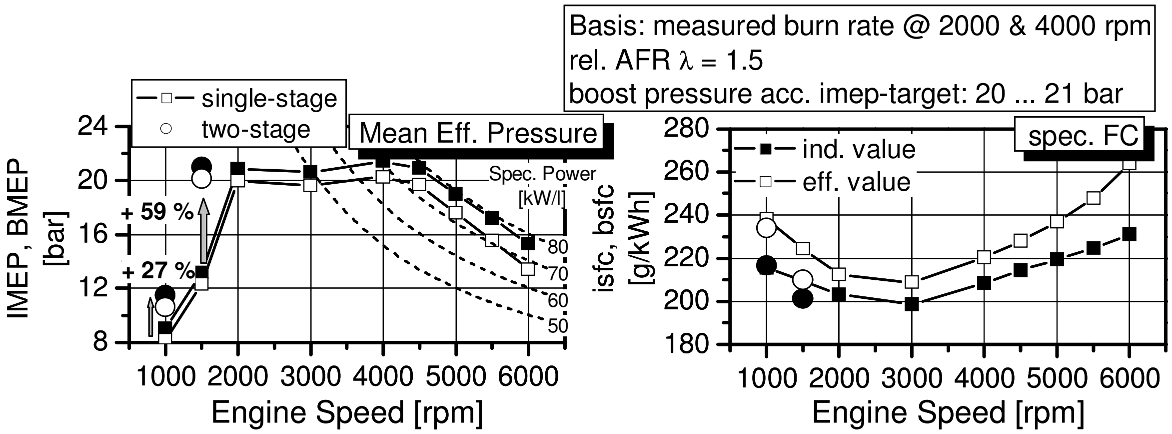


Fig. A2.4 Simulation full-size engine (input: 1-cyl. burn rate, TC-maps)

- The objectives reached with the new homogeneous lean-burn combustion system are shown in Fig. A2.5:
  - With the new homogeneous lean burn combustion system, FC and NOx-Emission of modern Diesel engines (series calibration = state-of-the-art) is achievable!
  - However, future emission standards (EUV, EUVI) will require further measures for lean exhaust aftertreatment (e.g. cooled EGR, NOx-storage catalyst, SCR)!
  - In comparison to stratified operation modes, fuel economy is approx. 5 % worse, but the NOx raw emission is less than 45 % of stratified operation.

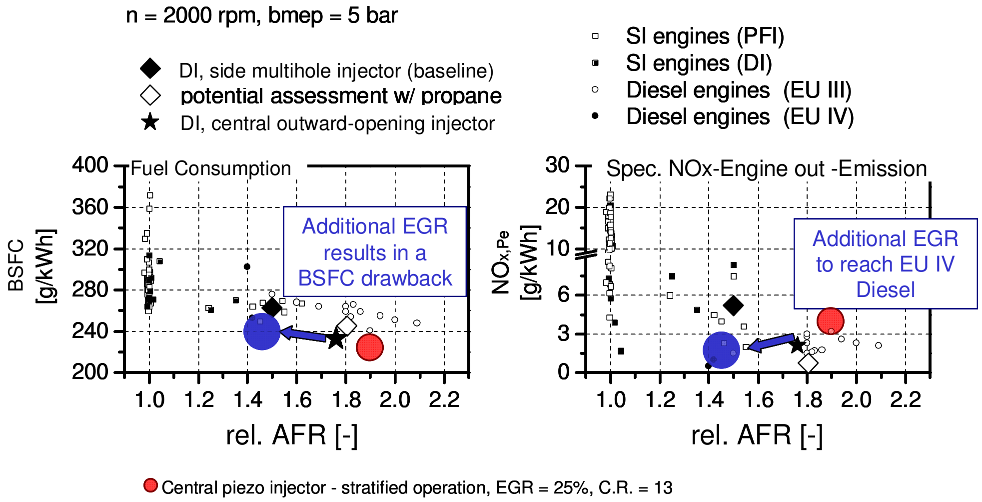


Fig. A2.5 Fuel consumption and NOx-emission assessment and benchmarking Comparison of baseline multi-hole DI in side position with outward-opening DI in central position and gas operation as potential

- A widely followed trend in SI engine development is the introduction of DI. In combination with turbocharging a spec. power level of > 90 kW/l is reached, offering the opportunity for fuel efficient downsizing concepts. Fuel consumption reductions of 16 % in NEDC compared to state-of-the-art PFI turbocharged engines have been proven. Introducing lean burn combustion the NEDC fuel consumption can further be reduced up to 9%, compared to most recent efficient TurboDI concepts, Fig. A2.6.
- It can be summarized that the homogeneous lean combustion system is a very promising concept that can contribute with a significant share for the CO_2-reduction of the passenger car fleet. Homogeneous lean combustion can be applied in the whole engine map but especially at higher load where stratified combustion yields too high NO_x–emission, it leads to significant fuel consumption reduction.

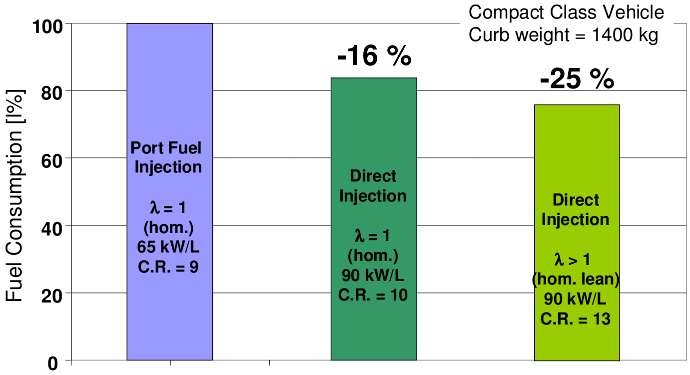


Fig. A2.6 Fuel consumption improvement through homogeneous lean burn combustion

2.2.3.3.b Turbocharging System

Downsizing requires a powerful forced induction system. The exhaust gas turbocharger invented by Büchi in 1905 is a particularly suitable charger variant. Its high efficiency, high achievable compression ratio, small space requirement and relatively moderate cost make it a concept that is frequently used. One difficulty this turbocharging system has not yet satisfactorily solved, however, is the turbo lag of the engine during rapid load increases from lower partial load and low engine speeds. If the load increases suddenly, large turbocharger speed ranges must be overcome until the necessary charge pressure is available. For a typical throttle controlled spark-ignition engine with a displacement of 1.8 to 2.0 l, this will result in a turbocharger speed range of 10,000 to 200,000 rpm. The delay in boost pressure build-up is caused by inertia and bearing friction losses during rotor run-up, as well as by the low enthalpy provided to the turbine in these operating ranges.

This investigation presents a concept that allows for maintaining the turbocharger speed at a significantly higher level during non-charged phases of operation. The higher initial turbocharger speed accelerates the boost pressure build-up during sudden load increases. Daimler calls this new charger concept DOT (Delay Optimized Turbocharger). The goal is to operate the turbocharger at a quasi-stationary speed state.

The energy necessary for the higher initial speed comes from using the enthalpy potential gained from the throttling principle, which is the basis of common spark-ignition engines. To do so, the radial flow compressor of the turbocharger is operated as a cold air turbine.
The necessary conceptual redesign of the classic turbocharger compressor and its effect on engine operation is investigated in this project. The layout of the DOT is shown in Fig. A2.7.

This investigation shows that using the throttle enthalpy potential of throttle-controlled spark ignition engines is thermodynamically possible and technically feasible for achieving turbocharger speed increases in exhaust gas turbochargers. To achieve this, the DOT (Delay Optimized Turbocharger) concept was investigated in detail.

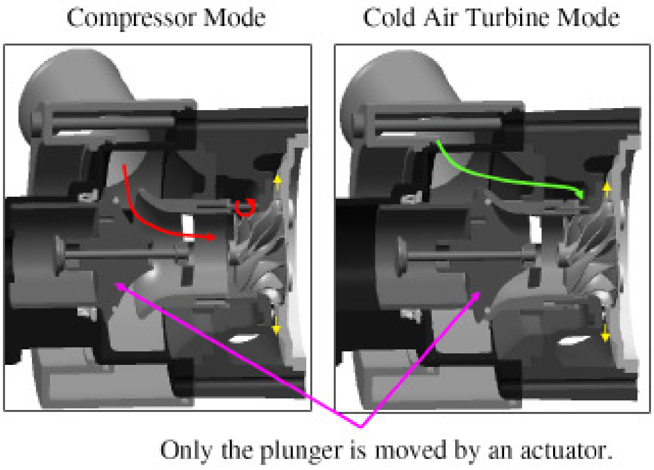


Fig. A2.7 Layout of DOT

First the effect of an increased turbocharger initial speed on the engine torque response was exhibited using 1D engine cycle simulations (Fig. A2.8). Here a direct impact of the turbocharger speed at the beginning of the acceleration process and the break mean effective pressure built-up is detected.

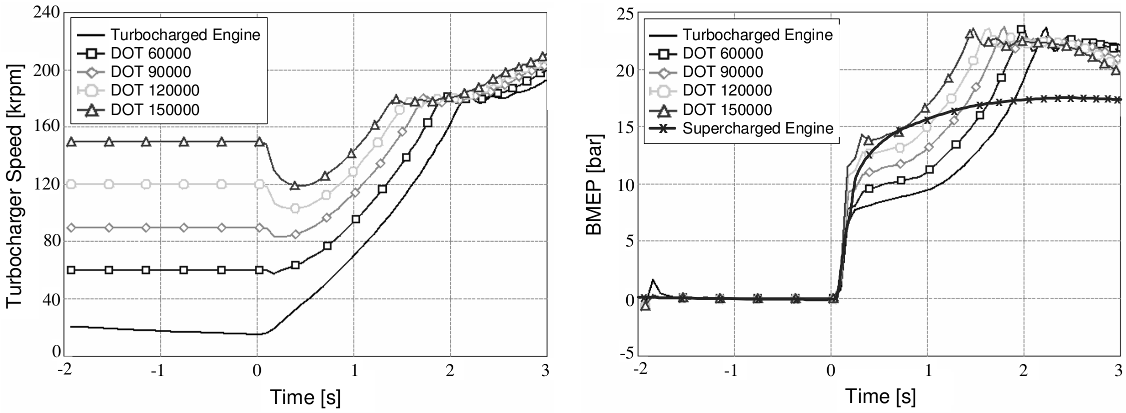


Fig. A2.8 Spark ignition passenger car engine, simulated acceleration processes from a driving speed of 20 km/h in second gear

In a next step the principle usability of a radial compressor wheel as a cold air turbine was investigated on a turbocharger test stand. Initial results from a simplified prototype with exchangeable, fixed-width guide vanes were presented. Using this technical design, it was demonstrated that the compressor wheel can act as a cold-air turbine on the turbocharger test bench. In addition, results from an engine test stand are presented. Here an increase in turbocharger speed of 50,000 rpm at an engine speed of 1,500 rpm and engine load of 2 bar brake mean effective pressure was achieved.

To finally increase the turbocharger speed as much as possible the cold air side of the DOT was investigated with 3D-CFD simulations to improve the efficiency characteristic in cold air turbine mode. As the flow field in the cold air turbine is very complex a numerical validation case with a standard radial compressor was set up to define a reliable simulation method for turbocharger simulations. These simulations were used to analyze the speed characteristic of the innovative cold air turbine. First optimizations based on 3D CFD calculations were outlined.

The 1D review shows that a further increase in rotor speed adds to a greater boost of the engine moment. Thus, in the next development phase, the goal is to achieve the highest possible initial speed of the DOT through efficiency optimization of the cold air turbine, adapted back pressure behavior of the hot gas turbine, and use of low-friction bearing technology. It should be possible to reduce the large speed range of the standard exhaust gas turbocharger from a factor of 20 to a factor of currently 3 and finally in future to a factor of 2, thus achieving the behavior of an exhaust gas turbocharger with quasi-stationary speed. This will enable fuel efficient downsizing concepts.

2.2.4. SPA2 – Technology Way 2

2.2.4.1 Objectives

- Technology Way 2 (TW2) aimed to develop advanced solutions for spark-ignited engine took into account that highly boosted downsized gasoline engines will represent one of the best ways for gasoline engines to improve the fuel consumption and emissions. TW2 has been mainly oriented to the optimization of mixture preparation with electro-hydraulic VVA (Variable Valve Actuation) and multiple injections.

2.2.4.2 Contractors involved

- Centro Ricerche Fiat SCpA [CRF]
- Università degli Studi di Genova [UNI-GE]
- Istituto Motori Consiglio Nazionale delle Ricerche [IM-CNR]

2.2.4.3 Work Performed & Final Results

- <u>Work performed</u>

    - Starting from the general specifications, two specific “mule-engines” (“Mule 1 - 2.0 GDI+TC” & “Mule 2 - 1.6 VVA+TC”) were designed and assembled to theoretically and experimentally assess the potential benefits deriving from the integration of advanced Turbo-charging (TC), Variable Valve Actuation (VVA) and Direct Injection (DI) Technologies.
    Considering the promising results showed by Mule 2, the “cost-target” referred to the final application, a “downsized” multi-cylinder 1.4l 16V engine integrating VVA and TC technologies has been developed and tested.

    - Additional experiments and simulations have been carried out in order to support the design of the mule/target engines by the analysis of:

  - alternative subsystem under dynamic conditions to evaluate transient response (CRF, UNI-GE)
  - TC performance and related control strategies to improve system dynamic response (CRF, UNI-GE)
  - knocking behaviour by simplified models (IM-CNR).

- <u>Final Results</u>

- Supporting Methodologies

The engine target design has been supported by theoretical and experimental developments by UNI-GE and IM-CNR.

UNI-GE efforts have been mainly focused on the development of advanced methodologies for the **experimental characterization of turbo-charging systems** in steady-state and transient conditions including:

- Measurement of steady flow performance maps for TC units in an extended range (Fig. A2.9)

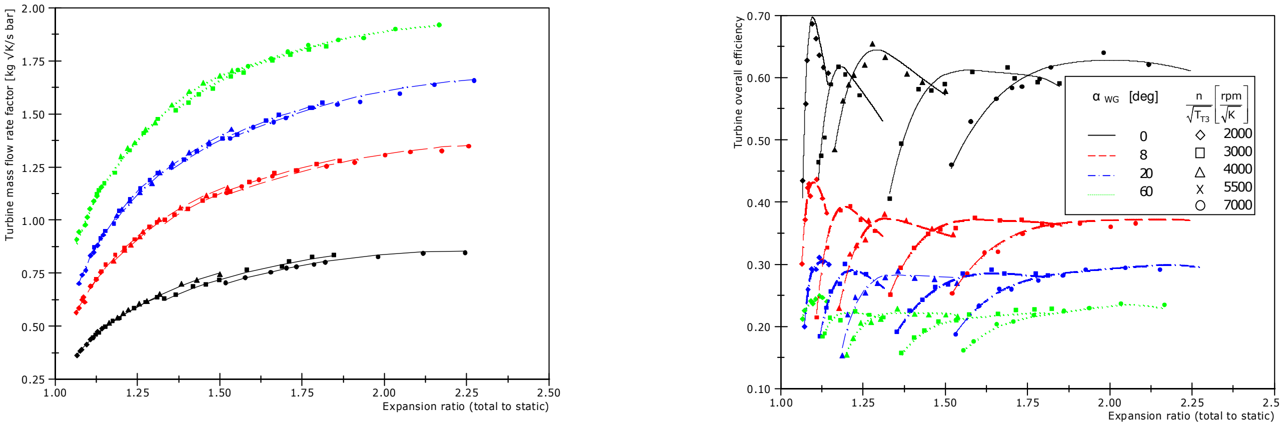
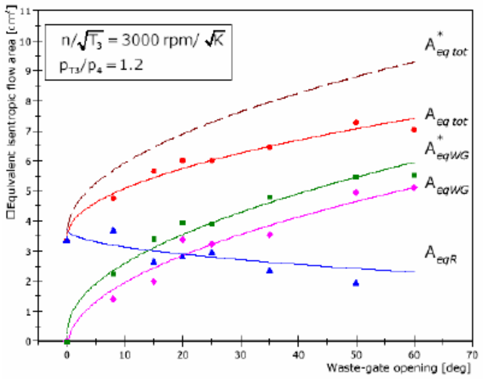


Fig. A2.9 Measured turbocharger turbine steady flow characteristics in extended range

- Analysis of TC turbine behaviour in transient conditions (pulsating flow) (Measurement of turbine inlet and outlet pressure diagrams, Wave propagation phenomena in the engine exhaust circuit, Turbine instantaneous mass flow rate, Evaluation of turbine unsteady flow efficiency)
- Analysis of the effect of waste-gate valve opening on TC performance (Mass flow sensitivity to WG setting, Mass flow contributions through the WG valve and the turbine impeller (Fig. A2.10), Effect of WG opening on wave propagation phenomena)



Mass flow rate expressed in terms of equivalent isentropic flow area A_{eq}:

- A_{eqR} turbine rotor (with combined flow)
- A_{eqWG} WG valve (with combined flow)
- A^*_{eqWG} WG valve (with no flow on turbine rotor)
- $A_{eq\,tot}$ rotor + WG (measured contributions)
- $A^*_{eq\,tot}$ rotor + WG (calculated as independent nozzles)

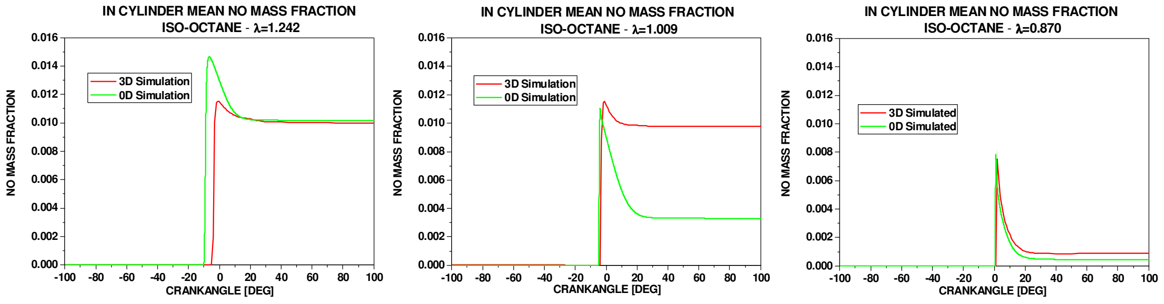
Fig. A2.10 Effect of waste-gate opening on turbine mass flow components

This methodology has been successfully applied for selecting, optimizing and characterizing the turbo-charging system for the Target Engine.

Main contribution of IM-CNR has been devoted to the development of a **simplified model for the analysis of knocking behaviour**. The advantages offered by SI engine downsizing with turbo-charging can be significantly limited by knock occurrence. Several detailed kinetic models are proposed in literature, but their direct employment in multidimensional codes for engine simulation is not convenient, since they would imply a huge computational effort and calculation time because of their complexity. A reduced-order kinetic model, considering a relatively small number of species and reactions, would be more suitable for knock simulation on SI engines in 3D codes. To this aim a proper procedure has been developed and experimentally assessed in order to identify a “reduced model” attaining the best compromise between accuracy and computational simplicity.

Six reduced kinetic schemes were chosen as candidate for the final experimental assessment. The schemes (base on Golovitchev, Keck and Ranzi models respectively) have been designed to consider Primary Reference Fuels blends, but can be used also for pure iso-octane and n-heptane and to include a set of reactions involving the NOx species. These six possible schemes were used for numerical testing and all of them were set for pure iso-octane.

In stoichiometric conditions all the considered schemes simulate fairly well the development of the combustion pressure in the cylinder, and give acceptable results on the simulated concentration of CO at Exhaust Valve Opening. As regards the results on auto-ignition crankangle (which is the decisive criterion in the final choice of the model to be adopted in 3D simulation), the reduced chemical kinetic models by Golovitchev and Ranzi give fairly good results in the lean range, but in the rich side give results that are far from experimental data. On the contrary the reduced kinetic model by Keck, modified with the addition of the set of reactions involving the NOx species, seems the most suitable for auto-ignition prediction in the range of the relative air/fuel ratio between moderate rich and slightly lean conditions. Based on this issue, this modified Keck model was chosen as the candidate for the simulation of auto-ignition on the CFR single cylinder engine within the 3D simulations.
Fig. A2.11 shows the average in-cylinder mass fraction of NO species. As expected, the most significant differences between the results of 0D and 3D are found at stoichiometric conditions. Here, 3D simulation takes into account the influence of NO concentration gradient following the temperature gradient, with effect on the freezing history of NO chemistry during the expansion stroke, leading to a higher final value of NO mass fraction with respect to 0D simulation, where temperature is considered uniform across the in-cylinder volume.



REL. AFR=1.242 **REL. AFR=1.009** **REL. AFR=0.870**

Fig. A2.11 Comparison of 0D and 3D simulated average NO mass fraction on iso-octane auto-ignition in the motored CFR engine, at lean, stoichiometric and rich mixture.

This results confirm on one hand the importance of a 3D analysis of the auto-ignition phenomenon based on a proper reduced kinetic model, and on the other hand the need of an accurate testing and verification of the features of a proposed model as performed in the described novel assessment procedure.

Engine Development

One of the main goal of TW2 has been the development and the adaptation of an **advanced system for the electro-hydraulic variable actuation of inlet valves**. The operating principle of the system is shown schematically in Fig. A2.2. The tappet piston and the engine intake valve are connected through an high pressure oil chamber, which is controlled by a normally open, on-off solenoid valve. When the solenoid valve is closed (activated) the intake valve essentially follows the cam motion (full lift).

Early intake valve closing (EIVC) is obtained by opening (deactivating) the solenoid valve at a certain cam angle. Oil flows out of the high pressure oil chamber into the low pressure channel. The motion of the valve is de-coupled from that of the tappet and, forced by the valve spring, the valve closes earlier than in the full lift mode. Soft landing of the intake valve is achieved through a hydraulic dampening unit (hydraulic brake). During the following re-filling of the high pressure oil chamber, oil flows back through the open solenoid valve also thanks to the presence of a spring-loaded accumulator. Similarly, late intake valve opening (LIVO) can be achieved by retarding the solenoid valve activation.

The flexibility of the UNIAIR electro-hydraulic actuator in terms of valve lift and timing variation is shown in Figg. A2.12 and A2.13

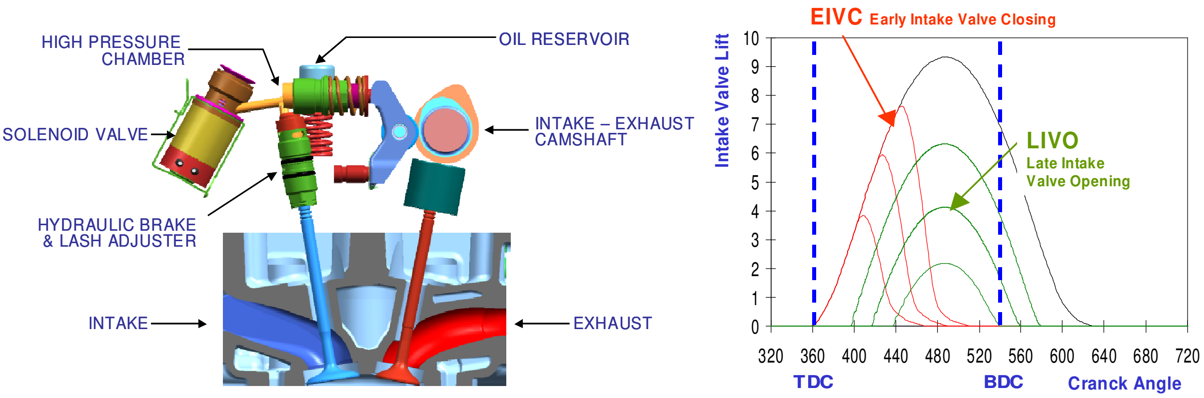


Fig. A2.12 *Electro-hydraulic valve actuation principle*

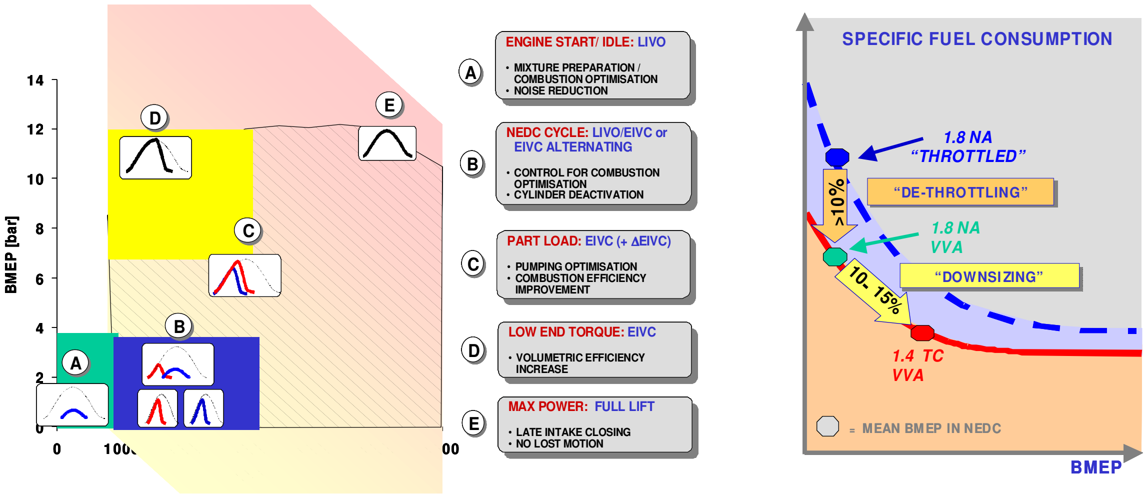


Fig. A2.13 *Main features of VVA system and its impact on fuel consumption*

Fig. A2.14 shows the cylinder head with components. In particular it is important to notice the single camshaft that drives intake (with electro-hydraulic actuation) and exhaust valves and the 8 solenoid valve that allow controlling the intake valves motion.

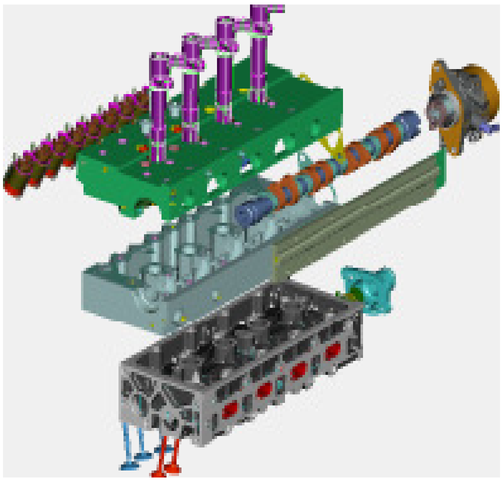


Fig. A2.14 *Cylinder head assembly & Upper cylinder head architecture*

The actuator has been optimized in order to improve system robustness and minimize the impact on the layout of conventional cylinder heads. The main design guidelines were oriented to achieve the following targets: use of the conventional engine oil with minor changes to the lubricating system; reduction of the moving masses and minimization of the mechanical energy consumption; reduction of the actuator performance dependence on oil viscosity; elimination of any kind of maintenance during actuator life.

The optimized engine head has been set-up and integrated on the 1,4l 16V engine. Several alternatives have been considered for cam-shaft, inlet/outlet and ignition timing, turbo-charger, inlet manifolds. Final configuration allow to achieve the following results:

• Low end torque	210 Nm @ 1750 rpm
• Maximum torque	232 Nm @ 4000 rpm
• Power	119 kW @ 5750 rpm

In order to compare the performance of "Mule 1 (2.0 GDI+TC)" , "Mule 2 (1.6 VVA+TC)" and "1.4 Downsized TC" Target Engine, some similar "Normal Production" engines have been considered. The 2.0 liter MPFI and the 2.0 liter GDI, both naturally aspirated, have been considered as "reference engines" and simulations were performed in order to determine the improvement of the prototypes in terms of fuel consumption in NEDC cycle and performance index.

Observing the graph in figure A2.15 it is important to notice the effects and the progress obtained using different technologies. So the first step is the increase of performance obtainable using gasoline direct injection and turbo-charging with the same displacement of base engine (even better with the use of a double variable cam phaser device). The second step shows an improvement of fuel consumption of about 20% due to downsizing (10%) and to the de-throttling (10%) possible with the VVA (Variable Valve Actuation) technology.

The final Target Engine configuration "1.4 Downsized TC" allows to achieve both fuel consumption in NEDC cycle and performance index very near to those of a Normal Production 1.9 16V JTD Diesel Engine. The fuel consumption reduction respect to the base engine configuration (2. 0 liter MPFI NA) is around 30%.

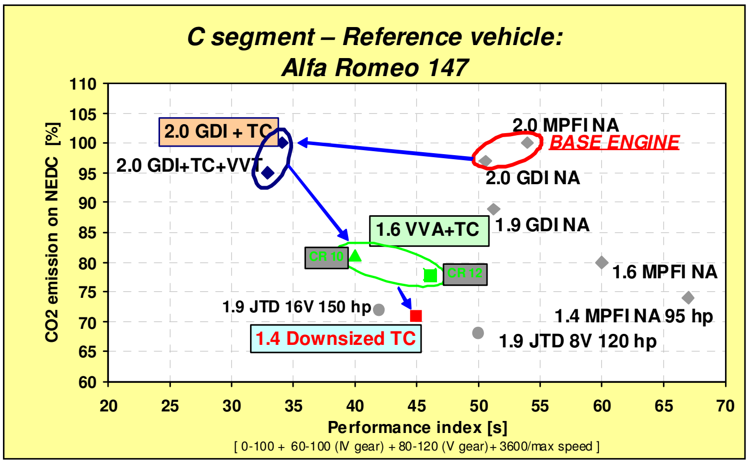


Fig. A2.15 Simulation of NEDC cycle and performance with reference to commercial engines

Same kind of simulation was done using the Artemis cycle in two different shapes (see fig. A2.16).

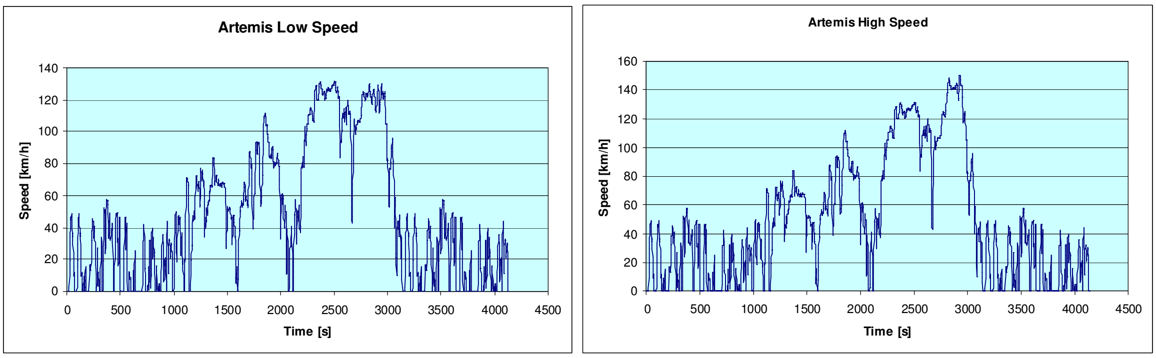


Fig. A2.16 Artemis low speed & high speed cycles

The results of the simulation to evaluate the improvement in fuel consumption respect to base engine are shown in fig. A2.17. The fuel consumption reduction respect to the base engine configuration (2. 0 liter MPFI NA) is around, in both cases, 20%.

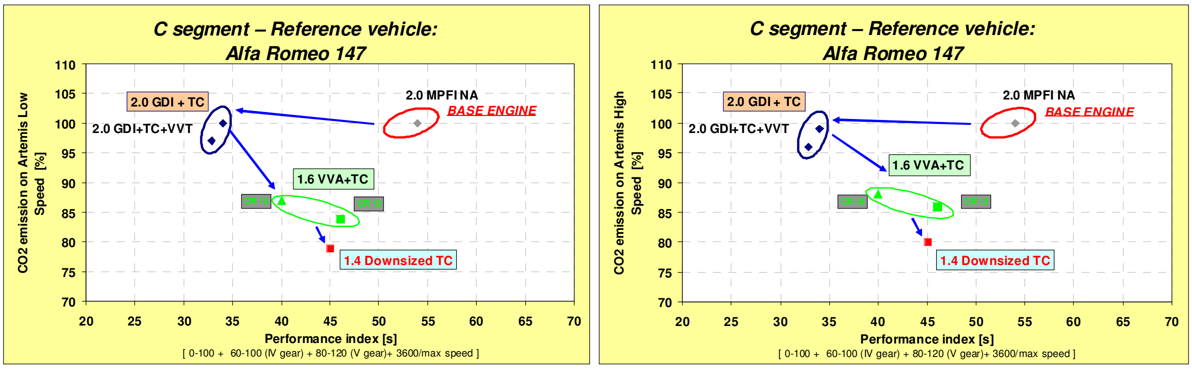


Fig. A2.17 Simulation of Artemis low & high speed cycles and performances

- General Conclusion
    - A breakthrough in SI engine technology is necessary to recover competitiveness towards modern Diesel
    - Dethrottling, turbocharging and Gasoline Direct Injection represent the major developments areas, to improve both fuel economy and fun to drive.
    - Throttleless air control, based on Electronic Valve Control (EVC), as the VVA system developed and integrated by CRF, offers a significant potential to improve engine efficiency, with competitive add-on costs.
    - Through the integration of EVC with turbocharging technology, further significant improvement can be achieved, due to the full exploitation of downsizing potentials.
    - The optimal approach towards advanced technologies is primarily dependant from engine size and mission.
    - On large, power oriented, engines, Turbo GDI represents a “state of the art” thanks to the optimal and synergic integration with cam phasing technologies, strongly improving gas exchange at full load (air scavenging)
    - On small/medium engines, where the market is mainly driven by costs and fuel economy, the NA EVC PFI technology represents the optimal solution to balance fuel economy and driveability benefits with very low add-on costs.
    - The extension of the EVC technology to downsized/TC engines makes possible to approach CO2 and fun to drive of diesels, with lower costs and maintaining the intrinsic advantages in terms of emissions and comfort.
    - SI powertrain offers intrinsic compatibility with Low Carbon Fuel technologies, opening the way to ultra low CO2 vehicles while maintaining complexity and costs compatible with wide marketing.

2.2.5. SPA2 – Technology Way 3

2.2.5.1 Objectives

Technology Way 3 aimed to develop an advanced multi-cylinder engine with a new integrated combustion system, meeting future emission levels and high demanding fuel consumption targets and able to operate with new alternative fuels

The fuel is in fact an important parameter for new combustion systems to fulfill future emissions levels and to reduce fuel consumption and CO_2-Emissions.
New integrated combustion systems have high demands on the chemical and physical fuel properties. The enlargement of the homogeneous load range for alternative combustion like “highly premixed late injection” (HPLI) and “homogenous charge late injection” (HCLI) is an example for fuel application. New tailor-made fuels will satisfy those high demands.
The common characterization of fuels refers to the cetane number (CN) and the boiling behavior.
Figure A2.18 shows a matrix, with different fuels, which have been investigated.

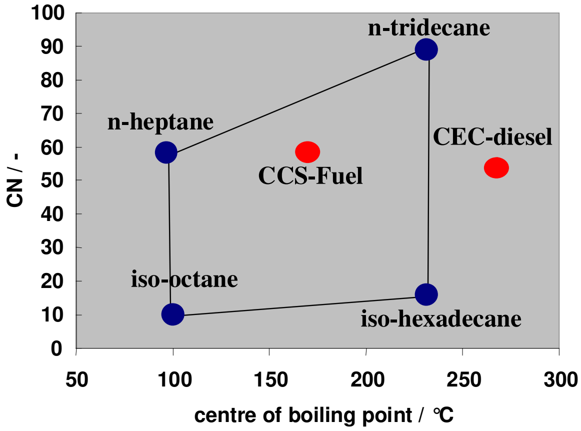


Fig. A2.18 Fuel Matrix

2.2.5.2 Contractors involved

- Volkswagen AG [VW]
- Czech Technical University in Prague [JBRC]
- AVL List GmbH [AVL]

2.2.5.3 Work Performed & Final Results

- Work performed
    - **Layout, design and setup of a new integrated combustion system, meeting future emission levels and high demanding fuel consumption targets.**
    - Based on calculations for the NEDC, 7 relevant points were defined, to be investigated by means of linked experiments such as optical investigations of the spray formation in a pressure chamber (VW), optical investigations of the combustion in a transparent engine (VW) and combustion system development and application work on a fully flexible **single cylinder research engine** (AVL). Several hardware/combustion variants were investigated to optimize the combustion system to alternative fuels as shown in table A2.1.

Parameters	specification
nozzle geometry	8 hole – flow rate 704.5 7 hole – flow rate 920 (Series) 5 hole – flow rate 1120 5 hole – flow rate 925.5
Start of injection	6.6; 10.6; 14.6°KW before top dead centre
EGR- Rate	0 % - 70 %
Swirl flap	0 % - 100 %
rail pressure	1200 bar; 1600 bar

Table A2.1: HW variants and main investigated combustion parameters

- The **multi-cylinder engine** tests at VW investigated the best outcome of piston bowl and injector nozzle from single cylinder tests performed by AVL. The measurement based on seven load points which are relevant to NEDC. To find the best setup for each load point four parameters have been varied:
    - Rate of EGR
    - MFB50% (mass fraction burned)
    - Swirl
    - Railpressure

  An experimental design created with DoE was used and executed for each load point. With these data polynomial models were built and local optimisation for all seven load points had been carried out. The optimised parameters for each configuration were weighted by NOx and time respectively. The outcomes were extrapolated emissions for the NEDC and an optimal configuration.
- The whole process was intensively backed by 1-D & 3-D simulations.

- **1D Simulations.** Simulation of injection by 1-D approach successfully predicted problems of low viscosity synthetic/renewable fuels concerning changes in injector control. 1-D engine and control system simulation was able to transfer the results from a SCRE to a full-size 4C one. The simulation was used to match the EGR system of a 4C experimental engine. The predicted problems of unsteady operation have been solved on preliminary level only to compare the potential of each EGR system in consideration. 3-D charge-exchange simulation of an advanced swirl controlling system was performed to assess the impact of charge exchange features variability on charge homogeneity, important for HCCI-like combustion.
- **3D Simulations.** The CFD code FIRE with newly extended methodologies for multiphase flows from AVL in subproject B1 was integrated into the Volkswagen computer hardware and software environment to perform parallel 3D simulations of transient cavitating injector flows. The 3D injector simulations of different NEDC points were performed for CEC Diesel and the alternative CCS-Fuel. Some effort has been made to investigate, collect and compare temperature and pressure dependent properties of the alternative fuel. Boundary conditions from 1D simulations performed by JBRC were applied. Time and area resolved results at the nozzle hole exit have been used for spray simulations using advanced models developed and reported within subproject.
- Benchmark assessment of the combustion system configuration with state-of-the-art CI technology

- *Final Results*

- Single Cylinder Engine tests
  - One single combustion system configuration (bowl/nozzle/variable swirl) can cover a wide variety of fuels (Distillation range: 150 – 360°C and cetane numbers of 45 to 60) burned in self igniting combustion mode
  - Correction of control pulse duration for common rail injection in order to inject same energy equivalents, a lambda control and correction of ignition delay are necessary in order to burn a variety of fuels with respect to the expected fuel diversification in Europe (and worldwide)
  - A closed loop combustion and torque control is the required engine technology in order to burn different fuels taking full use of low NOX-combustion
  - A highly flexible variable valve train was tested in stationary operation. No advantages were seen and it was concluded that a highly flexible variable valve train is not cost effective for a diesel engine
  - A matrix of 5 representative, alternative fuels of the 1st and 2nd generation was tested. The most promising fuels were RENEW (BTL) and FT-Kerosene (BTL or GTL)
  - The results for RENEW showed ~90% lower soot, ~50% lower THC and ~0.5% lower energy consumption at an NEDC (Steady State) NOx level of ~0.06 g/km in comparison to diesel fuel as a reference
  - The results for FT kerosene showed ~90% lower soot, ~8% lower THC and ~1.5% lower energy consumption at an NEDC (Steady State) NOx level of ~0.06 g/km. The results were confirmed on a stationary running multi-cylinder engine
  - The results clearly indicate the potential for reducing not only particulate emission but also energy consumption with new formulated fuels. With fuel detection means and closed loop combustion control, potential is shown how to run a wide variety of fuels in a normal diesel engine with a fixed hardware. Multi-fuel capability in conjunction with the ability to run the engine in combustion modes with high EGR and low NOx can thus be solved with enhanced ECU control functions based on the online processing of the cylinder pressure.

- Multi-cylinder Engine tests
  - In table A2.2 the optimal parameters, the emissions for all load points and the over all expected emissions for NEDC are shown. The over all NEDC limits also shown in table A2.2 were calculated from EU V limits multiplied by the distance of a NEDC. As displayed the limits concerning soot and NOx emissions were kept. But this is only a non transient extrapolation of the NEDC emission level.

AVL Bowl; 8 hole Injector	MFB 50% [°KW nOT]	EGR [%]	Rail-pressure [MPa]	swirl-flap [%]	FC [g/kWh]	HC [g/h]	NOx [g/h]	soot [g/h]
1200 rpm @ 40 Nm	7.9	46.6	53	4.9	288.3	27.7	3.0	0.002
1200 rpm @ 80 Nm	16.8	41.7	120	15.1	235.2	13.2	1.8	0.0008
2000 rpm @ 40 Nm	4.9	55.9	100	32.6	323.8	11.4	11.3	0.004
2000 rpm @ 90 Nm	27.6	43.6	85	85.0	283.0	44.6	22.7	0.002
2500 rpm @ 60 Nm	8.6	65.3	130	85.0	296.8	12.1	13.5	0.028
3000 rpm @ 80 Nm	21.9	42.0	80	7.2	286.6	80.9	39.2	0.671
3000 rpm @ 130 Nm	20.1	18.6	97	8.9	238.9	20.9	116.0	2.8
over all NEDC extrapolation							1.84	0.054
over all NEDC EU5 limits							1.98	0.055

Table A2.2: optimal parameter – 8 hole injector – AVL piston bowl

- The four cylinder engine with the new combustion system optimised for CCS-Fuel of first generation achieves EU V emission level concerning soot and NOx emissions without particle filter or NOx after treatment.
- To include the Artemis driving cycle in this consideration an extrapolation from the 7 load points has been done. Since the Artemis driving cycle includes more acceleration parts and higher velocities than the NEDC, the weighting factors for LP 1-3 were halve, the weighting factors for LP 5-7 were doubled and the weighting factor for LP 4 was unchanged. The results from this extrapolation are shown in

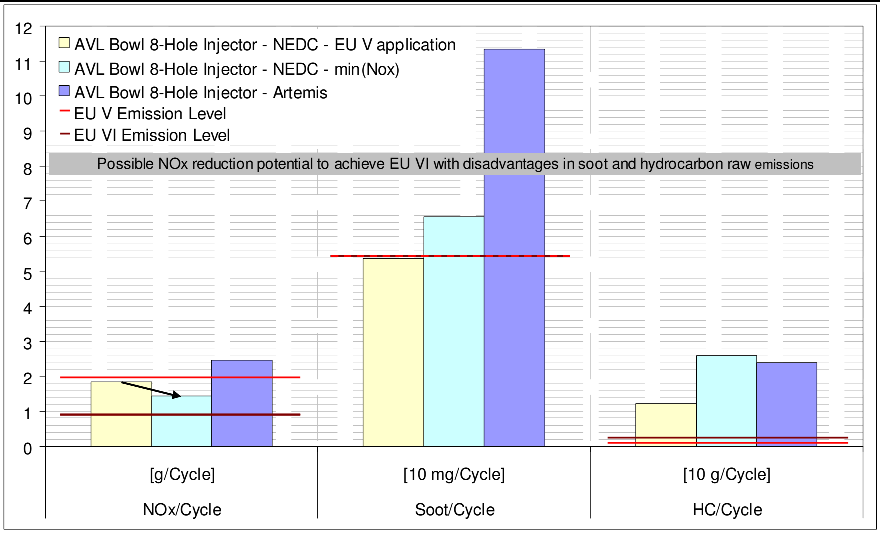


Fig. A2.19 Extrapolation to NEDC and Artemis Cycle

- . Additionally to the Artemis extrapolation a potential with minimized NOx emissions for NEDC is shown. A comparison of NEDC EU V and minimized NOx emissions show potential in NOx emissions to achieve EU VI emission level with disadvantages in soot emissions or a higher exhaustion of the particulate filter. The extrapolation for the Artemis cycle shows higher emissions for NOx, soot and hydrocarbons compared to the EU V application.

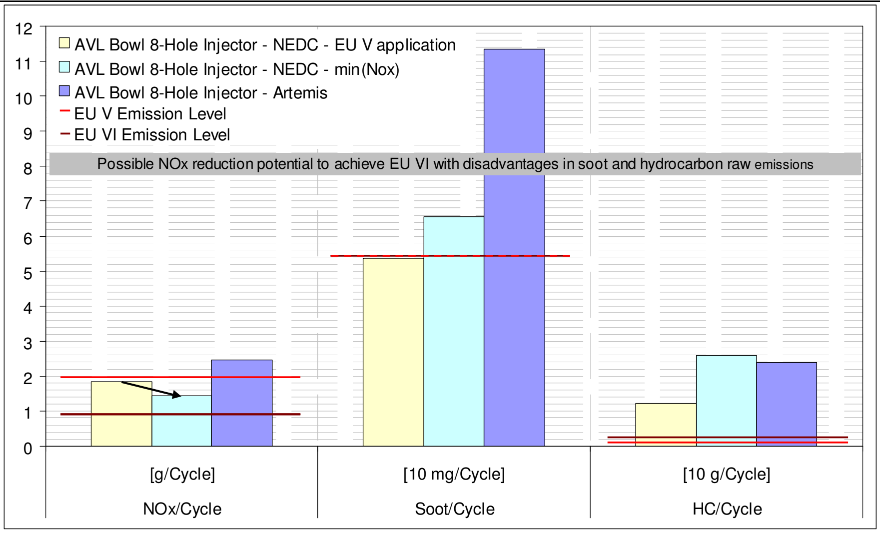


Fig. A2.19 Extrapolation to NEDC and Artemis Cycle

- Simulation
  - **1D Simulations.** The problems of low-viscosity fuels (like Fischer-Tropsch kerosene or even n-heptane/i-octane mixtures) do not create an important issue concerning CR control and ROI time patterns. A simple low pressure EGR system, using flow split downstream of a DPF, features no problems at steady and unsteady operation except for increased b.s.f.c. or road fuel consumption during NEDC. The inevitable impact of large time ("transport") delay, peculiar to this system, on engine emissions cannot be fully assessed by 1-D simulation. The use of naturally caused pressure losses for EGR driving pressure difference is of advantage concerning engine efficiency and road fuel consumption.
    Miller or Atkinson systems feature apparently no big positive impact on b.s.f.c.; they bring about neither new problems with EGR and air excess feasibility nor improvement in it.
    3-D simulations are useful as a quantitative assessment tool for design of complicated ports in cylinder heads of variable (controlled) swirl if carefully meshed with the whole duct (including control flaps, e.g.). Unsteady simulations are rather sensitive to mesh design and coarseness but already useful for finding weak points of charge exchange/combustion system. The homogeneity of cylinder charge has to be achieved by squish motion otherwise the natural stratification survives during a compression stroke.
  - **3D Simulations.** The post processing of the 3D injector simulations indicated increased cavitation in the needle seat region during lower needle lifts and near the nozzle hole entrance during the main injection phase for the CCS-Fuel compared to standard Diesel. This is mainly due to the lower viscosity of the alternative fuel. However, the mass flow rate through the injector is not effected by the increased cavitation beyond the expected effects of difference in density of the investigated fuels.

- <u>Degree of which objectives were reached</u>

- Multi Cylinder Engine Tests

The wide range of possible hardware variations and optimisable tailor made fuels, which are not yet investigated still provide reduction potential for emissions and fuel consumption. The conducted hardware, fuel and parameter variations gave hints to possible better configurations than the applied ones in this research. The mixture formation has high influence on emissions. Hence an injector with more than 8 holes may provide even lower emissions. Likewise a high potential for emissions and CO_2 reduction showed the CCS-Fuel first generation. An optimised fuel with a lower centre point of boiling and an adapted Cetane-number to influence the ignition delay may have high potential in soot, NO_x and CO_2 emission reduction. Also the different possible combustion processes like homogeneous charge compression ignition, homogeneous charge late injection, highly premixed late injection and dilution controlled combustion system combined in one engine for different load provide high reduction potential mainly for transient mode.

This knowledge builds the background for possible future investigations. Research demands are still in the fields of closed loop combustion control and optimizing fuel properties to achieve future emission levels.

- Simulation

1D Simulations. The future EGR system development requires to employ high-efficiency turbochargers and to start the development of new integrated components, e.g., a high-pressure DPF or the integration of an EGR system into a turbocharger. These new ways were found during project solution amending the current SOTA.

New integrated control systems for massive EGR and sufficient air supply were preliminarily designed and tested by simulation as a base for the future development.

New experience with predictive capacity of 3-D tools was acquired. The hints to charge exchange design considering in-cylinder motion for HCCI-like combustion were found.

3D Simulations. One objective regarding the injector simulation was to perform these transient 3D calculations in a stable and reliable way over night. Due to the successful software integration into the VW computer environment the simulation of one load point took about 8 hours, and has hence fully reached the expectations. Furthermore the predictions of the cavitating flow of different fuels inside the injector including geometrical variations helped to improve the understanding of the complex transient phenomena in this small and hence difficult to optically access engine component. On top they provided important time and area resolved boundary conditions for advanced multi-phase modelling of fuel sprays.

2.2.6. A2-List of acronyms

ATDC	After Top Dead Center
AVL	Partner N. 02
AFR	Air Fuel Ratio
BMEP	Brake Mean Effective Pressure
BDC	Bottom Dead Center
BSFC	Brake Specific Fuel Consumption
BTDC	Before Top Dead Center
BTL	Biomass-To-Liquid Synthetic Renewable Fuel
C	Carbon Content
CA	Crank Angle
CCS	Fischer-Tropsch Kerosene
CEC	Standard European Diesel Fuel (Coordinating European Council)
CFD	Computational Fluid Dynamics
CFR	Cooperative Fuel Research
CI	Compression Ignition
CN	Cetane Number
CR	Common Rail
CRA	Crank Angle measured from TDC
CRF	Partner N. 07
CRIP	Common Rail Piezoelectric-Controlled Injector
DC	Partner N. 01
DI	Direct Injection
DOE	Design Of Experiments
DOT	Delay Optimised Turbo
DPF	Diesel Particulate Filter
ECU	Electronic Control Unit
EGR	Exhaust Gas Recirculation
EMS	Engine Management (Control) System
EIVC	Early Intake Valve Closing
EO	Exhaust Valve Opening
ETA I	Indicated Efficiency
F	Fuel
FBP	Final Boiling Point
FEV	Partner N.09
FIE	Fuel Injection Equipment
FSN	Filter Smoke Number
FT	Fischer – Tropsch
GDI	Gasoline Direct Injection
GT	Gamma Technologies Inc.
GTL	Gas-To-Liquid Synthetic Fuel
H	Hydrogen Content
HP	High pressure (turbine inlet – compressor outlet)
HCLI	Homogeneous Charge Late Injection
HPLI	Highly-Premixed Late Injection
HSDI	High Speed Direct Injection Diesel
IBP	Initial Boiling Point
IC	Inlet Valve Closing
IE	Injection Ends
IM-CNR	Partner N. 13
IMEP	Indicated Mean Effective Pressure
ISFC	Indicated Specific Fuel Consumption

JBRC	Partner N.05
LP	Low pressure (turbine outlet – compressor inlet)
LPdownDPF	Low pressure (DPF outlet – compressor inlet)
LAMBDA	Air Excess
LIVO	Late Intake Valve Opening
M	Mechanical
MFB	Mass Fraction Burned [at 50% the center of gravity for ROHR]
MHI	Multi Hole Injector
(ND/N)M	AVL Paddle-Wheel Swirl Number
NA	Naturally Aspirated
NEDC	New European Driving Cycle
NICE	New Integrated Combustion System For Future Car Engines
Nox	Total Nitrogen Oxides Emission
NTP	Nozzle Tip Protrusion, location of spray root in a combustion chamber
OH	I-Octane 74% - N-Heptane 24% Mixture
PID	Proportional-integrating-derivating controller
PFI	Port Fuel Injection
PWM	Pulse Width Modulated Signal (used as a marker for swirl flap position, high numbers mean high swirl)
RHO	Fuel Density @15°C
ROHR	Rate-Of-Heat-Release, Approx. Rate Of Burning
ROI	Rate-Of-Injection
RON	Research Octane Number
RWTH/VKA	Partner N. 18
SCRE	Single Cylinder Research Engine
SFD	Space Filling Design, Latine Hypercube Sampling For Doe
SI	Spark Ignition
SOE	Start Of Energizing Of Piezo Stack – wanted start of injection at CR
SPI	Single Point Injection
T	Turbine
TC	Turbo Charging
THC	Total Hydrocarbons (Unburned Organic Compound Emission)
TDC	Top Dead Center
TDI	Turbocharged Direct Injection Diesel
TW	Technology Way
UNI-GE	Partner N. 22
VGT, VTG	Variable Geometry Turbine
VVA	Variable Valve Actuation
VVT	Variable Valve Timing
VW	Partner N. 25
WG	Waste Gate
WOT	Wide Open Throttle

2.3 Subproject A3

2.3.1. Objectives

Vehicles powered with natural gas are well known for a long time. However, today’s gas engines for passenger cars and commercial vehicles still have the heavy drawback of being developed as multi-fuel engines on the basis of conventional internal combustion engines. Optimized mono-fuel natural gas engines offer additional potential regarding fuel consumption, emissions and performance. Objective of this subproject is to evaluate this potential and to find out favorable technological concepts.

During the initial concept phase a downsizing concept with high boost turbocharging was chosen due to the high knock resistance of natural gas. Furthermore different technological approaches for mono-fuel turbocharged CNG engines have been generated:

- Technology Way 1:
  Direct injection (DI), high rail pressure, stoichiometric/lean mixture combustion.

- Technology Way 2a:
  Port fuel injection (PFI), overall (part load / WOT) lean mixture combustion via the Advanced Turbulence Assisted Combustion (ATAC) concept.

- Technology Way 2b:
  Port fuel injection (PFI), stoichiometric/lean mixture combustion.

The investigations conducted should show the advantages and disadvantages of each concept and demonstrate the potential. The goal was to reach the efficiency of a diesel engine. One further objective was the evaluation of the combustion process for bio/bio-blend gases.

2.3.2. Contractors involved

All partners of subpoject A3 are listed below:
- AVL List GmbH, Graz, Austria (AVL)
- BERU AG, Ludwigsburg, Germany (BERU)
- Cracow University of Technology, Cracow, Poland (CUT)
- Daimler AG (former DaimlerChrysler AG), Stuttgart, Germany (Daimler)
- FEV Motorentechnik GmbH, Aachen, Germany (FEV)
- Ford Research Center, Aachen, Germany (Ford)
- Politecnico di Torino – Dipartimento di Energetica, Torino, Italy (PT)
- Rheinisch-Westfaelische Technische Hochschule Aachen, Aachen, Germany (RWTH)
- Siemens CT, München, Germany (Siemens CT)
- Siemens VDO Automotive AG, Regensburg, Germany (Siemens VDO)
- Technische Universitaet Graz, Graz, Austria (TUG)

Fig. A3.1 gives an overview of contractors involved, their major tasks and the subproject structure.

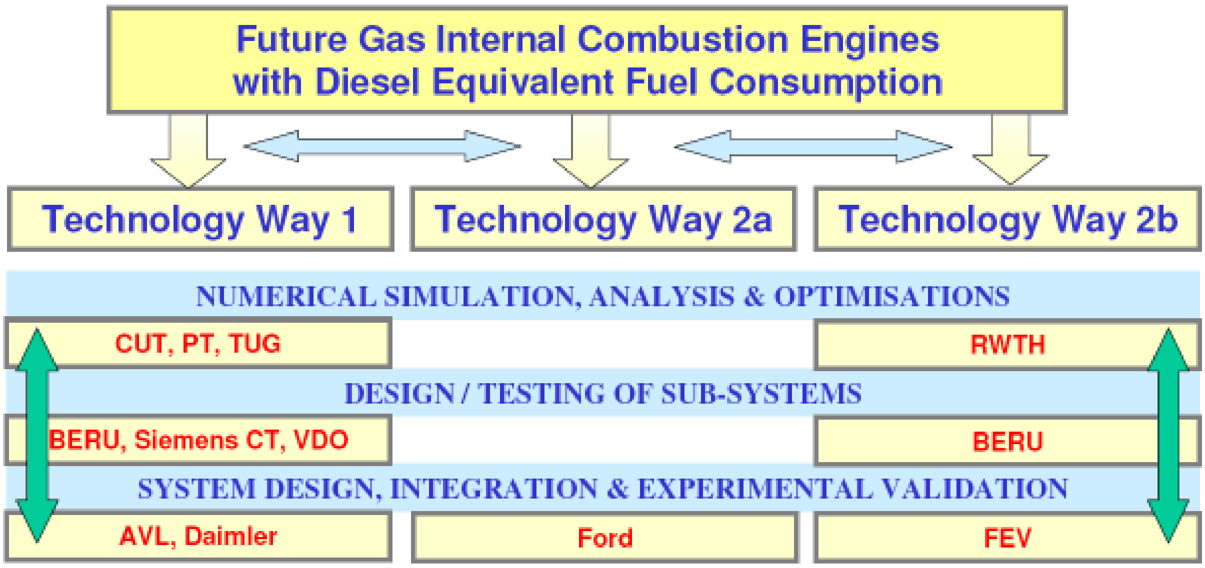


Fig. A3.1 Overview of contractors involved, their major tasks and subproject structure

2.3.3. Technology Way 1

2.3.3.1 Work performed

Direct injection of CNG exhibits several potential benefits:

- Lean burn combustion with stratified charge
- Improvement of volumetric efficiency via injection after intake valve closing, thus enhancement of torque and performance
- Simple conversion of gasoline engines with direct injection to a gas engine

The potential of CNG DI was investigated and evaluated within Technology Way 1.

For the investigations regarding CNG direct injection an efficient injection system was required. First considerations showed that an injection system derived from a gasoline injector with only little modifications was not practical. Because suitable direct injection systems for CNG were not available, the development of such an injector and build of prototypes for engine tests was a major task within this subproject. Politecnico di Torino carried out 3D numerical simulation of methane injection from a poppet valve injector into open and closed environment. These simulations supported the injector development at Siemens CT.

Siemens VDO developed and provided the engine management systems for both single- and multi-cylinder test engines and supported the application. The performed work is illustrated by Fig. A3.2

Technische Universitaet Graz carried out 3D numerical simulation of methane injection and mixture formation in the combustion chamber to support the development of the combustion system at AVL and Daimler. Different single-cylinder engines and a multi-cylinder engine have been designed, manufactured and built-up. Fig. A3.3 shows the configuration of the single-cylinder engine with centrally mounted piezo injector and the final design of the multi-cylinder engine with intake side mounted injector. The multi-cylinder engine features 4 cylinder (inline), a displacement of 1.8 liter, compression ratio 12.2, turbocharger BWTS K04 2070 ECD 4.82.

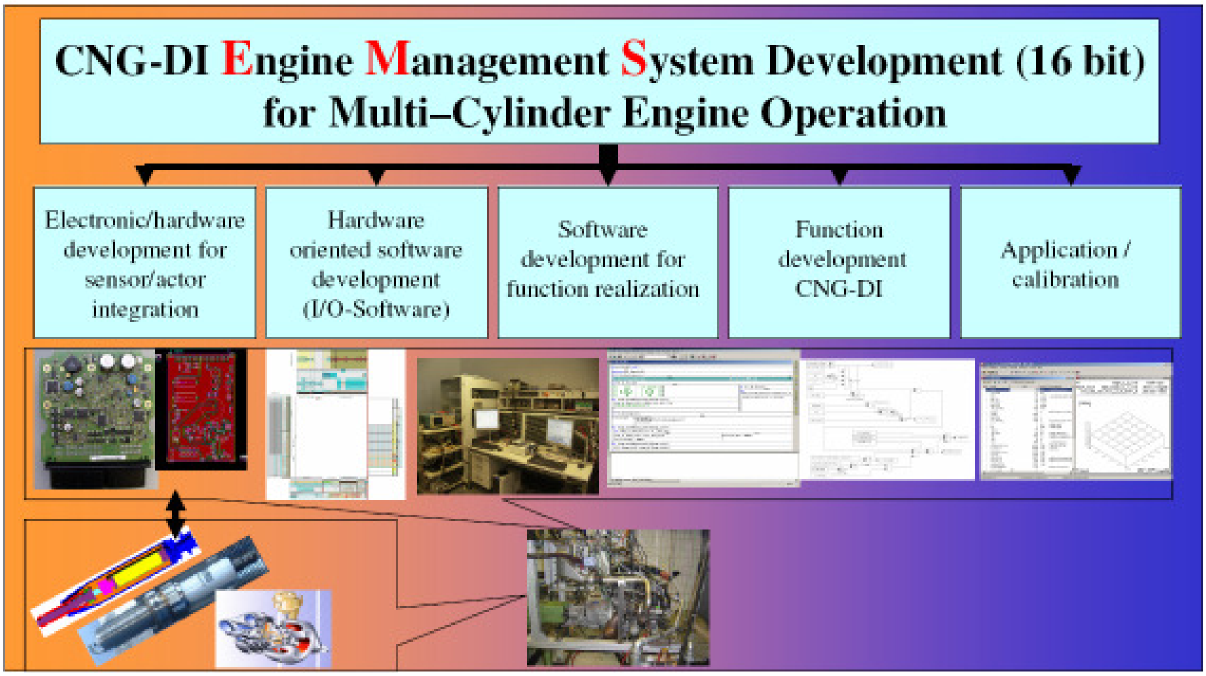
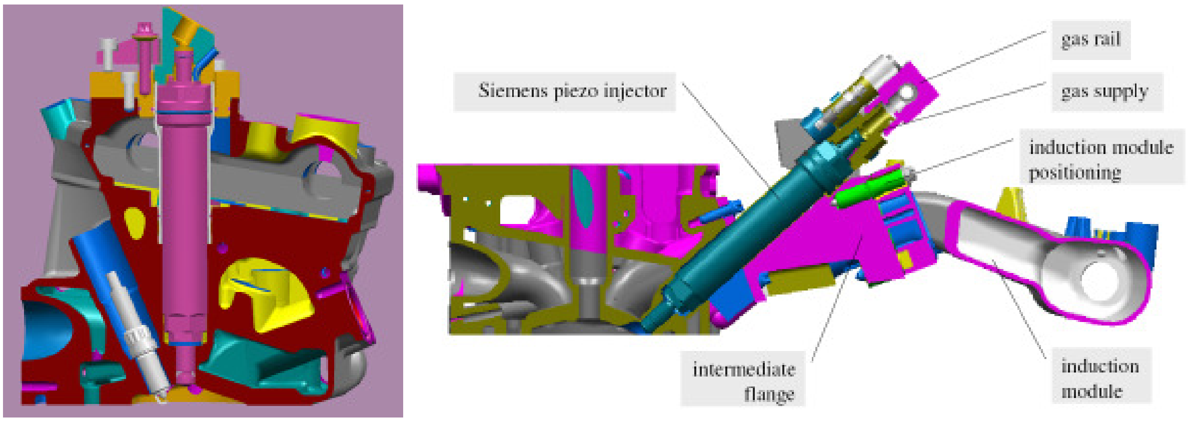


Fig. A3.2 Engine management system development



(a) (b)

Fig. A3.3 Single-cylinder engine concept with centrally mounted injector (a) and final multi-cylinder engine design (b)

The engine tests for Technology Way 1 at AVL and Daimler comprised a wide range of concepts and variants:

- Test engines:
  - single-cylinder engines
  - multi-cylinder engine
- Injectors:
  - Multi-hole injectors based on the Siemens Synerject injector with different nozzle geometries
  - AVL DMI injectors with different nozzle geometries
  - Newly developed piezo injector by Siemens CT with different stages of development

- Injector locations:
    - intake side mounted injector
    - centrally mounted injector
- Combustions systems:
    - air guided combustion system
    - wall-guided combustion system
- Fuels
    - natural gas
    - biogas
    - biogas-blends

2.3.3.2 Final Results

Injector for CNG DI

During the concept phase the specifications for the injector were determined:

Rail pressure	20 bar
Amount of CNG in full load per cycle	80 mg
Maximum injection time	8 ms
Maximum required CNG mass flow	10 mg/ms

3D simulations have been used to assess the needle cone angle. The influence of the needle cone angle on methane concentration contours for a given crank angle interval after start of injection is reported in Fig. A3.4. For the largest examined needle cone angle, the fuel jet tends to deviate towards the upper wall (last picture in Fig. A3.4). In this case, the needle-tip protrusion and the wall-injector relative orientation play a significant role in the definition of the jet shape and, hence, the whole mixture formation process. Finally, a needle cone angle of 75 deg was chosen.

It was decided to use 2 piezo stacks as actuator and transform the lift of the double stack with an appropriate component. For this purpose a hydraulic stroke transformer was chosen. The needle lift can be controlled to match the engine mass flow requirements. Fig. A3.5 shows the final design. The injector development was successful, the function and durability has been proved in single- and multi-cylinder engine tests.

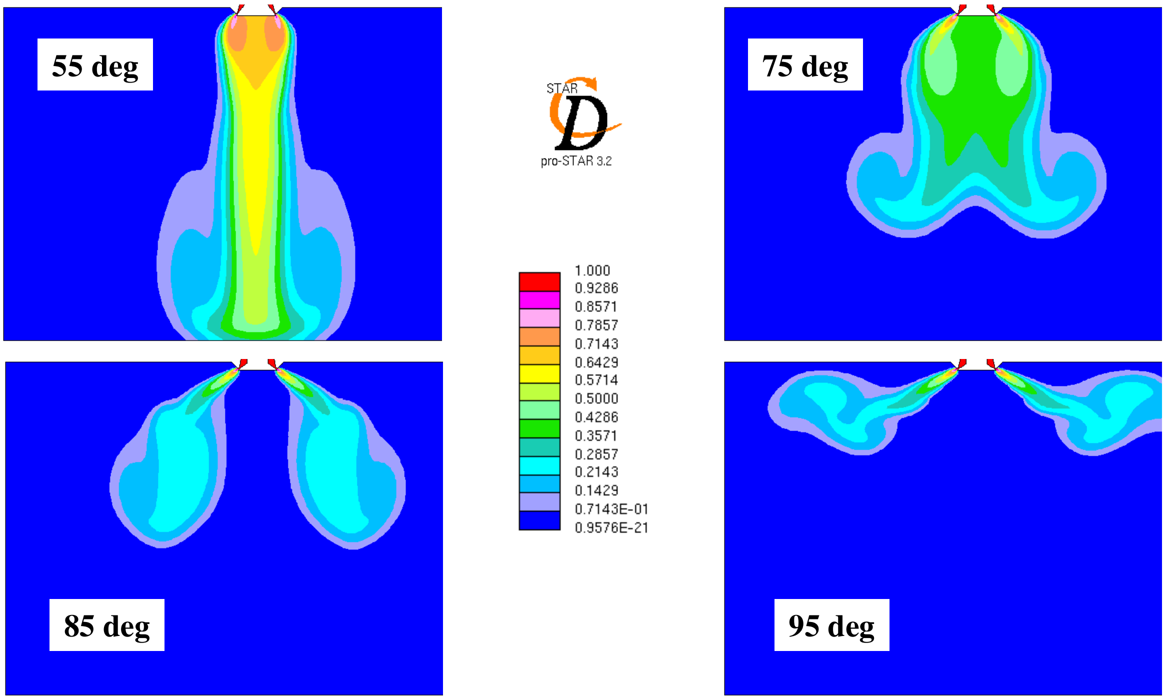


Fig. A3.4 Influence of needle cone angle on methane concentration contours – 17.5 deg after start of injection

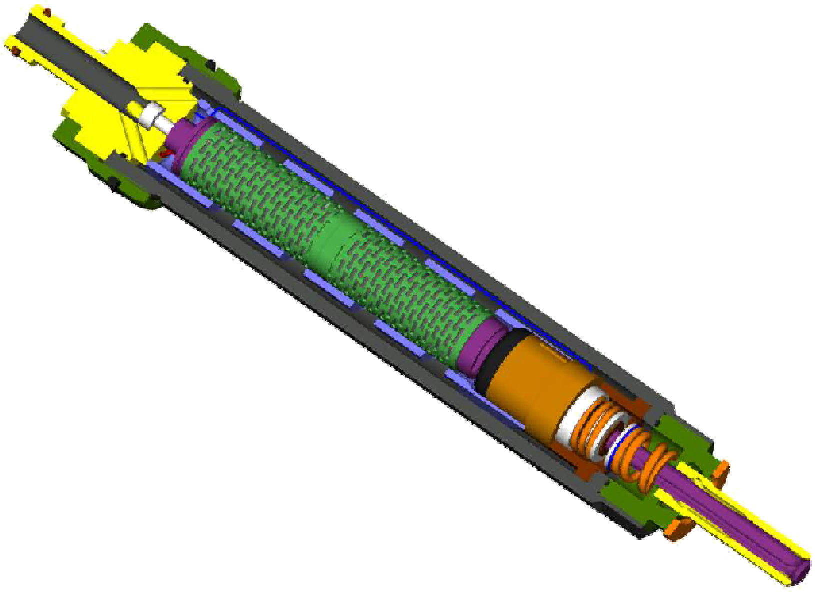


Fig. A3.5 Injector for CNG direct injection (Siemens CT)

Engine Management System

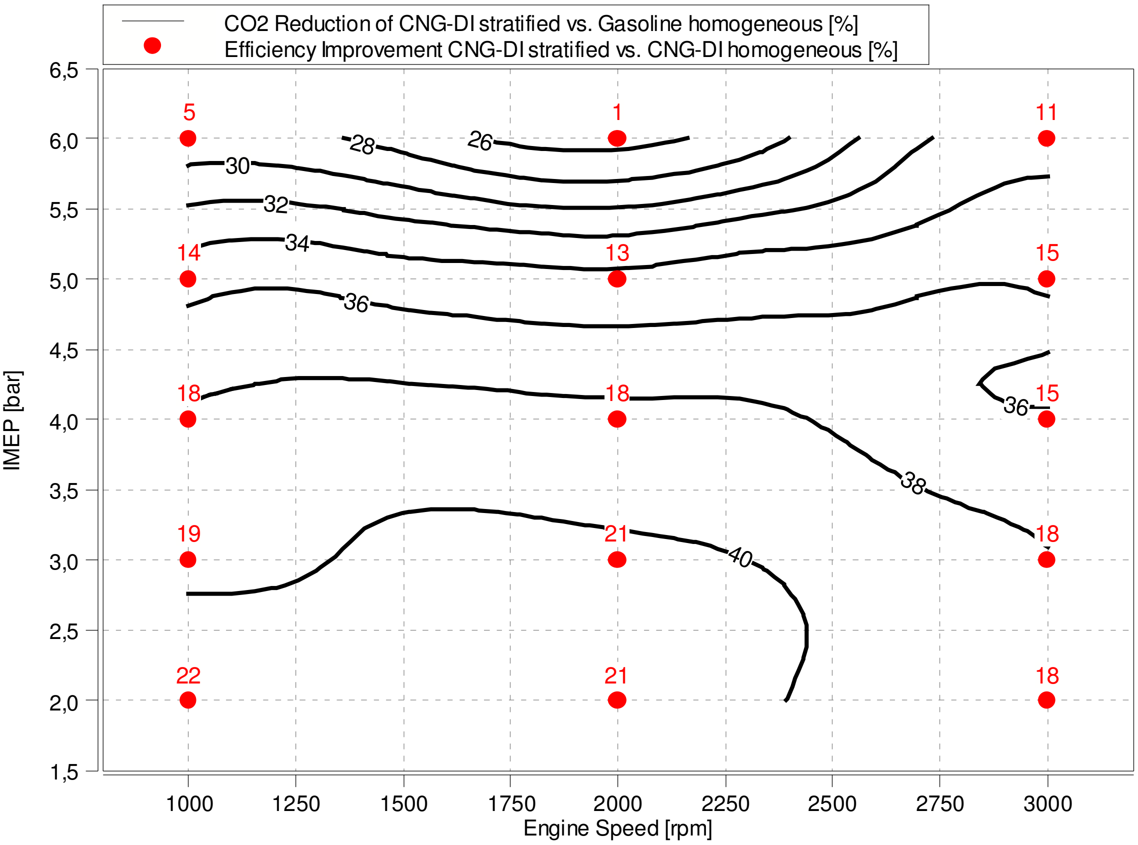
Siemens VDO developed the engine management systems for the single- and multi-cylinder test engines. The engine management system has to be imbedded inside the whole test environment. Therefore interfaces had to be clarified and hardware and software adapted to the different kind of electronic control units and measurement equipment. The major items concerning the engine management systems are listed below:

- The interface between engine management system und piezo injector power stages (HW/SW) were defined.
- The ECU specification for the use of the CNG piezo injector (HW and SW) was updated.
- ECUs for a single-cylinder and a multi-cylinder engine were provided.
- The model-based turbocharger control functionality was successfully integrated in the ECU.
- Additional ECU functional highlights:
    - up to 5 injections possible
    - cylinder selective injection time correction
    - end of injections can be freely calibrated
    - implementation of ECU changes related to new ignition system

Charge Stratification

Single-cylinder engine tests showed that charge stratification works well with a centrally mounted injector and an outwardly opening injector. The gas jet was directed at the piston bowl, where it was deflected towards the spark plug. Thus a wall-guided combustion system was chosen.

In part load the lean stratified approach shows best efficiency improvement up to 22 % compared to today's MPI engines (not optimized for CNG). Compared to a homogeneous operated gasoline basis this is over 40 % CO_2 reduction, see Fig. A3.6.



Map_strat.cly, 10/04/2006

Fig. A3.6 Relative efficiency improvement and CO_2 emission reduction compared to a Lambda = 1 gasoline engine

Lean Burn Operation

Lean burn combustion with homogeneous air-fuel mixture was investigated as well as with stratified charge (see above). In both cases considerable reductions in fuel consumption were achieved. However, it turned out that the exhaust-gas temperatures under these conditions (high compression ratio, turbocharging, lean combustion) are very low, what in combination with the high light-off temperature of the catalyst for natural gas leads to unfavorable conditions for exhaust-gas aftertreatment. Due to this fact there is no chance to reach EU5 emission limits in near future. Therefore the further investigations were focused on the evaluation of DI potential for homogeneous operation.

Stoichiometric Operation

The BSFC map (Fig. A3.7) shows the fuel consumption of the multi-cylinder engine at stoichiometric operation for different operating points. In that case the camshafts were not shifted, though maximum loads are relatively low and do not represent the maximum values. The fuel consumption in the NEDC (steady state replacement test) is 9.6 % lower compared with a standard CNG engine due to the increased compression ratio and turbocharging. The optimization of the intake and exhaust valve timing leads to a further efficiency improvement of 2.1 % due to increased internal EGR.

Compared with single-cylinder engine results the O_2 emissions have been somewhat higher, what indicates that mixture formation is better in the case of centrally mounted injector (SCE) than with intake side mounted injector (MCE), and that there is further potential regarding the multi-cylinder engine results.

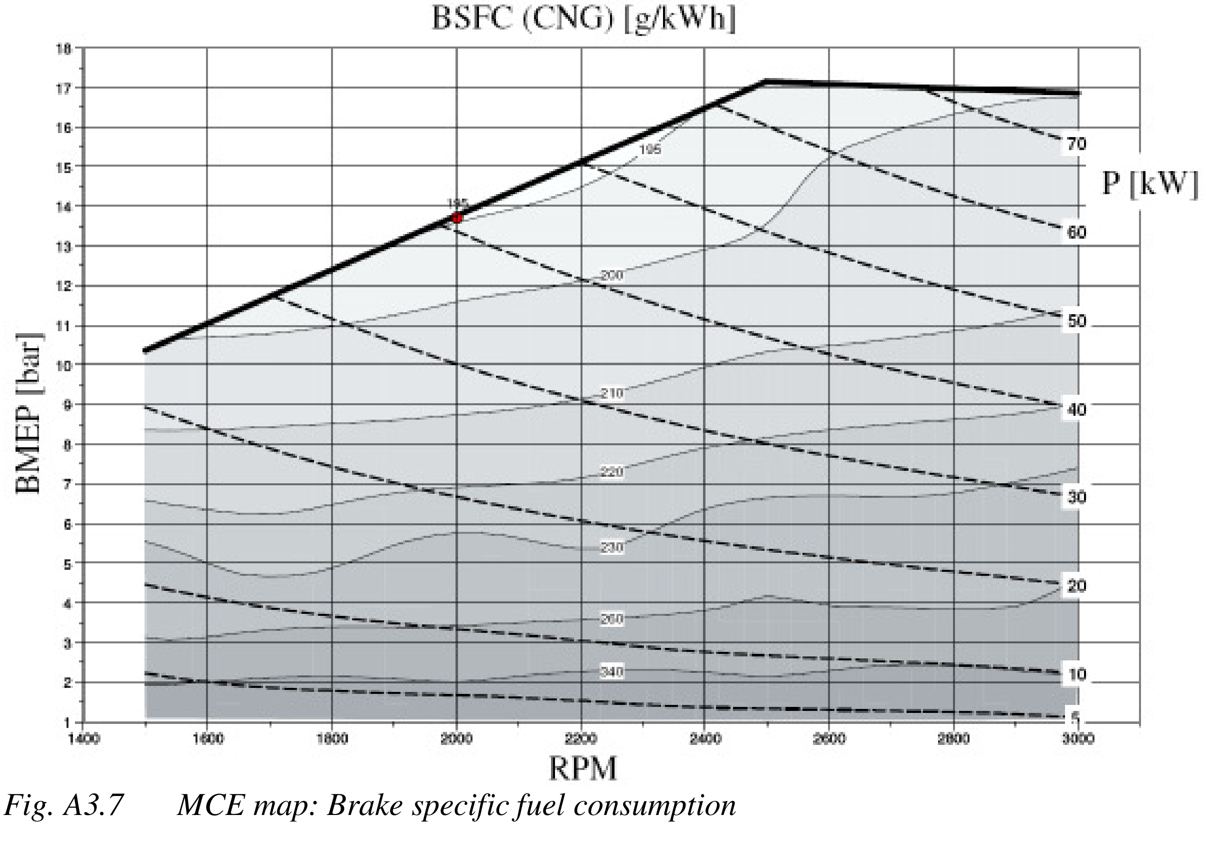


Fig. A3.7 MCE map: Brake specific fuel consumption

Full Load Behavior

In a single-cylinder engine test the boosting capability with high compression ratio was investigated. Therefore the boost pressure was increased up to 1900 mbar at 2000 rpm. This leads to an IMEP value of 32.1 bar for 140 bar maximum cylinder pressure and 31.2 bar IMEP for 120 bar maximum cylinder pressure. Also at this high load maximum cylinder pressure is the limitation and not knocking combustion, even with compression ratio 13. The high peak firing pressure shows the demand for a stronger engine structure for such high boosted applications to gain the full potential of boosted CNG engines.

Injection of gas after intake valve closing leads to improvement of volumetric efficiency. Hence, enhancement of torque and performance is possible, provided that mixture formation works well. Fig. A3.8 shows the results of investigations on single-cylinder engine with centrally mounted injector. The benefit concerning torque occurs especially at low engine speed, the increase of IMEP via direct injection compared to manifold injection is up to 10 %. However, the multi-cylinder engine test showed almost no benefit concerning torque. The cause is the inferior mixture formation of the multi-cylinder engine with intake side mounted injector.

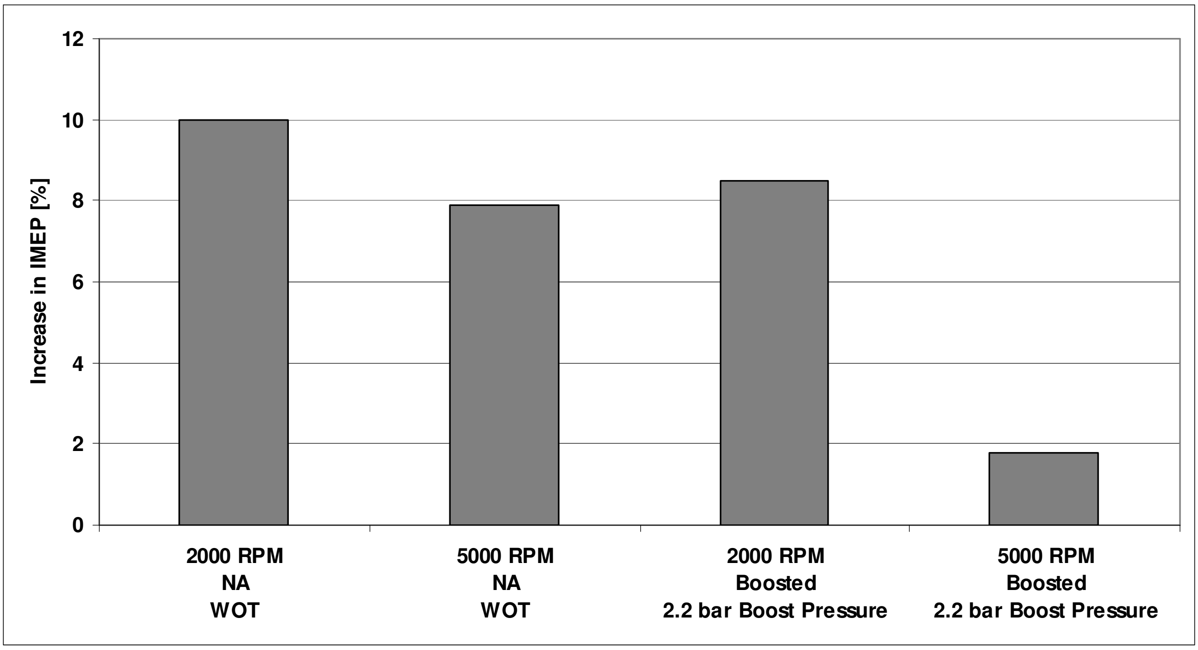


Fig. A3.8 Increase in IMEP via direct injection compared to manifold injection

Biogas/biogas blends

The effect of biogas and biogas blends was tested in homogeneous operation. Main focus was the effect of the gas composition on the combustion itself and the advantages given by direct injection.

In naturally aspirated operation with port fuel injection (done by early injection) the gases show more than 5 % difference in torque output due to differences in calorific value and gas density because of the fresh-air displacement effect. With late direct injection this effect can be fully compensated.

The negative effect on the combustion process caused by a high CO_2 content like in biogas can be compensated by hydrogen blended biogas. A remaining disadvantage for mobile applications will be the reduced driving range. Fig. A3.9 shows some combustion relevant values of different gases and gas mixtures at lean part load operation. A high CO_2 content (above 20 %) has a negative effect on ignition delay and combustion duration as well as on combustion stability. This leads to somewhat lower indicated efficiency. With the addition of hydrogen these disadvantages can be fully compensated.

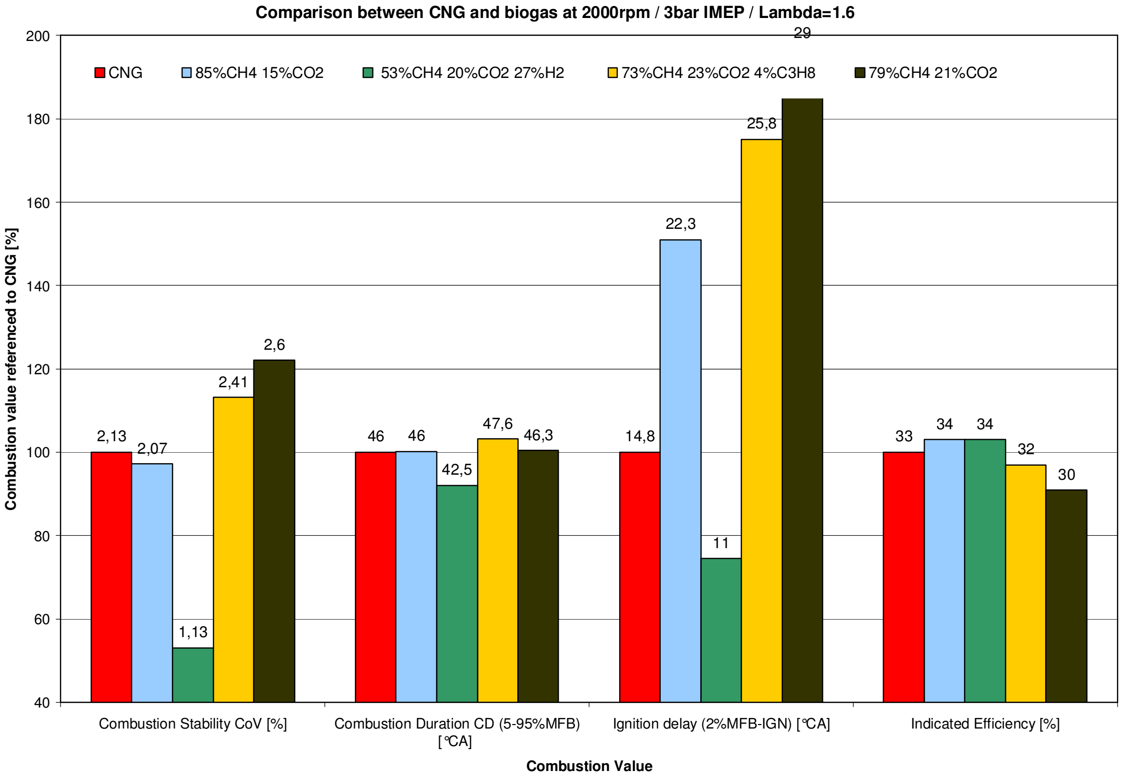


Fig. A3.9 Combustion behavior with biogas and biogas-blends

2.3.4. Technology Way 2a

2.3.4.1 Work performed

Technology Way 2a (Ford's approach) is based on a gasoline engine. The combustion strategy of this PFI turbocharged engine is lean at lower loads and switches to stoichiometric at higher loads. The lean operation ($\lambda > 1.3$) at lower loads increases the engine efficiency and reduces the NO_x raw emissions. The stoichiometric operation at higher loads enables the use of a three way catalyst, especially needed for the NO_x conversion. It also increases the exhaust gas temperature which is extremely important for the HC conversion in the upper load area of the NEDC. $\lambda = 1$ at higher loads also means a reduction in peak cylinder pressure to levels below 120 bar in order to use a gasoline based engine with its lower friction. This limitation leads to a maximum compression ratio of 12.5:1. That moderate value also increases the exhaust gas temperature (in comparison to higher compression ratios), guaranties better boosting conditions and supports the catalyst light-off. Besides, the lower compression also reduces the NO_x raw emissions. The fuel economy advantages of Technology Way 2a vs. Technology Way 2b (FEV's approach) are mainly in the area of the NEDC and real world with its comparable low loads where the low cylinder pressures do not require the strong cylinder block of a diesel based engine with the related higher friction and heavier weight. Additionally will the cheaper gasoline based engine with its smaller changes to the mass production derivatives help to get the NICE engine propagated.

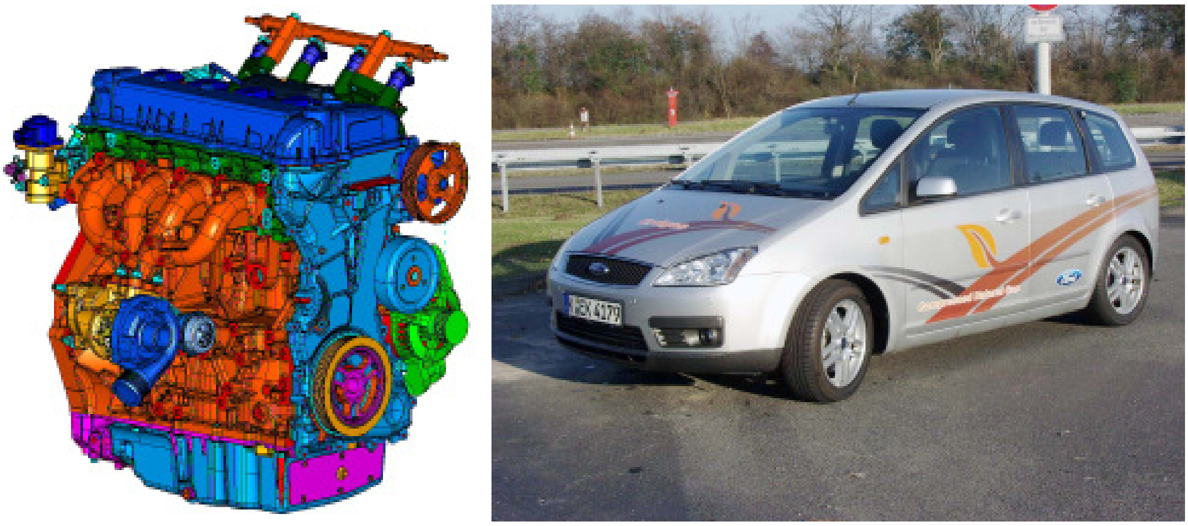
Sub tasks of Technology Way 2a are the engine simulation, -build-up and testing as well as a vehicle build-up with the related testing.

Engine Build-up

The Technology Way 2a demonstrator engine (Fig. A3.10) has been built-up on the basis of a 2.260 ccm, inline, four cylinder production engine with turbocharger and gasoline direct injection. The engine originally has a compression ratio of 9.5:1 and delivers 191 kW at 5500 rpm and 380 Nm at 3000 rpm.

To adjust the engine to CNG and the new efficiency targets the following changes have been introduced:

- Pistons for compression ratio of 12.5:1
- Intake camshaft with shorter events. An intake VCT can shift the events by 30° in the early direction.
- Intake manifold with additional bosses to fix the CNG injectors.
- Exhaust manifold with a new symmetrical design and a changed turbocharger flange.
- Two versions of turbocharger (BorgWarner Turbo Systems K03-482 & K03-588).
- CNG injection system from Keihin (CNG injectors with a wider operation range have been build for this project. The Keihin production pressure regulator has been modified to the expected high pressure in the intake manifold. The injector driver is a Keihin production part.)



(a) (b)

Fig. A3.10 Gasoline engine based NICE technology demonstrator (a) and NICE Ford Focus C-MAX demonstrator vehicle (b), Technology Way 2a

Vehicle Preparation

As NICE technology demonstrator a Ford Focus C-MAX has been built-up (Fig. A3.10). The vehicle is controlled by two control units. The main vehicle functions like cluster and ABS are served by the production control unit. The CNG engine itself got a separate controller for prototype development which has already been used for the engine testing in the dynamometer cell. The vehicle is equipped with a close coupled catalyst with 1.2 l volume, a CNG specific layer with a precious metal content of 150 g/ft³ and the ratio of 0:14:1 (Pt:Pd:Rh).

2.3.4.2 Final Results

The described technology approach with a highly compressed turbocharged CNG engine makes it possible to gain thermal efficiencies of over 40 % which is close to the efficiency level of state of the art diesel engines (208 g/kWh diesel equivalent fuel consumption). Due to the better H/C ratio of CNG it is even possible to beat the diesel engine in terms of CO_2 emissions.

The CO_2 emission in NEDC of the NICE Focus C-MAX appears at the lower end of the scatter band level of state-of-the-art production vehicles (see Fig. A3.19). The NICE vehicle with the $\lambda = 1$ calibration without fuel shut off results in 149 g/kWh ,the lean calibration also without fuel shut off leads to 139 g/kWh. The most viable calibration is stoichiometric combustion with fuel shut off and results in 145 g/kWh.

Lean operation, in comparison to stoichiometric operation, improves the fuel economy in NEDC by 6 %, NO_x by 30 % and CO even by 85 %. As HC is deteriorated by 40 %, stoichiometric operation seems to be more beneficial in terms of exhaust gas emissions. The NO_x and HC raw emissions are too high to reach Euro 4 or even Euro 5 limits in both stoichiometric and lean mode.

The reduction of NO_x raw emission can be achieved by a more precise control system. HC additionally requires an advanced aftertreatment system. State-of-the-art exhaust-gas aftertreatment systems are not sufficient to convert the HC and NO_x emissions at the given temperature level to the required figures. The average temperature level of the shown NICE engine in NEDC is about 370 °C. The required temperature to convert at least 50 % of the hydrocarbons is about 450 °C and occurs only at the end of the NEDC test in the extra urban part. Roughly 500 °C would be required to convert the THC to the Euro 4/5 limit of 0.1 g/km. Reaching Euro 5 limits would mean to achieve ~90 % HC conversion and ~ 95 % NO_x conversion. CO is already below the limit. Catalyst heating would help to reach the catalyst light off temperature, but would also cause further CO_2 emissions. Deleting NICE features like high compression ratio, turbo charging or lean burn combustion would clearly help on the temperature side, but would directly lead to an „old-fashioned“ naturally aspirated engine with its bad fuel efficiency.

2.3.5. Technology Way 2b

2.3.5.1 Work performed

Fuel metering using port fuel injection (PFI) is a basic feature within Technology Way 2 (TW 2). Differing to TW 2a the engine operation of TW 2b is overall lean with high air excess especially during high load. This way a profoundly benefit regarding fuel consumption is expected. The realization of high specific loads enables the option of downsizing with furthermore fuel saving potential.

Concept Phase

The reachable combustion velocity is of vital importance regarding the combustion system layout, especially if it is intended to operate the engine with high air excess and/or higher-than-average compression ratios. Fig. A3.11 underlines that with increasing combustion velocity the operation limits regarding detonation (rich mixture) as well as misfiring (lean mixture) can be expanded impressively. Fig. A3.11 is related to max torque operation of a 2.0 l engine (20 bar BMEP @ 2000 rpm). It can be seen, that there is the need for fast burn behavior to enable trouble-free engine operation combined with favorable parameters regarding engine efficiency and engine out NO_x emissions.

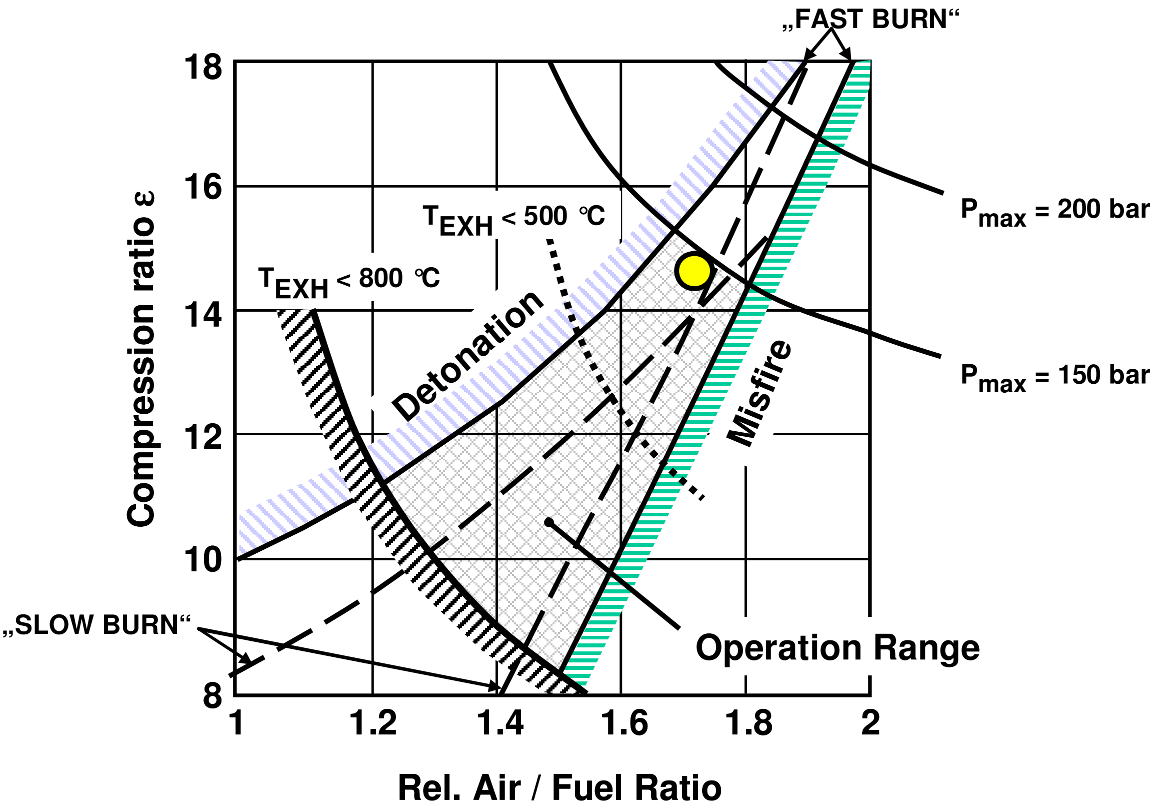


Fig. A3.11 Operation behavior of lean burn otto-cycle engines (full load)

Key factor regarding the improvement of the burning behavior respective combustion velocity is the in-cylinder turbulence. The result of comprehensive calculations using CFD tools is given in Fig. A3.12. This figure points out, that the FEV ATAC combustion system (Advanced Turbulence Assisted Combustion) enables an increase of the turbulent burning rate of 16 % during the compression stroke compared to a conventional combustion system.

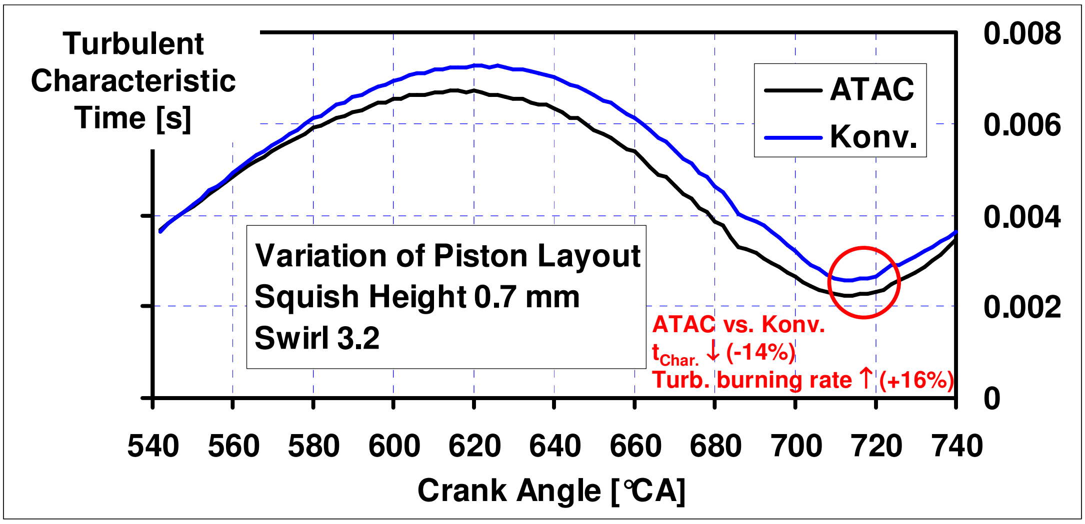
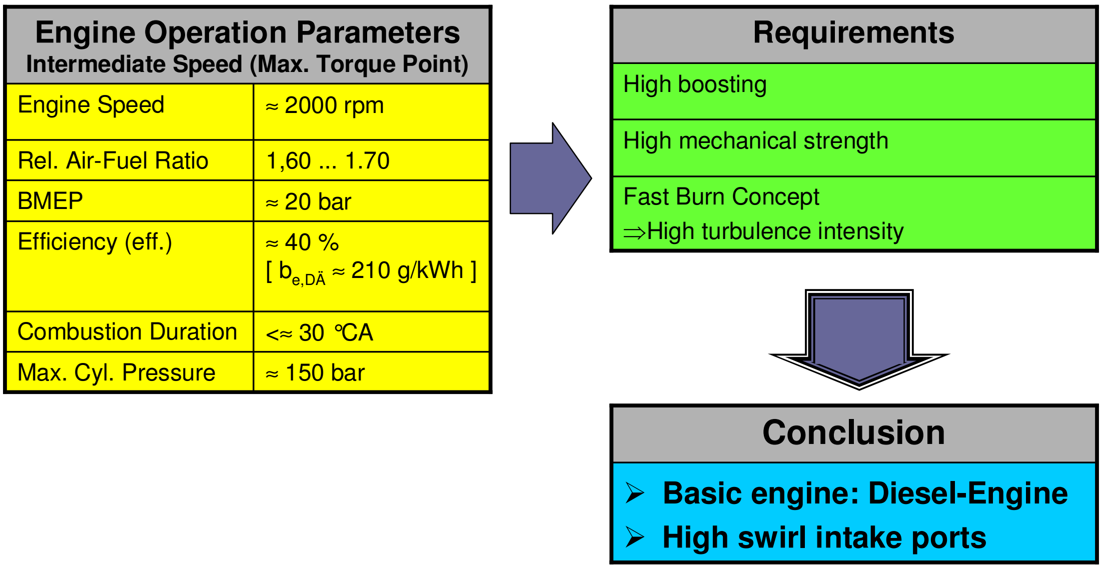


Fig. A3.12 CFD-Analysis: Influence of piston layout

Fig. A3.13 summarizes the strategy of TW 2b. The essential conclusion of the displayed line of argument is the necessity to use a basic diesel engine. Typical gasoline engines by far do not cover the required peak pressure of approximately 150 bar. High swirl intake ports are used to generate high turbulence intensity.



Engine Operation Parameters Intermediate Speed (Max. Torque Point)	
Engine Speed	≈ 2000 rpm
Rel. Air-Fuel Ratio	1,60 ... 1.70
BMEP	≈ 20 bar
Efficiency (eff.)	≈ 40 % [$b_{e,DÄ}$ ≈ 210 g/kWh]
Combustion Duration	<≈ 30 °CA
Max. Cyl. Pressure	≈ 150 bar

Requirements

High boosting

High mechanical strength

Fast Burn Concept
⇒High turbulence intensity

Conclusion

- **Basic engine: Diesel-Engine**
- **High swirl intake ports**

Fig. A3.13 Engine strategy of Technology Way 2b

Engine Build-up

Basic engine regarding Technology Way 2b is a 2.0 l, inline 4-cylinder production DI diesel engine with a stroke-to-bore ratio of 86 mm to 86 mm. The engine is supercharged using a turbocharger with variable turbine geometry. The conversion from diesel operation towards natural gas operation mainly covers the following described topics:

- Cylinder head:
  Instead of the diesel injectors spark plugs have been applied. The basic twin port concept with two swirl ports has been modified by forming one tangential port and one swirl port

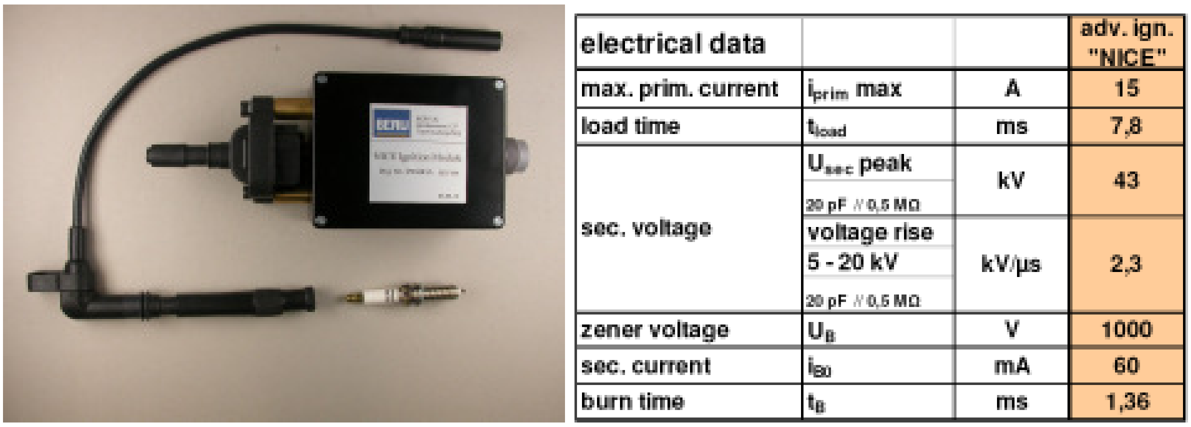
using a swirl chamfer. This way the originally swirl ratio has been increased from 1.7 to 2.8 units with a slightly reduced flow coefficient.

- Pistons:
  Three versions of modified pistons have been designed and manufactured. They covered the compression ratios of 14.2, 13.3 and 13.0 units. The final version has the CR of 13.0 due to best full load capability and NO_x effective performance.
- Intake manifold / fuel metering:
  Due to packaging the dimensions and the port routing of the basic diesel intake manifold has been kept unchanged. Both ports of each cylinder have been equipped each with one production natural gas injection valve (SIEMENS) to increase the rate of injection. This way even at full load operation the injection interval can be kept in-between the compression stroke. Natural gas rail and upper cover of the gas valves has been combined in one component.
- Exhaust system:
  Replacement of the basic diesel oxidation catalyst by a state-of-the-art otto-cycle catalyst.
- Ignition system:
  The complete ignition system has been provided by BERU.

Ignition System

For the application of gas engines in car operation, especially in lean operation, with turbocharging and intense charge motion, an advanced ignition system was developed by BERU. The objective was to supply the necessary ignition voltages at enlarged pressures at ignition timing, to avoid side sparking or energy loss by fast secondary voltage rise up and an enlarged burn time for proper ignition and combustion.

Prototypes of the ignition system composed of electronic boxes with electronic driving unit, the corresponding ignition wire set and the spark plugs were running well on the engine in test bench and vehicle operation at FEV. No restrictions on data performance for ignitability of fuel were detected on engine operation. Electrical data of the ignition system together with design and gap dimension of spark plug fit the requirements. Durability was not under consideration.



electrical data			adv. ign. "NICE"
max. prim. current	i_{prim} max	A	15
load time	t_{load}	ms	7,8
sec. voltage	U_{sec} peak 20 pF // 0,5 MΩ	kV	43
	voltage rise 5 - 20 kV 20 pF // 0,5 MΩ	kV/µs	2,3
zener voltage	U_B	V	1000
sec. current	i_{B0}	mA	60
burn time	t_B	ms	1,36

Fig. A3.14 Components and electrical data of ignition system (BERU)

Prototypes of the ignition system consists of the electronic driving unit (see box in Fig. A3.14) based on a capacitive discharge system with thyristor switch, with internal current limitation, self protection and spark free soft shut down function, a capacitor as primary energy store and a choke as secondary energy source. High voltage is generated by an ignition transformer. Spark plug connector is realised with reduced diameter to fit in the small plug hole. Spark plug was chosen to M12, with double platinum electrodes (diameter 0.6 mm), extra long reach thread, "cold" plug with heat value 4, spark gap is set to 0.3 mm. The small gap is acceptable for gaseous fuels and helps to reduce high voltage need, keeping the possibility to enlarge gap size for combustion purposes. The realised output data are shown in Fig. A3.14. The nominal driving current was set to 15 A. The maximum secondary output voltage will be well above 50 kV. The secondary output voltage given as reference in the table is limited by the electrical load to allow protection of equipment in the lab. The according voltage rise time with >> 2 kV/µs ensure proper sparkover.

The development of the ignition system was supported by fundamental investigations and simulations at Cracow University of Technology.

Engine-/Vehicle testing

Engine operation with high air excess is the central idea of Technology Way 2b. Fig. A3.15 shows the influence of varied air/fuel ratios at medium speed/load condition (6 bar BMEP @ 2000 rpm). Compared to stoichiometric operation the NO_x reduction is more than 90 % when air/fuel ratio (λ) of 1.65 is applied. Simultaneous the HC concentration increases by 85 %. Fuel consumption can be lowered by approximately 10 % in a large λ-window from 1.35 up to 1.75. The combustion stabilty is sufficient up to air/fuel ratios of about 1.8.

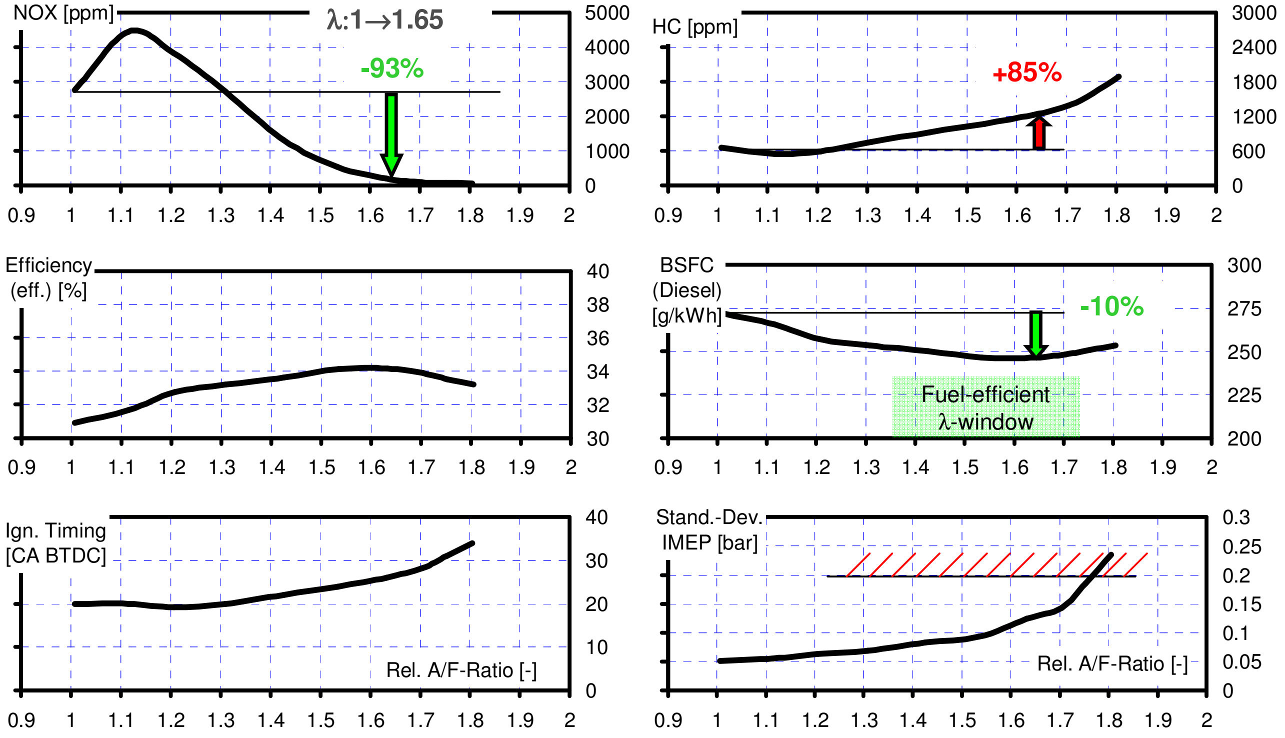


Fig. A3.15 Lean-mixture driveability (6 bar BMEP @ 2000 rpm)

In a wide speed range the engine can operate with BMEP close to 20 bar (1500 rpm – 3000 rpm) as Fig. A3.16 points out. The corresponding air/fuel-ratio is 1.5. Higher air excess would lead to impermissible peak pressure values (> 150 bar). Max. power is restricted by the boosting device (Diesel basis). Above 4000 rpm the power is nearly flat line 100 kW. Regarding peak pressure and ignition system capability there seems to be a potential to increase the power output by rising the rated speed. Fuel consumption behaviour is competitive to DI Diesel counterpart. BSFC (diesel equivalent) below 205 g/kWh at intermediate speed and below 235 g/kWh at rated speed correspond to good DI Diesel values.

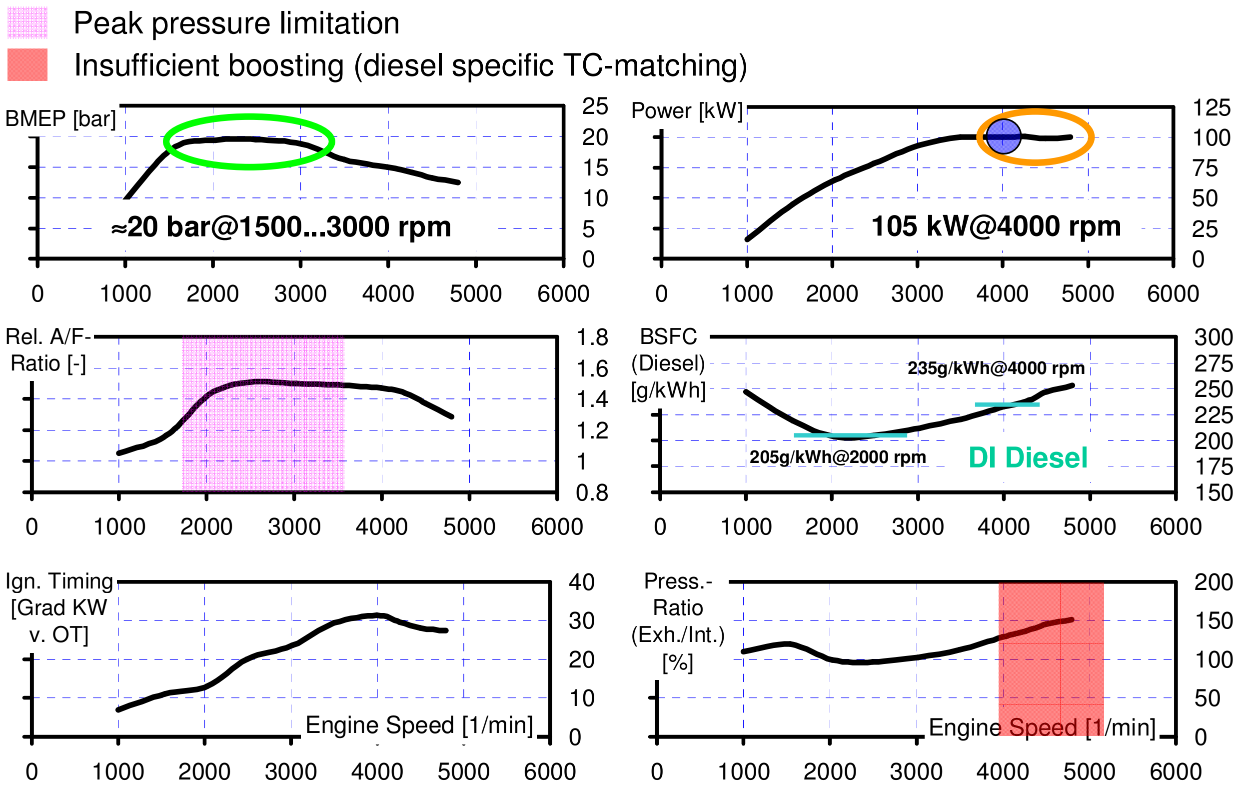


Fig. A3.16 Full load performance

2.3.5.2 Final Results

Vehicle Testing

Fig. A3.17 displays the results of vehicle testing with regard to the realized application strategy for NO_x-lowering. The chart shows the cumulated (raw) HC, NO_x and CO emissions and the cumulated fuel during the test cycle (NEDC). Compared to stoichiometric operation the lean variant with λ up to 1.4 enables a NO_x reduction of 65 % (5.31 g/km → 1.83 g/km) and a fuel saving of 8.8 % while the HC deterioration is 51 %. As expected the lean mode reduces the CO emission significantly by 56 %. Concerning further NO_x-lowering higher air excess (λ up to 1.5) in combination with retarded ignition timing has been applied. This way a further NO_x decrease by 73 % combined with a comparatively low HC increase of 15 % has been achieved. Inspite of the significant NO_x improvement the fuel consumption is slightly improved by 0.8 %.

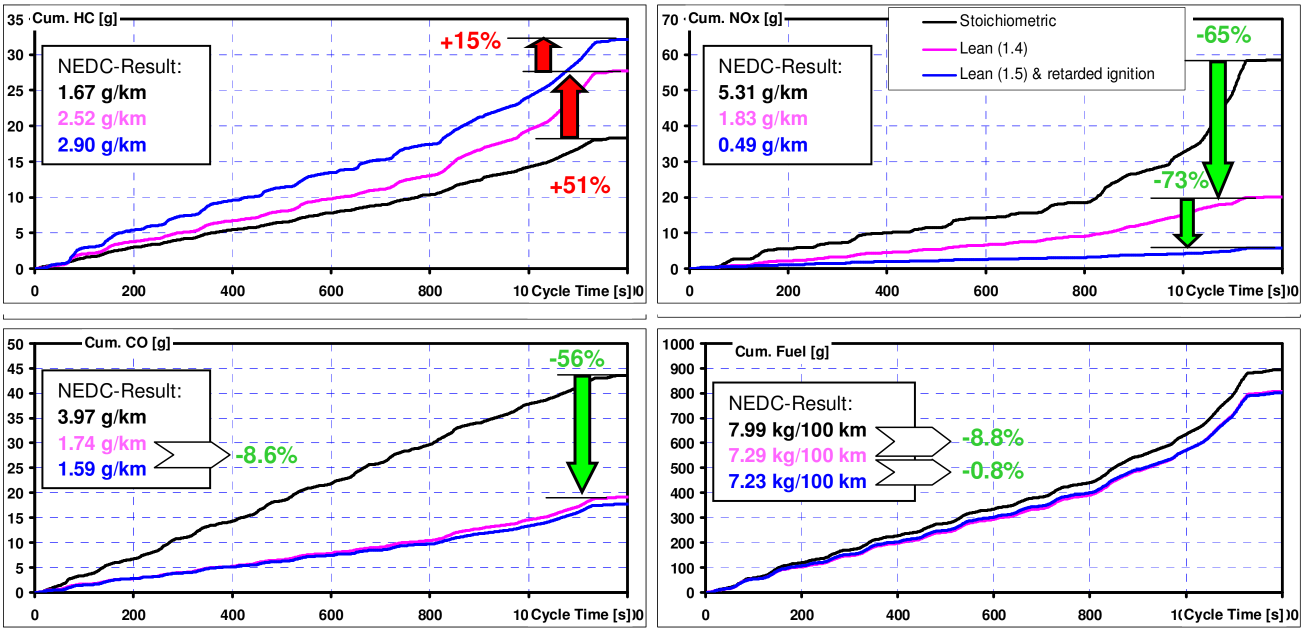


Fig. A3.17 NEDC testing (chassis dynamometer)

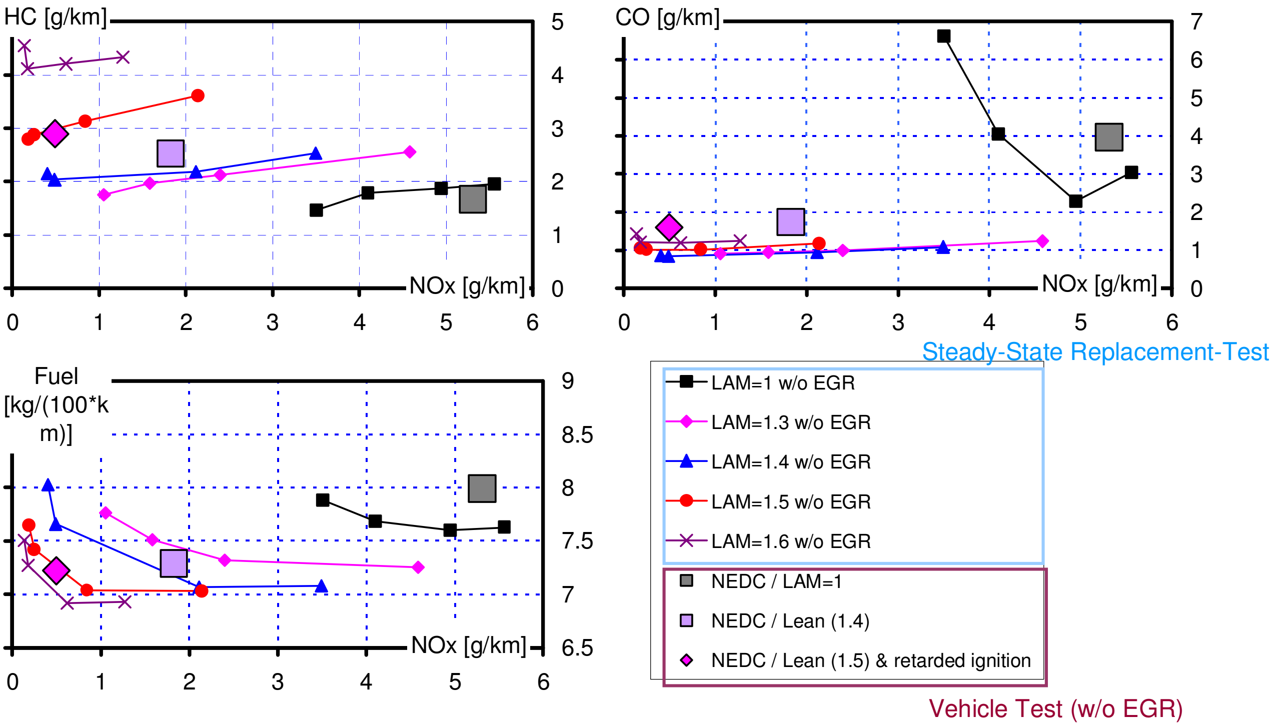


Fig. A3.18 Result comparison vehicle testing / Steady-state replacement-test

Fig. A3.18 gives information about the correlation of the vehicle test results in comparison to the pre-calculated NEDC test results out of stationary test bench measurements.

The results out of real vehicle testing comply very well with the projected stationary test results. With comparable high air excess and retarded ignition timing the NO_x emission has been reduced to approximately 0.5 g/km. The corresponding trade-offs regarding HC versus NO_x respective fuel consumption versus NO_x show a similar progression as the pre-calculated test results. With improved control functionalities of the engine management system – especially regarding air/fuel ratio control respective boost pressure control – it seems to be possible to reproduce the stationary projections. This way the realization of raw NO_x emissions in the range of 0.11 g/km (EU 4 limit; Light Duty Vehicle) seems to be possible. Due to the progressive HC increase the expected HC emission will exceed 4 g/km. Therefore an oxidation-catalyst efficiency of approximately 95 % is required to reach the EU 4 limit of 0.16 g/km (Light Duty Vehicle). Investigations with a state of the art (oxidation) catalyst point out, that due to the low exhaust gas temperature level at most 1/3 of the required catalyst efficiency could be achieved.

In comparison to existing diesel vehicles with same curb weight the CO_2 emission of the NICE NG vehicle ranks at the lower end of the scatter band. Considering the average value for the diesel vehicles, the CO_2 lowering during NEDC amounts to 25 %. Compared to the lower efficient gasoline vehicles the improvement is even 36 % (see Fig. A3.19).

The described technology makes it possible to gain thermal efficiencies of over 40 % which is close to the efficiency level of state-of-the-art diesel engines. Due to the favorable H/C-ratio of natural gas the CO_2 emission can be reduced in the range of 25 % compared to diesel engines.

The raw emission levels of NO_x and HC during vehicle testing are too high to reach EURO 4 or even EURO 5 limits. Due to high air excess the CO emission is not critical.

The necessary reduction of NO_x raw emission can be achieved (borderline) by a more precise control system using very lean mixtures as attested by stationary investigations. HC additionally requires an advanced aftertreatment system. Main focus here should be a high methane selectivity combined with lowered light-off temperatures of the catalyst.

2.3.6. Summary and conclusions of the sub-project

All three Technology Ways showed the big potential of future monovalent CNG engines:

- Just for CNG engines turbocharging is a very interesting option to compensate the lack of power and torque and to gain downsizing effects.
- Due to the high knock resistance of natural gas high compression ratios are possible, even in combination with high boost pressure.
- Direct injection is a very interesting option even if stoichiometric operation is applied. Mixture formation works well, the benefit concerning low-end torque was shown. Direct injection with centrally mounted injector leads to improved mixture formation compared with intake side mounted injector.
- Homogeneous lean combustion improves the fuel consumption in the NEDC up to 9.5 %, compared with stoichiometric operation.
- Stratified lean combustion by means of direct injection works well. This was demonstrated by a wall-guided combustion system. Compared to stoichiometric operation the benefit regarding fuel consumption amounts to 16 % in the NEDC.

For comparison the CO_2 emissions of the different Technology Ways together with the values of existing diesel and gasoline vehicles are shown in Fig. A3.19 (in case of Technology Way 1 the CO_2 emission was calculated from steady-state engine tests). NICE NG vehicles rank at the lower end of the scatter band.

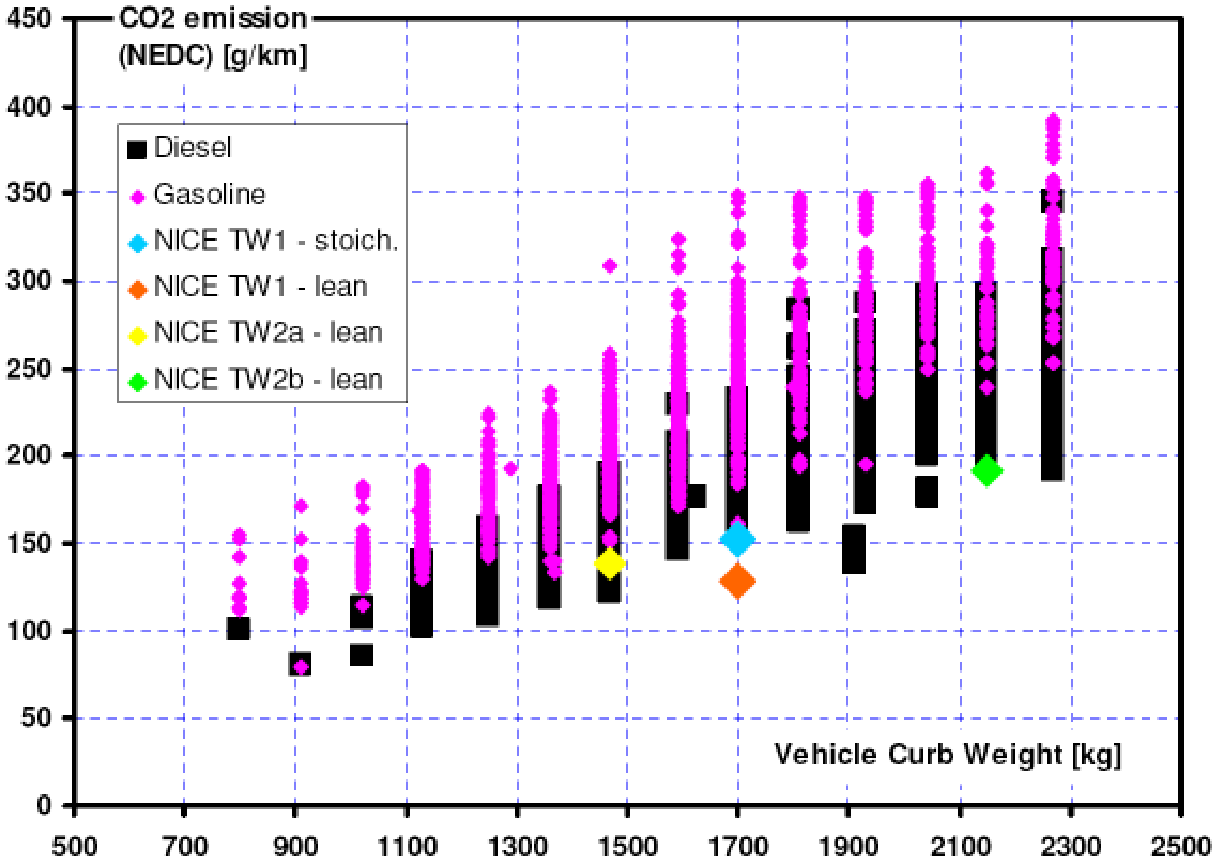


Fig. A3.19 *CO_2 emissions of different NICE Technology Ways vs. existing diesel/gasoline technology (KBA 2007)*

However:

- With homogeneous lean and also with stratified lean combustion the emission limits could not be reached. The low exhaust-gas temperature level associated with the chemically stable methane molecule leads to little HC conversion in the catalyst.
- Furthermore exhaust-gas aftertreatment for NO_x is indispensable in the case of stratified lean operation. For homogeneous lean operation the necessary reduction of NO_x raw emission can be achieved (borderline) by a more precise control system using very lean mixtures.
- Even stoichiometric operation at high compression ratio in combination with turbocharging leads to low exhaust-gas temperatures and thus the fulfillment of the emission limits will be a challenge.

The compliance of the emission limits is the major challenge for future CNG engines. New concepts for exhaust gas aftertreatment are required, or a modification of the emission legislation (limitation of non-methane hydrocarbons instead of total hydrocarbons). Otherwise future CNG engines will set their potential aside. We would therefore recommend that future research projects concerning CNG vehicles emphasize on emissions and exhaust-gas aftertreatment.

2.3.7. A3-List of acronyms

A/F-Ratio	air/fuel-ratio
ATAC	Advanced Turbulence Assisted Combustion
BD 10-90	burn duration 10-90°
BDC	bottom dead center
BMEP	brake mean effective pressure
BP 50	burn percentage 50 %
BSFC	brake specific fuel consumption
BTDC	before top dead center
CA	crank angle
CFD	computational fluid dynamics
CNG	compressed natural gas
CR	compression ratio
DI	direct injection
EGR	exhaust-gas recirculation
H/C	hydrogen/carbon
HR	heat release
IMEP	indicated mean effective pressure
KBA	Kraftfahrt-Bundesamt (German Federal Motor Vehicle Registration Agency)
MFB	mass fraction burned
MPI	multi point injection
MVEG	Motor-Vehicle-Emission-Group
NEDC	New European Driving Cycle
NG	natural gas
NMHC	non methane hydrocarbon
PFI	port fuel injection
TDC	top dead center
VTG	variable turbocharger geometry

2.4 Subproject B1

2.4.1. Objectives

Numerical simulations have today a substantial impact on the development of the combustion system of an engine. For instance, most companies base their design of intake and exhaust manifolds on results from calculations thereby avoiding high testing costs and reducing lead times. At the same time the quality of the final product increases compared to what could be obtained without calculations. For diesel engines the intake flow is optimized together with the shape of the piston bowl to achieve a desired flow pattern during fuel spray injection and combustion. The step to also include predictive simulations of spray and combustion would provide a tremendous improvement to the engine development process.

Prior to the project, modelling of diesel engine combustion had reached a stage where heat release and in-cylinder pressure could be predicted with good accuracy although problems remained for cases with very high injection pressures and with long injection durations. Having a picture of the local in-cylinder temperature makes it possible to study the heat transfer to walls which, for example, is of crucial importance for the piston design. Also NOx formation could be modelled with sufficient accuracy in many cases. Soot emissions were more difficult to incorporate but useful results could be obtained with a combination of detailed CFD modelling and simple semi-empirical soot models. Combustion models that might work well for conventional engines were, however, not good enough for the new combustion concepts investigated in NICE and new and improved models needed to be developed. For alternative and renewable fuels new chemical descriptions needed to be developed and for conventional fuels chemical models needed further improvements. Models for fuel injection, spray and mixing were not accurate enough, particularly at high injection pressures and high loads. Also the numerical solution in engine CFD codes needed to be improved in terms of accuracy and CPU time demand.

The work in subproject B1 was organised to provide a solution to some of the remaining critical issues in diesel combustion modelling with special focus on the novel engine solutions developed in NICE. Some models were simply not available prior to the project such as models to predict the long ignition delays at high EGR conditions typical for the new NICE combustion concepts and models for alternative/optimised fuels. In other areas as spray, mixing and basic combustion available models were further improved and adapted. All models were carefully validated and implemented in engine CFD codes resulting in useful simulation tools also for the development of novel combustion processes. In addition, the modelling of conventional engines has become more mature also including the capability to model soot formation with a sufficient degree of accuracy.

It was the aim of B1 to interact strongly with the subprojects A1-A3. This was achieved for A1 and A2 but was not feasible for A3.
The interaction with A1 included the use of engine test results as a validation base for the newly developed ECFM-CLE-H combustion. The validation results showed that the new model is capable of predicting the combustion modes investigated in A1 and will thus surely be useful in the further advance of the technology developed in A1. The interaction with A2 included the specification of the alternative CCS-Fuel as well as injector flow simulations. Also shock tube measurements for the CCS-Fuel were provided which were crucial for the development of the CCS mechanism in B1. The use of the CCS mechanism in CFD

simulations will allow for a further optimization of the combustion system to the CCS fuel in future development. Originally, it was also planned to interact with A3 but this proved to be unfeasible since only Diesel-like Nice combustion models were developed in B1 which are not applicable to any of the different CNG technology ways in A3. As a replacement additional activities focussing on HD truck and marine Diesel combustion were conducted.

2.4.2. Contractors involved

AVL List GmbH	A
Daimler Chrysler AG	D
Institut National des Sciences Appliquees de Rouen	F
Universität Cottbus	D
Universität Karlsruhe	D
Institut Francais du Petrol	F
Renault Recherche Innovation	F
University of Cambridge	UK
Volkswagen AG	D
Volvo Technology Corporation	S

2.4.3. Injection and Mixing

2.4.3.1 Work performed

Two important processes occurring in Diesel engine combustion are the injection of the fuel and the subsequent mixing of the evaporated fuel with the air in the cylinder. Fuel is injected at very high pressures in modern Diesel engines through small orifices in the range of a couple of hundred micrometers in diameter. The liquid core exiting the orifice is broken up into small ligaments and droplets which are evaporated due to the high pressure and temperature conditions prevailing in a Diesel engine. The evaporated fuel is then mixed with the surrounding air where turbulence effects play an important role. The accurate modelling of these two processes is of crucial importance. During NICE work was performed on both sub models.

The fuel, or mixture fraction, variance is used in internal combustion engine modelling to estimate the level of fluctuations in turbulent fuel/air mixing. This variance is usually accessed via the solving of its balance equation. In the case of liquid fuel injection, the mixture fraction variance is affected by the spray evaporation. Improved modelling is discussed for those effects. A new closure was proposed in NICE that is based on a presumed expression for the conditional source of variance in mixture fraction space.

Impinging jets are of great interest for many practical applications in engineering and a better description of various phenomena characterizing this flow is still needed, as scalar mixing and heat exchange at the wall, turbulent mixing in the very near wall jet region, etc. In the present work, a fully compressible parallel solver was used to perform Large-Eddy Simulation of such flows.

A methodology for tabulating mixture fraction PDF-shapes as a function of the mean and the variance was developed, implemented as a CFD-callable software module and delivered to project partners.

2.4.3.1 Final Results

Spray Model

Based on the previous work in the European I-Level project, the Euler spray model as well as the physical modelling have been enhanced and modified within NICE B1.

In the first stage of the project the overall performance of the Eulerian spray model and the multiphase solver of the CFD code AVL FIRE have been enhanced. The multiphase solver has been developed for full compressible flows. Furthermore, a sufficient number of transport equations were provided to enable the transport of fuel species and the droplet number densities of every droplet size class. The fluid property database of FIRE was linked to the general multiphase solver and twelve new fluid types and additional user fluid entries have been introduced to enable spray simulations with a wider bandwidth of fuels. Furthermore, the two species model for the gas phase fluid properties was extended to take into account effect of temperature and composition.

The functionality for rezoning of the Eulerian spray grid, which is essential for engine calculations, was provided by appropriate mapping of the new flow quantities between grids. This feature and all available Eulerian spray models were adapted for MPI calculations. The Eulerian spray set-up was fully integrated into the graphical user interface of the FIRE code for improved usability of the model.

An important step in the spray modelling procedure was the link of the spray formation to the cavitating nozzle flow. Therefore, flow field tables from previous detailed 3D injector flow simulations are stored on data files, which then act as boundary conditions for the spray simulation. This interface is fast and flexible, since different injector flow simulation can be combined with different spray simulations. A model for the initial spray formation (primary break-up) taking into account the conditions from the injector flow and aerodynamic effects has been further developed. The validation of the models showed that the interface to nozzle flow is essential for predicting asymmetries in the spray contour and the initial spray tip penetration curve.

Two new evaporation models have been implemented into the Eulerian spray model. The modelling of the turbulence interaction between the liquid and gaseous phases was improved by implementation of an advanced turbulence dispersion force model. Furthermore, the effect of dispersed particles causing damping of the turbulent kinetic energy has been taken into account by the implementation of damping source terms in the turbulence equations. However, this approach needs further improvement in future work.

To overcome under-prediction of evaporation and reduced resolution by accumulation of droplets in the smallest droplet size class during downstream evolution of the spray, flexible drop sizes and variable drop class boundaries have been introduced. For this purpose additional transport equations for the droplet number density are solved for each liquid phase. The inter-phase source term exchange has been modified by improved search algorithms for assignment of inter-phase sources between the various liquid phases.

The improved models have been validated extensively with data from the I-Level and DIME project for which nozzle flow simulations as decisive input data have been available. Taking into accounts the spray initialisation and primary break-up from the nozzle flow data gave improved agreement with measured data for transient spray penetration of liquid and gaseous phase.

Essential for the application of the Euler spray model is the interface to engine simulation. Therefore, the interface ACCI (AVL Code Coupling Interface) has been developed during this project. The idea was to perform the Euler spray simulation and the engine simulation in different simulations, which are clients to the server, and couple them via a TCP/IP data interface provided by the ACCI server. On the one hand the Euler spray simulation gets the flow field boundary and initial conditions form the engine simulation. On the other hand the Euler spray simulation submits the interaction between gaseous and liquid phases, such as source terms due to drag, evaporated mass, energy transfer, and species sources, to the engine simulation. The two computational domains are overlapping and hence, the gas flow field is calculated on both clients. The ACCI server performs the spatial mapping and the time management of the exchanged data. A test example with FIRE-FIRE coupling of the Euler spray multiphase simulation and the FIRE engine simulation on a Diesel engine segment demonstrates the successful development of the ACCI interface.

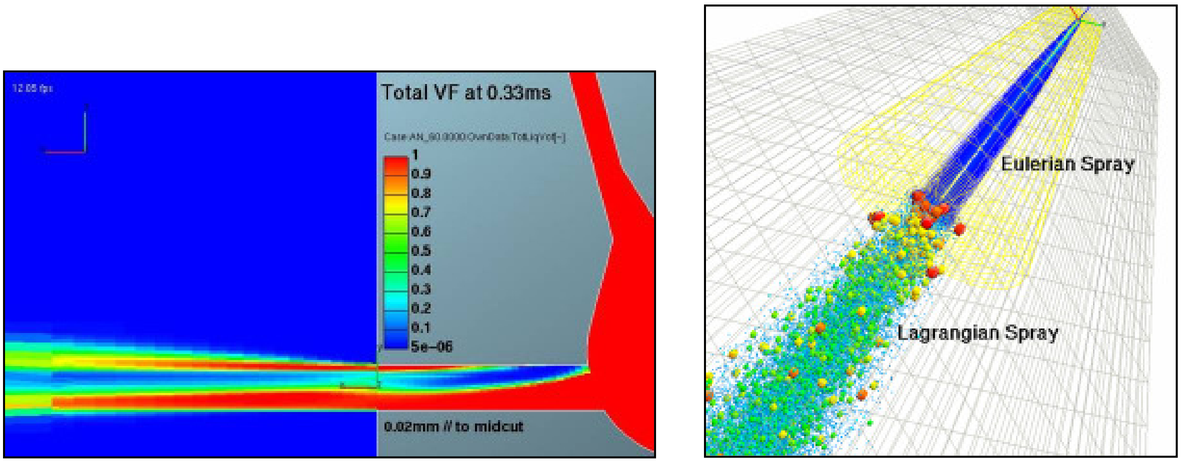


Fig. B1. 1 Illustration showing cavitating injector flow coupled with the Eulerian multiphase spray model (left) and the coupling of the Eulerian and the Lagrangian spray (right).

The ACCI interface is flexible, since it allows coupling of FIRE simulations even with non-FIRE CFD codes. The project partner Daimler coupled the Euler spray of AVL with an engine simulation performed with StarCD.
The final version of the model has been implemented into the actual FIRE version and has been delivered to the project partners together with a comprehensive documentation and validated test cases.

Application and validation of multiphase injector simulation and the Euler spray model
The final version of the Euler Spray model as implemented in the FIRE code was used for transient 3D injector flow simulations performed by Volkswagen within the subproject A2. Partners in A2 provided geometrical data for the CRI3-Piezo injector and boundary conditions for NOx relevant NEDC points and 2 different fuels. The operating points were investigated for standard Diesel fuel and the alternative CCS-Fuel.

Figure B1.2 indicates the calculated Diesel fuel vapour fraction for NEDC 1 in a section cut through the spray axis compared with a measured fuel vapour cloud, whereby the visible region for the latter starts only at 10 mm downstream from the nozzle hole. However, the overall comparison is good; the vapour penetration is just slightly under predicted with a tip that stays sharp longer than measurements show. Furthermore the predicted liquid penetrations match very well the measured data for this operating point (Figure B1.2). Similar conclusions can be drawn for other NEDC points with Diesel.

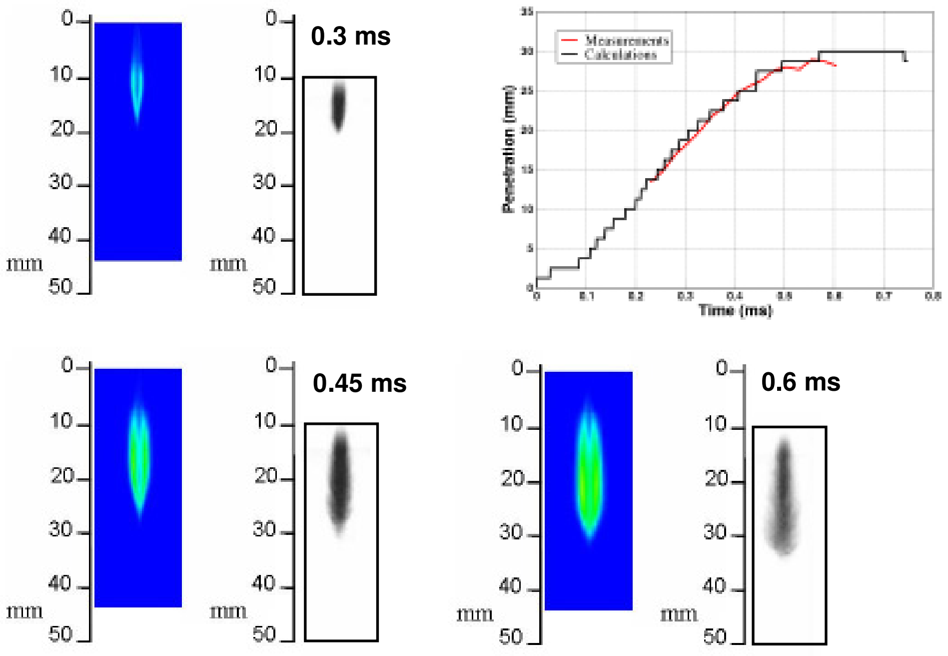


Fig. B1. 2: Diesel fuel vapour fraction distribution and liquid fuel penetration for NEDC 1.

Modelling the alternative CCS-fuel with an initial boiling point of about 150°C and a final boiling point of about 240°C and a C-atom range of roughly 7 to 13 was a challenge and done for the very first time. Due limited available fuel property data n-decane was selected as model fuel for which all necessary data for a wide range of temperature are available from the extended data base in FIRE.

Applying the boundary conditions and needle lift curves from 1D simulations done by partners in subproject A2 the transient 3D injector predictions show little differences in terms of cavitation during the main phase of injection for the different fuels. But at small needle lifts increased regions of fuel vapour were indicated behind the entrance of the nozzle hole and below the needle seat. The CPU time for such an injector simulation with about 265000 cells is 8 to 10 hours on a 30 processor Linux cluster. The computational domain for the Euler Spray simulations contained about 30000 cells and took roughly 24 hours on a single processor to perform.

The predictions with CCS-fuel were performed with the same numerical and sub-model settings as for Diesel with the exception of the predefined fixed droplet size classes. The distribution and penetration of fuel vapour (Figure B1.3) indicate for the alternative fuel as for Diesel an under-prediction compared to the available measurements which might be due to the approximation of fuel properties. Hence it will need more investigation and measurements regarding the alternative CCS-fuel and its properties to achieve more precise predictions.

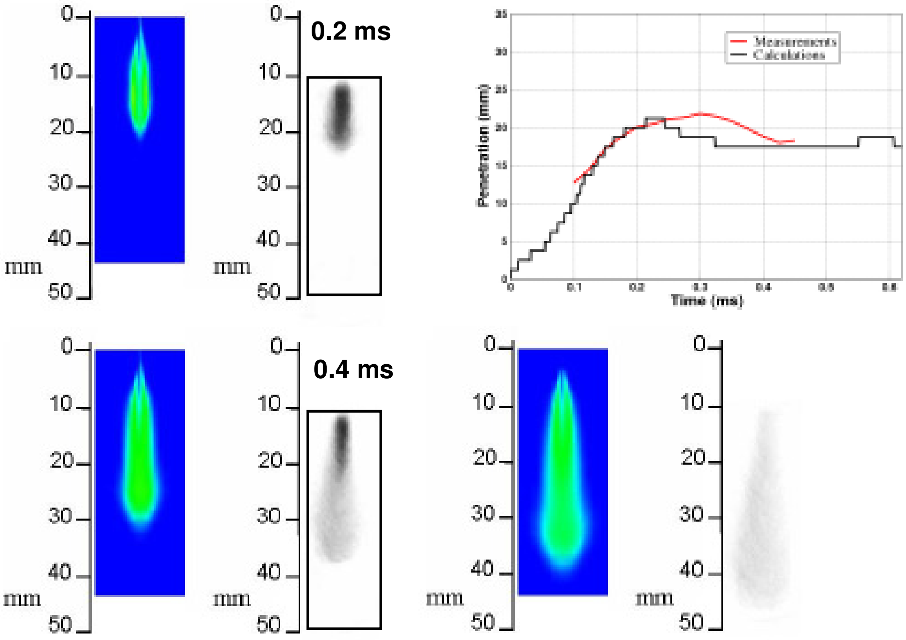


Fig. B1. 3 *CCS fuel vapour fraction distribution and liquid fuel penetration for NEDC4.*

Eulerian spray model validation

Further spray validation was accomplished by comparing with experimental results obtained on an optically accessible high pressure cold chamber. The injector is mounted on an adapter on the backside of the chamber, which is equipped with three optical accessible windows. Comparisons between simulated spray shapes and experimental images are shown in Figure B1.4. The simulated sprays show good agreement with experimental images, also in the prediction of spray asymmetries.

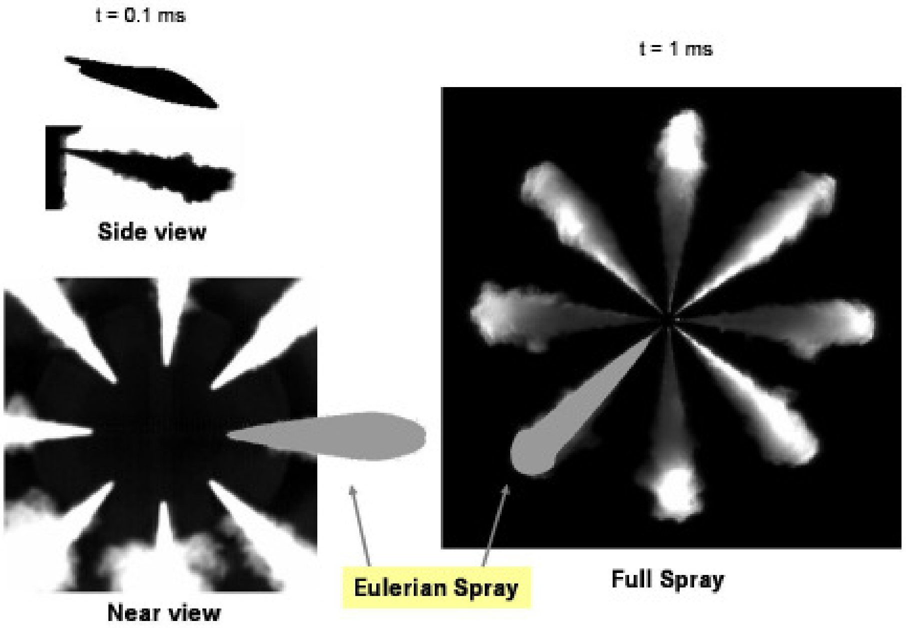


Fig. B1. 4: *Coupled spray for VCO nozzle: simulation (iso-surface 0.01 of total liquid phase) in comparison with experiments.*

The strong spray atomization in the bottom spray plumes of the near view in Figure B1.4 is due to needle displacement at the beginning of injection. As the needle opens directly on the holes, fluctuations lead to orifice obstructions and therefore strong effects on spray formation. The method of coupling simulations between nozzle and Eulerian Spray produces satisfactory results on the spray formation process and visualized penetration; therefore, it enables the transfer of nozzle information to the mixture formation process in the combustion chamber.
Figure B1.5 shows a comparison between two state-of-the-art models (DDM and ICAS) and the coupled Euler model for a diesel engine simulation. The liquid penetration length prediction is improved compared to the DDM method and a more realistic distribution of fuel vapor close to the nozzle is obtained.

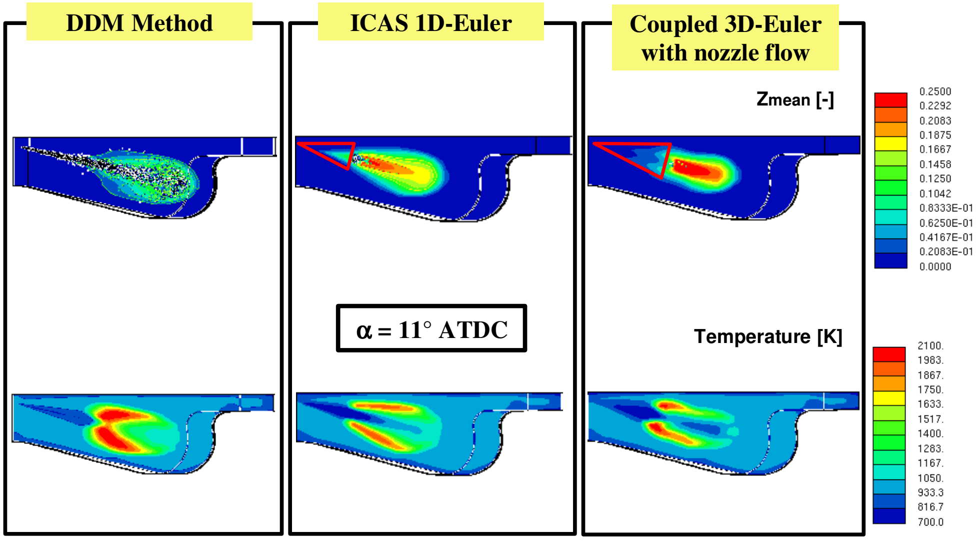


Fig. B1. 5: Comparison of two state-of-the-art spray models (DDM and ICAS) with the coupled Euler model developed in NICE (right panel).

Mixing
At small scale, molecular diffusion dissipates the variance of mixture fraction and the mixture fraction dissipation rate is also influenced by evaporation. Improved modelling for this term was developed within NICE. In this novel approach, the impact of the evaporation source on the fuel dissipation rate is calibrated from a simplified one-dimensional problem. A correction to usual scalar dissipation rate closures is obtained from this one-dimensional analysis.
Both models for the source of variance and scalar dissipation rate are cast in the form of look-up tables that are ready for their integration in CFD software, this integration was performed by IFP and RENAULT.

To formulate an improved model for wall effects on mixing Large-Eddy simulation of a jet impinging on a wall were performed (see Figure B1.6). Since the Large Eddy simulations are much very refined and use fewer model assumptions they can be used as “numeric experiments”. In the present calculations the computational domain is a Cartesian grid with the x-axis aligned with the axis of the jet; therefore the impingement wall is parallel to the y-z plane. All the boundary conditions are enforced using the NSCBC strategy: no-slip adiabatic wall condition for the impingement wall, subsonic non-reflecting outflow for the four lateral sides and subsonic non-reflecting inflow with relaxed velocities and temperature. The outflow condition has been modified to handle local flow inversion zones as those that are present where coherent vortical structures cross the boundary. Furthermore, a correlated random noise is injected at the inlet with a time-step independent sampling rate computed from the characteristic convective velocity and length scale.

Two meshes have been used depending on the domain width, 1.5M mesh points for the smaller domain and 4.1M for the larger one. The results were validated against experiments.

From this very detailed and time consuming simulation, mixing behaviour at the wall was studied. Using the results a simpler model that can be used in RANS models typically used for the simulation of diesel combustion has been obtained. This new law-of-the wall was derived for the mechanical to scalar mixing time ratio.

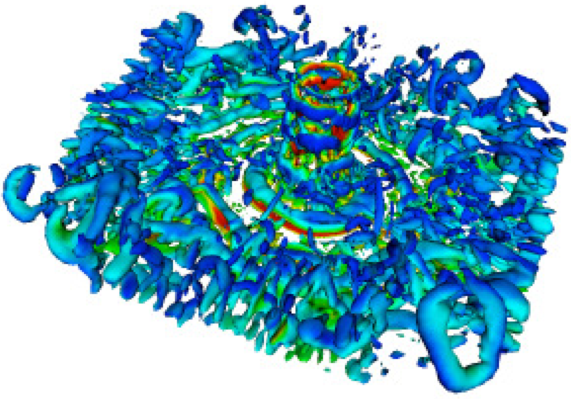


Fig. B1. 6 Iso-Q of the turbulent wall-jet mixing simulations (Q is a quantity defined to detect vortical structures).

PDF-shapes

In engines with stratified loads (especially, Diesel engines and engines with gasoline direct injection), the mixture fraction, a measure for the local fuel/air ratio, is not homogeneous, but more or less statistically distributed over different locations in the combustion chamber. This distribution has strong implications onto the progress of the chemical reactions in the engine that are responsible for ignition, combustion and pollutant formation, and a physically correct description of this distribution is therefore crucial for CFD simulations. Currently, the so-called β-PDF approach is used to describe the statistical distribution (probability density function, PDF) of the mixture fraction for given mean and variance. It is not clear whether this approach is realistic.

In order to investigate the correctness of this approach, Monte-Carlo PDF simulations of a fuel-jet impinging into air were used to obtain a database of realistic PDF-shapes as a function of mixture fraction mean and variance. From this database, a strategy for an improved description of mixture fraction PDFs was inferred and implemented as an efficient software module that can easily be called by CFD codes.

Figure B1.7 shows for illustration of the method an empirical PDF (gray solid line), as it is obtained from a Monte-Carlo PDF-simulation. This simulation is for a jet of fuel that mixes with air; since this kind of simulation treats the statistics of the mixing process very realistically this shape is considered to be close to the real shape. The spread of this PDF shows that the mixture fraction attains values between about 0.6 and 1 (mixture fraction 1 corresponds to pure fuel, and mixture fraction 0 corresponds to pure air) in this case, and that 0.8 is the most probable mixture fraction. This statistical distribution delivers a mean of ~0.8, and a variance of about 0.005. Based on these values, PDF-shapes can be computed for a β-PDF and the new, double Gaussian shape. Both shapes are shown in the figure, as well. It is obvious that the „traditionally“ used PDF-approach fails to render the correct shape of the mixture fraction PDF. In contrast, the new PDF-shape (double-Gaussian, red dash-dotted line) comes very close to the correct shape. CFD-Codes that use the new approach can be expected to better describe mixing processes, and therefore also the associated influence onto chemical reactions (including issues like extinction and pollutant formation) than the traditional β-approach.

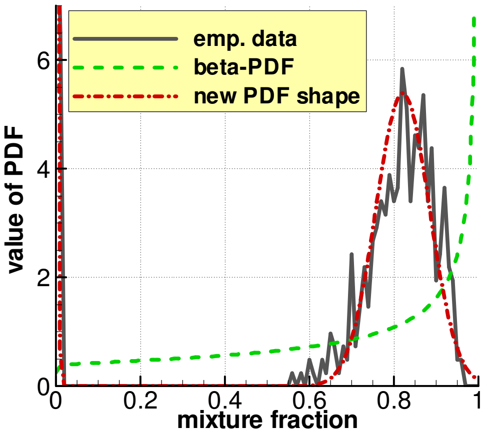


Fig. B1. 7 Comparison of an empirical mixture fraction PDF (taken from a Monte-Carlo PDF simulation of a fuel/air mixing scenario) and a fit with a β-PDF and the new (double Gaussian) PDF.

Chemical kinetics

NICE-like combustion is characterized by long ignition delay times which are controlled by chemical kinetics. Accurate modelling of the gas phase reactions is thus significant in engine CFD simulations of NICE-like combustion. Work was performed on improving the description of gas phase reaction for gasoline, Diesel but also for a bio-fuel. A main aspect in this work was to improve the detailed reaction mechanism for n-heptane, iso-octane and n-decane which are often used as model fuels describing the complex mixtures of hydrocarbons in real gasoline and diesel. The work resulted in an accurate prediction of laminar flame velocities and high temperature processes which were validated against shock tube experiment. The prediction of major species profiles was improved and validated against plug flow reactor, jet stirred reactor and burner stabilized flame experiments. An important step was also the addition of PAH and NOx chemistry to facilitate an accurate description of emission formation.

Using the new mechanisms new libraries for soot formation were constructed. These are now available in STAR CD through user defined functions.

A novelty in the present work was that a detailed mechanism for the oxidation of n-decane of 344 species and 3232 reactions was built automatically by using the REACTION mechanism generator which is a program partially developed within NICE. The detailed mechanism consists of two parts, a validated base sub-mechanism, produced manually and a generated sub-mechanism. The final detailed scheme for the mixture of n-decane, n-propylcyclohexane and iso-octane contains about 489 species with 5152 reactions.

Another important progress was the development of a mechanism for the oxidation of FT-kerosene (CCS bio-fuel). The CCS-Fuel was analysed by the central lab of Volkswagen and detailed results of the analysis were delivered to the University of Cottbus. Volkswagen also provided results from shock tube measurements for the improvement, validation and reduction of the mechanism. Using the physical and chemical properties of the FT-kerosene used by Volkswagen, the alternative fuel (CCS model fuel) was modelled as a mixture of n-decane, n-propylcyclohexane and iso-octane.
Validation calculations have been performed for jet stirred reactor and shock tube experiments (see Fig B1.8 for an example on the validation of ignition delay times).

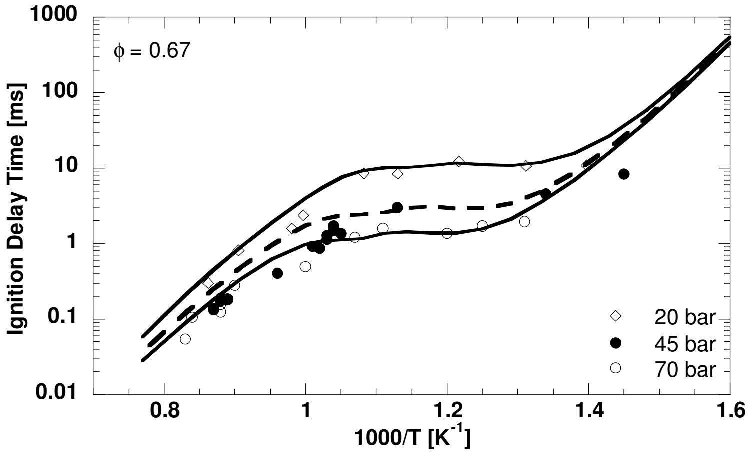


Fig. B1. 8: CCS fuel (n-decane and n-propylcyclohexane) ignition delay time at ϕ = 0.67 and p=20, 45 and 70 bar. Comparison between the Kerosene mechanism simulations (lines) with the experiment (symbols).

2.4.4. Combustion model development

2.4.4.1 Work performed

The extensive incorporation of data from the calculation of detailed combustion chemistry in CFD calculations is important to describe not only the point of ignition like in one step chemistry models but also effects like the pre-ignition phase, extinction and pollutant formation. Since Nice like combustion is characterized by long ignition delay times chemical kinetics is more significant than for classical Diesel combustion where ignition delay times usually are very short. Under Nice-like conditions often a so called cool flame occurs before auto-ignition. In a cool flame low temperature chemical reactions are occurring leading to a built-up of certain chemical species but also a heat release. The effect of a cool flame can only be modelled if detailed chemical kinetics is used and implemented into the combustion model. Therefore several different models for the realistic treatment of chemical reactions in engine relevant simulations were developed and implemented in CFD codes.

2.4.4.2 Final Result

ECFM-3Z

The ECFM-3Z model was already available before the start of Nice but was improved during the project by the implementation of realistic chemistry and the mixing models mentioned above. This was accomplished by developing an approach where the two relevant ignition delay times (cool flame and auto-ignition) are tabulated. The method ensures a very low CPU cost. The chemical models for Diesel (n-decane and α-methylnaphthalene) developed within Nice were implemented into ECFM-3Z using the tabulation technique and are now available for the users of ECFM-3Z within STAR-CD. Also the FT kerosene mechanism was tabulated and is available to use with ECFM-3Z.

The auto-ignition model available prior to Nice was only based on mean local composition (fuel/air equivalence ratio). To calculate auto-ignition the flow was thus treated as locally laminar. A model that takes the local fluctuations (turbulence) into account was implemented using among others the mixing models developed within NICE which were described above.

The ECFM-3Z model in STAR-CD was validated against results from measurements and results obtained with former versions. Predictions looked promising. The importance of a double delay tabulated auto-ignition model was underlined, especially when calculating engine operating points with partially homogeneous conditions and alternative fuels. The final version of this advanced combustion model together with the CCS mechanism was also used in A2.

ECFM-CLE-H

The ECFM-3Z model was also further developed into the ECFM-CLE-H model using the new methods generated within NICE. These include the auto-ignition model, the kinetic mechanism and the scalar dissipation rate model. An extensive validation against engine data was performed with the new model. A comparison between a measured and simulated rate of heat release is shown in Fig. B1.9. This model will also be available in forthcoming versions of STAR-CD and will be the new standard tool for virtual 3D engine development within Renault.

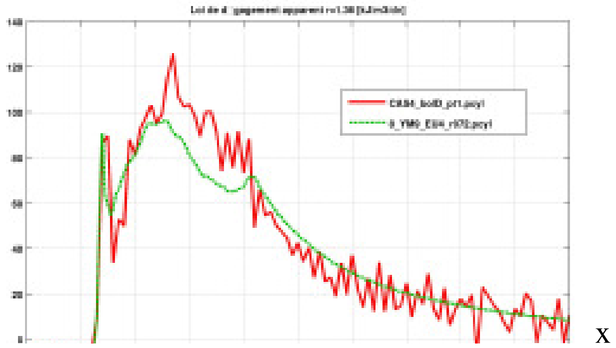


Fig. B1. 9: Pressure and heat release curves for full load conditions.

Progress variable model

The model is based on a progress variable (PV) which describes the progress of the chemical reactions during ignition and combustion, from the unburned fuel/air mixture to the completely burned exhaust gas. The focus of the model lies on a realistic treatment of the temporal rate of change of the progress variable, such that phenomena like auto-ignition can be described accurately. This rate is tabulated and stored for a set of conditions (mixture fraction, enthalpy, pressure), for both homogeneous and stratified fuel/air ratio fields. A software module that performs an interpolation of these data to deliver the progress variable rate for each condition is provided as a part of the deliverable. This allows solving a transport equation for the progress variable, so that a realistic treatment of chemical reactions can be coupled with an accurate description of the flow-field in engine CFD simulations.

The developed progress variable model is an adequate method to implement realistic chemistry results in CFD calculations in an accurate way, as it is seen from the fact that the PV model reproduces the ignition delay time almost exactly.
All sub models and the final progress variable model have been tested permanently during the development in close cooperation with the project partner Daimler.

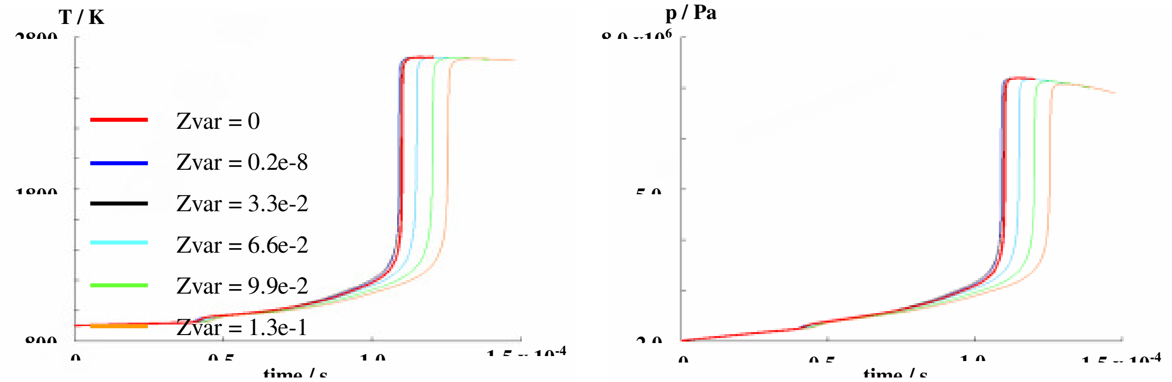


Fig. B1. 10: Temperature and pressure profiles for a simple test engine case with constant mean mixture fraction and different mixture fraction variances (at stoichiomety).

Figure B1.10 shows, as one example, the temporal development of temperature and pressure for a simple test simulation of an engine model. For constant mean value of the mixture fraction, cases with different mixture fraction variances were calculated. The variance increases from the blue to the orange line in equidistant steps. The red line is the solution for a homogeneous reactor without any mixture fraction fluctuations. The effect of a load with varying mixture fraction is predicted by the model.

Application of the Progress variable model

The extension of the 7 species PDF-Timescale model combined with the progress model was tested in a homogenous reactor test code which uses the KIVA3v thermodynamic database. This model is capable to treat all combustion phases including chemically controlled ignition and premixed combustion. The detailed chemical information is stored in a pre-calculated library which also includes the mean and variance (presumed β-pdf) of mixture fraction as independent variables, so that fields with inhomogeneous fuel/air mixtures can be treated.
In CFD only a small number of variables (progress-variable, 7 active species) are transported. Besides the chemical source term, additional source terms appear in the transport equation of the progress variable. These terms describe the change of the progress variable due to mixing effects as well as vaporization of liquid fuel. To avoid problems in the late expansion phase the progress-variable model is coupled to the 7-species PDF-Timescale model for diffusion combustion.

The comparison of homogenous reactor calculations has shown that the heat release of the detailed chemistry is captured very well with the progress-variable model. Further, the coupling of the progress-variable model to the PDF-Timescale model was verified. CFD-calculations on a 2D-mesh under DI engine conditions have shown that the evaporation and mixing source term for the progress-variable as well as the integration of the chemical source term (in mixture fraction space) is essential for highly inhomogeneous mixtures to predict the heat release and ignition delay.

CMC

The objective of the work performed at the University of Cambridge was to develop a methodology that can incorporate turbulence-chemistry interactions in diesel combustion in a computationally-efficient manner. This methodology was based on the Conditional Moment Closure method and the computational code written for the solution of the model's equations has been interfaced to the code STAR-CD. The package has been validated against experimental data from simplified configurations and from complex engine geometries. The computational efficiency was achieved (i) by averaging over selected regions of the CFD grid and hence reducing the size of the equations that need to be solved in the CMC method; (ii) by using fractional step integration methods.

The combined STARCD-CMC code has also been used for a truck diesel engine and the predicted pressure trace is very close to the experiment (Fig. B1.11). This demonstrates that the code is fully operational and can be used by the industrial partners for calculations of complicated engine geometries. Very detailed insight into the structure of diesel combustion can be obtained by the multi-dimensional CFD – CMC code. For example, the location of radicals that are detectable experimentally such as OH can be predicted (Fig. B1.12).

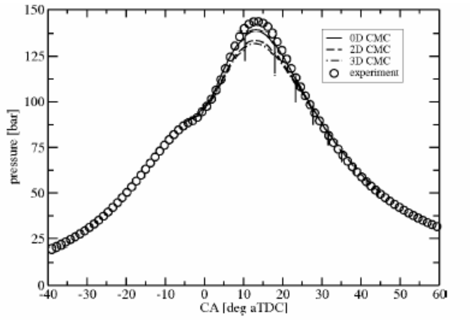


Fig. B1. 11: Measured and predicted pressure trace for a diesel engine. Experimental data and engine geometry from Y.M. Wright (PhD Thesis, 2005, ETH Zurich).

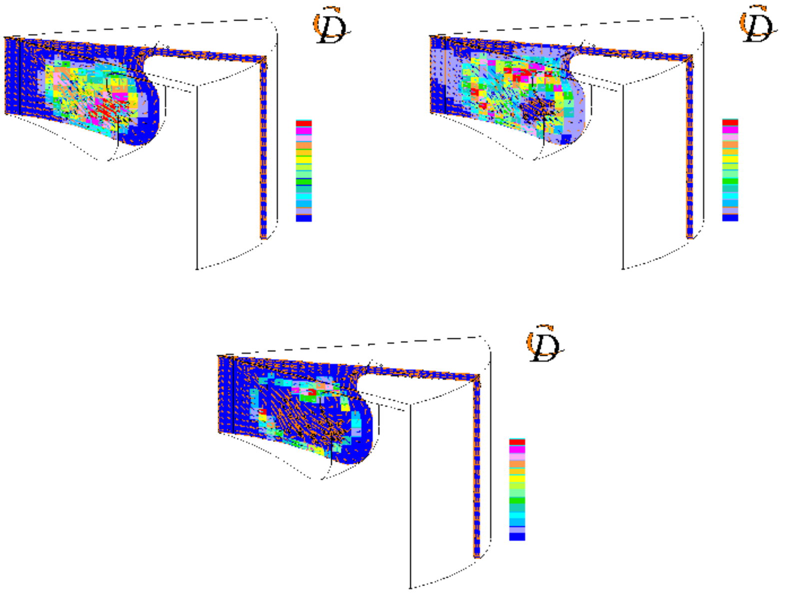


Fig. B1. 12: Mean mixture fraction (top left), temperature (top right), and OH mass fraction (lower) during the flame expansion phase following autoignition in a diesel engine.

Application of the Eulerian Spray Coupling Method with Combustion Analysis

For the validation of the introduced coupling concept, CFD simulations for a heavy duty truck engine were compared to measurements of a single cylinder engine and optical diagnostics. In the first step of the simulations the transient flow in the nozzle was simulated to obtain the dynamic and turbulent boundary conditions at the nozzle orifice, see Fig. B1.13. These are the boundary conditions for the multiphase 3D Eulerian spray which is calculated in the next step in an orifice resolved region just outside the nozzle hole, while the further engine domain is simulated in the classical 1-phase approach.

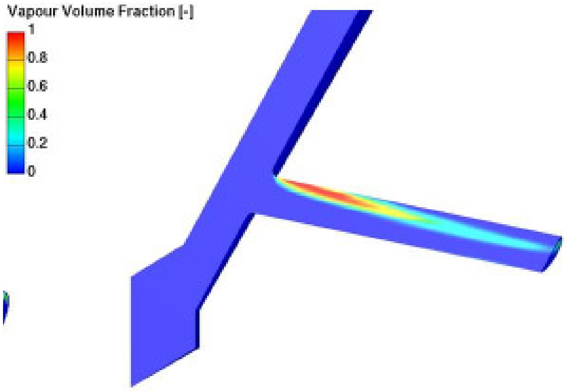


Fig. B1. 13: Results from 3D nozzle flow simulations. Fuel is entering the nozzle from above and flows into the nozzle hole towards the nozzle orifice to the right. The red color indicates the existence of vapor and thus cavitation (blue color = liquid phase).

A load point was selected representing a case with high injected fuel mass and an intense combustion process after the occurrence of ignition. Nevertheless, the results in Figure B1.14 show an overall acceptable agreement in terms of pressure traces. During the expansion however pressure values appear to be underestimated; this is probably due to the still not complete confidence in the Eulerian spray model initialization. Further analysis on evaporation, dispersion and break-up processes in the hot environment are therefore required.
The heat release rate diagram in Figure B1.14 confirms that the ignition time matches well with experiments, even if the diffusion combustion peak appears underestimated and energy is afterwards slowly released during the expansion stroke.

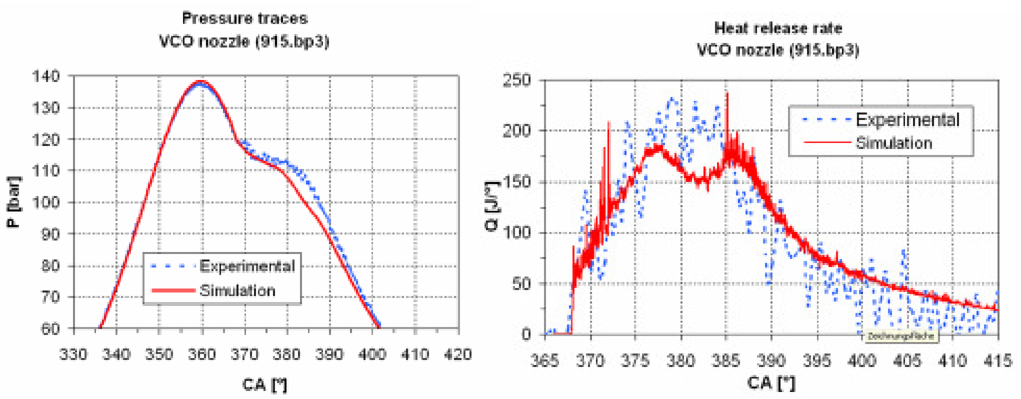


Fig. B1. 14 Pressure traces and heat release rates for the Eulerian spray coupled simulation.

Soot emissions

To really apply simulations of diesel engine combustion predictive emission models are essential. This is in particular valid for the modeling of soot formation.
Within the concept of NICE combustion the phenomenon of flame lift-off plays a crucial role. Flame lift-off allows air to be entrained into the spray and thus a high degree of premixing prior to combustion which in turn leads to a decrease in soot formation. The prediction of lift-off is thus crucial for capturing this trend in soot. Within NICE the flamelet combustion model was further developed to be able to predict lift-off. A comparison of the state-of-the-art model and the new method is shown in Figure B1.15. Correct soot trends with regard to parameters that affect lift-off such as injection pressure and temperature were achieved.

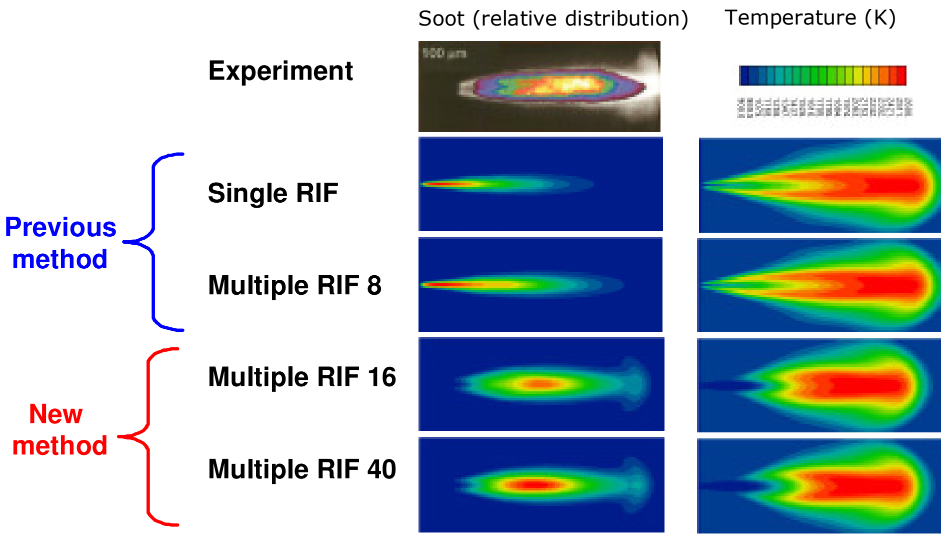
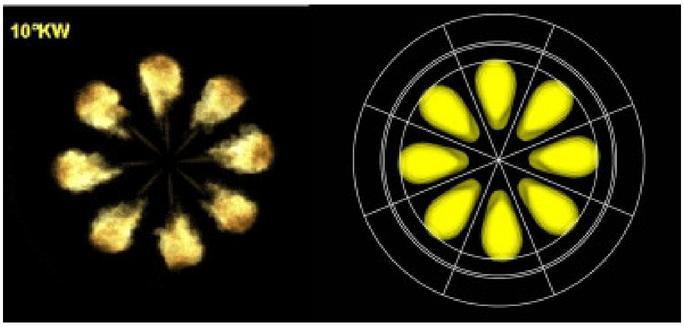
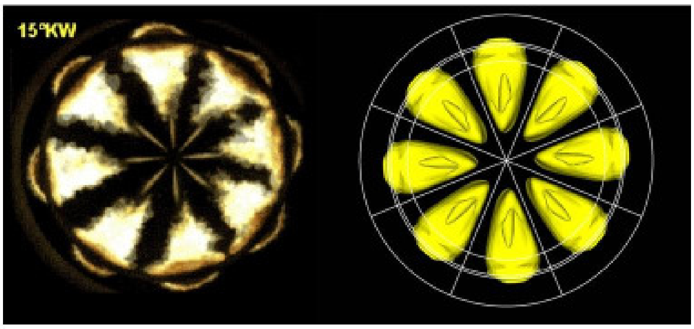


Fig. B1. 15: Comparison measured (top) and simulated soot (left) and temperature (right) distributions in a Diesel flame. The improved method is able to describe the flame and soot lift-off seen in the experiment.

To validate soot library models developed within NICE simulation results were compared by Daimler to measurements in an optically accessible bowl. The engine relevant features are identical to a modern single cylinder test facility. A special elongated transparent piston containing a quartz window allows the optical access from the bottom of the bowl, which is also machined into a quartz piston. The pictures luminescence could be associated with the soot radiation. Simulation results in Figures B1.16 are displayed with luminosity iso-surfaces according to a characteristic value.



10° ATDC



15° ATDC

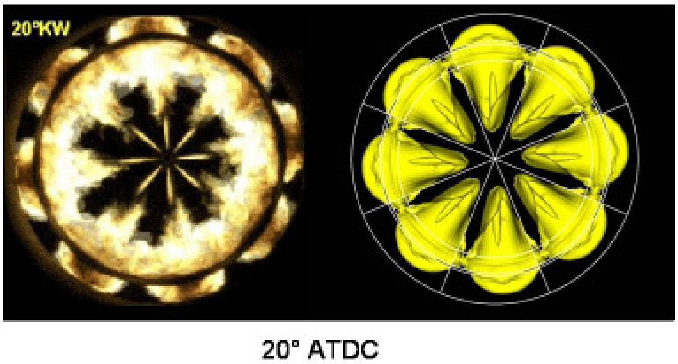


Fig. B1. 16 Comparison between simulation and diagnostic for heavy duty truck engine with VCO nozzle (left: photographic sequence of the combustion cycle; right: calculated luminosity of soot).

The results in Figure B1.16 show a good agreement between simulation and diagnostic results. The iso-surfaces on the right hand side have to be considered mostly according to their shape, as the emissions of the under laying volume cannot be represented with this kind of post processing.

Local characteristics of injection and combustion processes are well predicted, even if it appears form the measurements that the flame shows a bit stronger radial diffusion. Simulated penetrations appear slightly under predicted, but this could be explained by the lower gas density in the transparent engine: in fact, the piston has a higher elasticity than in the simulation or single-cylinder measurements. Another reason could be found in the unavoidable distortion of the quartz piston window, which could influence the definition of geometrical boundaries in the experimental pictures.

Chemical Kinetics

Modification of fuel properties have proven to carry big potential for the reduction of emissions, in particular a low boiling range is advantageous, while aromatic components increase the soot emissions. Furthermore a low cetane number leads to better homogenisation behaviour and lower soot emissions. Apart from chemical and thermodynamic analysis, measurements regarding the auto-ignition behaviour, the spray characteristics and the potentials for emission reduction have been shown for different fuels by Volkswagen in subproject A2. As a result of these investigations the Fischer-Tropsch Kerosene called CCS-fuel (Combined Combustion System fuel) has been selected as the alternative fuel for the NICE project.

The CCS-Fuel together with standard Diesel fuel was applied in CFD simulations regarding cavitating injector flows and fuel sprays in the FIRE code. Furthermore the development and validation of a chemical mechanism for the alternative fuel was supported by measurements funded by Volkswagen. The target was the integration of this mechanism in 3D CFD to predict ignition delays correctly. Additionally the application and validation of early versions of the ECFM-3Z model were performed. The aim was to help in the development of the new combustion system; however, the interaction with partners in A2 also provided important data to validate the new and improved CFD models and methods in B1.

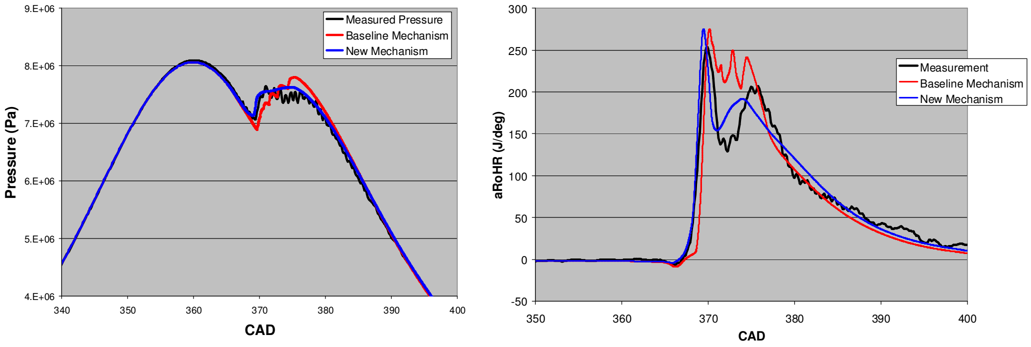


Fig. B1. 17: Comparison between measured and simulated pressure traces (left) and rate of heat release curves (right).

The new chemical mechanism for Diesel fuel was successfully implemented into the flamelet model and tested in engine simulations of a heavy-duty truck engine, see Fig. B1.17. For the validation a case with long ignition delay and a high degree of pre-mixing was selected. With the new kinetic model a more accurate description of the ignition delay is accomplished and predictions of the pressure and the rate of heat release are improved compared to the state-of-the-art model.

- Relation of the results to the state of the art

The following list summarizes main achievements within NICE B1. Many new models have been developed and other existing models have been improved. All models were implemented into commercial CFD codes and are thus available for use. Most of the models are today part of the state-of-the-art simulation tools that are used within the OEMs engine development processes.

The Euler spray model

- makes the direct coupling between models for nozzle flow, spray, combustion and emissions possible
- much lower grid dependency and better statistical convergence
- Euler model in dense parts and Lagrangian model in the dilute spray combine the benefits of the two approaches
- spray penetration well predicted
- Implemented in AVL FIRE; can be coupled to other CFD codes

Fuel/air mixing

- important effects of spray evaporation and walls taken into account
- improvements for diesel simulations reported by Renault
- new PDF shape gives good agreement with empirical data
- models used in ECFM3z, ECFM-CLE-H, CMC

Chemistry

- kinetic models with predictive capability also for low temperature combustion conditions
- reduced chemical mechanisms made available
- Available in ECFM3z, ECFM-CLE-H, progress variable model and RIF

Chemistry for alternative fuels

- first detailed schemes available
- comparison with experimental data promising
- reduction not yet done
- Available for ECFM-CLE-H format

Combustion Models

- **ECFM3z/ECFM-CLE-H**
  - realistic fuel chemistry
  - composition fluctuations, qualitative improvements on ignition
  - adaptation of spray model
  - pollutants coupling ongoing
  - robust and fast
  - Implemented in STAR-CD

- **Progress Variable Model**
  - new model developed
  - combines detailed chemistry and turbulence interaction
  - quick and accurate
  - tested by DC for engine CFD
  - Implemented in STAR-CD

- **CMC**
  - adapted for engine calculations
  - accurate prediction of ignition time, pressure rise, lift-off height, qualitative structure of diesel combustion
  - Implemented in STAR-CD

Soot

- “emission” chemistry updated
- library soot model improved and available in STAR-CD
- multiple RIF promising
- CMC interfaced with soot, high potential

2.4.5. List of acronyms B1

3D Three Dimensional
ACCI AVL Code Coupling Interface
CD-ADAPCO Company developing and distributing the CFD code STAR-CD
CA Crank Angle
Ca nozzle area contraction coefficient
CAXX Crank Position in CAD at XX% heat release
CCS Combined Combustion System
CFD Computational Fluid Dynamics
CLE-H combustion limited by thermodynamic equilibrium
CMC Conditional Moment Closure
DDM Discrete Droplet Model
DI Direct Injection
DIME European research project
ECFM Extended Coherent Flame Model
ECFM3z Extended Coherent Manifold Model 3 zones
EGR Exhaust Gas Recirculation
Fire CFD code developed by AVL
FT Fischer-Tropsch
GUI Graphical User Interface
HCCI Homogeneous Charge Compression Ignition
IC Internal Combustion
IEM Interaction by Exchange with the Mean
IMEP Indicated Mean Effective Pressure
IFP-C3D CFD code developed by IFP
I-Level European research project
JSR Jet Stirred Reactor
Kiva CFD code
kε Commonly used RANS turbulence model
LES Large Eddy Simulation
LIEF Laser Induced Exciplex Fluorescence
MPI Message Passing Interface
NEDC New European Driving Cycle
NSCBC Navier-Stokes Characteristic Boundary Conditions
PAH Polyaromatic Hydrocarbon
PDF Probability Density Function
PEA Partial Elimination Algorithm
PRF Primary Reference Fuels
PRISM Piecewise Reusable Implementation of Solution Mapping
RANS Reynolds Average Navier-Stokes
RIF Representative interactive flamelet
RNG Re-Normalization Group
SGS Subgrid-scale
STAR-CD CFD code developed by CD-Adapco

TDC Top Dead Centre
TED Turbulent Energy Dissipation
TKE Turbulent Kinetic Energy
VCO nozzle valve covering orifice nozzle
β-PDF Presumed beta function Probability Density Function

3 Section 3 – Final plan for using and disseminating the knowledge

3.1 Introduction

In this section we will present exploitable results achieved in the IP NICE during whole project run time. The results are 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.
Both past and planned future activities should be included.

3.2 Exploitable results overview table

The following table gives an overview about the exploitable results within the project NICE:

#	Exploitable Knowledge (description)	Exploitable product(s) or measure(s)	Sector(s) of application	Timetable for commercial use	Patents or other IPR protection	Owner & Other Partner(s) involved
1	Lean burn combustion of spark ignition engine	Specific knowledge of lean burn combustion	Automotive and supply industry	2008	Pre-existing patents and patent applications	FEV
2	Knowledge on analysis and improvement of gas exchange and mixture formation of lean burn SI gas and gasoline engines Validation of simulation tools for lean mixture formation	Specific Knowledge to improve academic standards and research	Automotive and University lessons	2006 to 2008		RWTH/ VKA/ PT
3	Combustion system requirements, application methodology and emission reduction potential for new DI Diesel operating modes based on high exhaust gas recirculation rates and tailored fuels	Application know how and -methodology for synthetic fuels in combination with alternative combustion modes	1.Automotive industry / Car manufacturers 2. Suppliers of Fuel injection systems 3. Suppliers of engine I systems (ands sensors)	2007	Pre-existing patents for alternative combustion	AVL List GmbH (owner)

#	Exploitable Knowledge (description)	Exploitable product(s) or measure(s)	Sector(s) of application	Timetable for commercial use	Patents or other IPR protection	Owner & Other Partner(s) involved
4	Combustion System Development for CNG-Direct Injection to reduce CO2 emission	Development know-how for engine equipped with CNG-DI	Automotive, use in the upcoming EU IP INGAS	2008	A Patent for DMI (Direct Mixture Injector) owned by AVL exists (PatNr: AT,GM 856/2002)	AVL List GmbH (owner) DC, Siemens
5	DOT - Delay Optimized Turbocharging (new turbocharging concept)	Turbocharging concept	Automotive industry	2014	Patent DE 199 55 508 C, other patents pending	DC
6	Application of Variable Valve Actuation to supercharged gasoline engines	Electronically controlled Variable Valve Actuation system	Automotive industries	2010	Several patents pending	CRF
7	Model for turbulence-chemistry interactions	Code to solve model equations. Name: “CMC code”	1. Energy 2. Chemical	2007	IPR protected by Consortium Agreement	UCAM
8	Feasibility, design, simulation, component-test, procurement and sample build of a DI-CNG –Piezo injector, controlling the direct injection	DI-CNG-PIEZO-Injector, Engine-Management System-Functions for injection time correction and part lift control	Automotive industries, use in the upcoming EU IP INGAS	2010	Several patents for ECU and injector pending	Siemens VDO, Siemens AG
9	Methodology for a realistic and efficient description of chemical reactions in engine CFD simulations	Multi-parametric tabulation of chemistry Modular chemistry code for use in CFD codes	Automotive industry – improved development of Diesel engines	2006	—	ITT Partner: DaimlerChrysler (not owner)

#	Exploitable Knowledge (description)	Exploitable product(s) or measure(s)	Sector(s) of application	Timetable for commercial use	Patents or other IPR protection	Owner & Other Partner(s) involved
10	2. Improved PDF—model for the description of mixing and reaction in Diesel engines	Strategy for the implementation of the PDF-model into CFD applications	Automotive industry – improved development of IC engines	2006	—	ITT Partner: DaimlerChrysler (not owner)
11	Characteristics of new ignition systems in the combustion chamber for variable CNG mixtures at different pressure	SI Engine equipped with DI system of CNG	Automotive industry + University lessons	Worldwide Congress & Conferences	The research measurement systems will be patented	KU
12	Advanced physical models and mixture formation, advanced numerical techniques for code coupling	Advanced simulation tool for mixture formation in IC engines	Automotive	2007	Commercial CFD Code FIRE 8	AVL List GmbH (owner)
13	Knowledge on turbocharging systems performance in unsteady flow conditions and correlation criteria between steady and transient performance	Specific Knowledge to improve academic standards and research	Automotive + University lessons	~~2006~~ Worldwide Congress & Conferences		UNIGE
14	Codes for 1-D radial turbine modelling v. 2006 and code for evaluation of turbine parameters at working engine	Specific knowledge to improve academic standards and research	Automotive + Turbocharger manufacturing + University lessons	2006	IPR protected by Consortium Agreement	JBRC
15	Stratified lean combustion system for CNG direct injection engine	Knowledge of charge stratification with CNG-DI	Automotive	2010	Patent application in progress	AVL List GmbH, DC
16	Guidelines on CNG injector sprinkler-head design through 3D numerical investigation of gas-jet flows, their capabilities of air entrainment and of mixture formation	Specific Knowledge to improve academic standards and research	Automotive industry and University teaching	Worldwide Congresses and Conferences		PT

#	Exploitable Knowledge (description)	Exploitable product(s) or measure(s)	Sector(s) of application	Timetable for commercial use	Patents or other IPR protection	Owner & Other Partner(s) involved
17	Basic aspects of high-pressure supersonic gas-flow injection in an open environment and its dependence on wall to nozzle tip distance, through 3D flow simulation inside the injector and spray	Specific Knowledge to improve academic standards and research	Automotive industry and University teaching	Worldwide Congresses and Conferences		PT
18	Design of cylinder head	Specific knowledge of conception of cylinder head with 0 degree valve shape	Automotive	2012	Pre-existing patents and patent applications	Renault
19	Design of intake manifold	Specific Knowledge to design a manifold with Variable Swirl	Automotive	2012	Pre-existing patents and patent applications	Renault
20	Design of LP EGR Loop	Specific Knowledge to design LP EGR Loop components	Automotive	2012	Pre-existing patents and patent applications	Renault
21	Design of H_WAB piston for HCCI combustion	Specific Knowledge to optimize a piston bowl for HCCI Engine	Automotive	2012	Pre-existing patents and patent applications	Renault
22	Optimize Hard ware for HCCI Combustion	Specific Knowledge to Optimize Hard ware for HCCI Combustion	Automotive	2012	Pre-existing patents and patent applications	Renault
23	Design for Variable valve lift VVA system to implement internal EGR and control of effective compression ratio.	None	Automotive engine production	2010 or beyond	None during the period	Mechadyne / Renault

#	Exploitable Knowledge (description)	Exploitable product(s) or measure(s)	Sector(s) of application	Timetable for commercial use	Patents or other IPR protection	Owner & Other Partner(s) involved
24	Spray-guided Combustion System with Turbocharging	Know-How in Gasoline Direct injection	Automotive	2009	Pre-existing patents and patent applications	FEV
25	Combustion system development for CNG direct injection	Engine with CNG-DI engine	Automotive	2014	None	Daimler
26	HCCI combustion	Specific knowledge of mild HCCI combustion	Automotive and supply industry	2012	Essentially know-how. Various existing patents	IFP/ Renault/ UPVLC
27	Mechanical Variable distribution	Exhaust valve reopening during intake valve opening	Automotive and supply industry	2015	Pre-existing patents and patent applications	IFP/ Mechadyne/ Renault
28	Double turbocharging management strategy	Switching strategy	Automotive and supply industry	2012	Essentially know-how. Various existing patents	Renault/ UPVLC
29	Engine management strategy	Mild HCCI combustion strategies (injection and air path)	Automotive and supply industry	2015	Essentially know-how. Various existing patents	Delphi/ Renault

3.3 Description of the exploitable results

Detailed description of each result mentioned in the chapter 3.2

1. Lean burn combustion of spark ignition engine (FEV)

While turbocharging, homogeneous lambda=1 concepts currently represent the most common state-of-the-art gasoline engine technology, first generation lean burn concepts focused on stratified operation in the NEDC relevant mapping area. Future gasoline combustion concepts with focus on reduction of fuel consumption and CO_2 emission primarily aim at downsizing/boosting in combination with lean burn and high compression ratio. Both, high lean burn capability and low knocking sensitivity rely on

1. sufficient fast combustion process with stable inflammation, and
2. sufficient mixture homogenization.

Therefore, the main project targets are the specification of requirements for such a combustion system. This specification mainly concerns the injection system, the combustion system (e.g., including charge motion, combustion chamber design, compression ratio). The engine investigations, being performed on a single-cylinder research engine, focus on part load and high engine load.

Based on pre-existing know how and pre-existing patent applications FEV improves its specific know how on lean combustion processes. This specific knowledge of lean combustion process will be used for publications and for commercial projects with its customers.

2. Knowledge on analysis and improvement of gas exchange and mixture formation of lean burn SI gas and gasoline engines (RWTH/VKA/PT)

RWTH/VKA develops specific Know How in its fields of participation within the project NICE. This Know How will be protected by IPR; so far it is useful. Especially work is done to assess the in-cylinder flow, the injection, the spray propagation and finally the mixture formation process by CFD simulation in order to get information about the charge homogeneity, which is critically limiting the engine operation range. By parameter changes, e.g. charge motion number, geometry modifications, injector types and positioning, detailed knowledge about optimized mixture and combustion characteristics for future SI combustion systems is gained. The results of calculation are frequently exchanged with the project partners in order to define an optimized combustion system layout.

PT developed and validated a 3D-CFD model for the simulation of methane direct injection into a SI engine combustion chamber. Basic knowledge about the influence of injector protrusion, injection timing and A/F ratio on the mixture formation process has been produced.

3. Combustion system requirements, application methodology and emission reduction potential for new DI Diesel operating modes based on high exhaust gas recirculation rates and tailored fuels (AVL)

Beside conventional diesel fuel, non-crude oil based diesel fuels will be available on different markets in extended and more varying specifications in the future. Thus measures have to be taken to achieve performance and emission compliance of engines and furthermore – in case of highly designed fuels – to gain full use of the fuel potential for a further reduction of emissions.

In course of the project NICE a new application methodology for a fuel specific optimisation of combustion was developed, were fuel properties, fuel specifically optimised engine operating parameters and emissions are correlated based on regression models, were engine operation in combustion modes with very high exhaust gas recirculation rates (HCLI Homogenous charge late injection; alternative combustion system/mode) is covered as well, which is beneficial to achieve very low smoke and low NOx emissions at part load.

Based on baseline studies, the new methodology and the extrapolation of fuel specific emissions in the New European driving cycle (NEDC) it was shown, that one single combustion system hardware (injection nozzle and bowl design, variable swirl) in conjunction with a flexible injection system (common rail system of the state of the art) and enhanced control functions of the engine management system can cover engine operation with conventional and synthetic fuels (GTL, BTL, Bio fuels of 2nd generation) at very low emission levels.

These control strategies to be included are a closed loop combustion control to scope with differing ignition behaviour (varying cetane number) and a closed loop torque control correcting fuel injection quantities to compensate different densities and lower net calorific values of various fuels. Furthermore the stoichiometric air demand, varying with the H/C ratio and the oxygen content of the fuel, needs to be considered as well. A closed loop combustion control will be necessary in any case to operate the engine in alternative combustion mode. Furthermore operation with conventional diesel fuel must be possible in any case.

If the above mentioned requirements are considered synthetic fuels show high potential for a further reduction of engine out emissions. Even in conventional diesel combustion systems soot reductions up to more than 60% can be achieved. There are no significant fuel specific advantages in view of NOx emissions.

4. Combustion System Development for CNG-Direct Injection to reduce CO2 emission (AVL)

The developed combustion system will combine gasoline typical full load performance by somewhat better efficiency due to the higher CR which can be used because CNG‘s knock resistance. The biggest advantage compared to gasoline combustion will be the significant CO2 emission reduction, especially in view of the self-commitment of the EU for CO2 reduction.

The disadvantage of actual CNG port injection engines in terms of full load performance, can be nearly eliminated be direct injection and boosting.

The definition of the requirements of a suitable injector type and ignition system will be a secondary output of the combustion system development.

The knowledge will primarily be shared with DC (responsible for engine development), Siemens (injection system and ECU) and Beru (ignition system).

One key question for broad commercial use of CNG-DI engines in passenger cars will be the availability of CNG and the supply-density. With respect to e somewhat lower operating range the nation-wide supply network together with the CNG storing (200bar or more – canister) issue has to be solved.

5. DOT (DCAG)

Delay Optimized Turbocharging (DOT) is a new concept intended to improve the driving behaviour of turbocharged engines. The philosophy consists of a stationary rotor speed turbocharger. Rather than the rotor speed varying with engine load and engine speed, the rotor speed remains at a high level. The high rotor speed is achieved by using the throttle energy to increase the turbocharger speed. The technical solution is a two-way turbo engine on the TC air side composed of a variable cold air turbine and a variable compressor. This device determines the engine air flow.

6. Application of Variable Valve Actuation to supercharged gasoline engines (CRF)

The CRF VVA system is an electronically controlled electro-hydraulic Variable Valve actuation system. In the NICE framework the VVA will be fully integrated in the turbocharged gasoline 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.

The fully un-throttled engine operation and the flexible combustion rate control, improve significantly the overall engine efficiency, while the high dynamic performance represents a breakthrough to eliminate the well known issues related to “turbo-lag” on gasoline engines, improving engine and turbocharger response. This will give a significant contribution to enable market penetration of small displacement “downsized” gasoline engines thanks to the enhanced vehicle fun to drive.

7. Model for turbulence-chemistry interactions (UCAM)

The equations describing the interactions between turbulence and chemistry, collectively named “CMC model”, have been solved in a computational code called “CMC code”. This code has been interfaced with the commercial CFD package STAR-CD and this interface is an integral part of the “CMC code”, owned by the University of Cambridge.

The code can be used for practical diesel and HCCI engine calculations and is being installed to the industrial partners R&D labs.

The CMC code has also attracted interest from the gas turbine industry and licensing discussions with various companies are under way.

8. Feasibility, design, simulation, component-test, procurement and sample build of a DI-CNG –Piezo injector, controlling the direct injection (Siemens VDO, Siemens AG)

The requirements for gas flow inside a DI-Injector are 10 times larger compared to actual liquid direct injection. Therefore a completely new approach was necessary. Solenoid technology has shown not enough driving energy. This can be delivered by Piezo Actuators, but the travel of such actuators is to low. The problem is solved by using a hydraulic travel transducer. The concept was developed by multi-physic modelling and 1d-simulation of the mechanics/hydraulics. The feasibility of the valve and the Piezo Actuator was validated in long term tests in CNG atmosphere. To get more information about the needle movement during motor tests, an eddy current stroke sensor is implemented in the injector. The Injector was designed and parts procured and a first sample was built.

Controlling the direct injection process of CNG is very challenging in respect of the high number of parameter of influence as e.g. CNG-pressure in injector, pressure in cylinder especially during compression stroke and the gas-composition of CNG. The variation of these parameters results in a correction of the injection time in relation to a basic calibration which is controlled by the engine management system. A model for short and long time gas-composition identification was developed and results in an algorithm suitable to the real-time requirements of the EMS.

9. Multi-parametric tabulation of chemistry

The progress of chemical reactions occurring under conditions in engines is represented by a small (typically 1-3) set of reaction progress variables. The rate of chemical progress (based on detailed chemistry for engine-relevant model fuels) is first evaluated by a detailed chemical simulation code for varying conditions (stoichiometric ratio, pressure, specific enthalpy of the mixture) and then stored in form of a table. A software module (designed for

coupling with CFD-codes) is provided that delivers the rate of chemical progress (the speed at which fuel/air mixture is transformed into burned gas via ignition and combustion) in dependence of physical parameters (e.g., pressure, mixture stoichiometry).
The tabulation and the code development was performed at Karlsruhe University; implementation into CFD Codes is done in cooperation with DaimlerChrysler (NICE Partner). Implementations of the progress-variable chemistry method are expected to be of high commercial value for engine developers (increased accuracy of CFD simulations that use the progress variable module – therefore a faster development process of engines).
No thresholds or obstacles (technical or commercial) occurred or anticipated yet

10. Improved PDF model for the description of mixing and chemical reactions

Physical/chemical model for the description of fuel/air mixing in CFD simulations of internal combustion engines with multi-phase flows (fuel sprays), based on a Probability Density Function (PDF) approach. The model will be coulped with CFD codes in order to improve engine simulations. To accomplish this coupling, a precalculated table of realistic mixture fraction pdf-shapes in fuel/air mixing processes is tabulated for subsequent use in CFD coes (calculation of means). Easy-to-use subroutines for the interpolation in this table and the calculation of pdf-shapes as a function of the mean variance have been created.

11. Characteristics of new ignition systems in the combustion chamber for variable CNG mixtures at different pressure

The measurements of the different ignition systems delivered by BERU in the caloric chamber gave the information of the current and voltage variation in the primary and secondary circuits. These tests enable the determination of the required energy in the secondary circuit for sparking the CNG mixtures at different compression pressure and excess fuel ratio. Measurements determined the total efficiency of the tested ignition systems. The new measurements units and systems were worked out and applied for determination of current and voltage at short period.
The remarks of the ignition system were sent to the producer.

12. Advanced physical models and mixture formation, advanced numerical techniques for code coupling (AVL)

The coupling of the novel method of Eulerian multiphase spray simulation applied on a fine grid close to the injector with a standard engine simulation using the Lagrangian spray model on a coarser engine grid allows for a higher accuracy and predictivity of mixture formation simulation. An important benefit of this approach is the higher accuracy and resolution, better stochastic convergence and stability of the spray simulation as well as the easy link to injector flow simulation. The latter provides the initial conditions for the injected spray as well as the conditions govering primary fuel break-up, i.e., initial size distribution and spray angle. The code coupling concept allows to use these benefits of a detailed Eulerian spray simulation close to the injector together with the advantages of the well established standard method for combustion simulation by doing two simultaneous simulations exchanging all of the relevant data via a newly developped code coupling interface. The code coupling interface is designed as an open and flexible tool which allows to couple the Eulerian spray model with the FIRE code as well as with other CFD codes for engine simulation.

13. Knowledge on turbocharging systems performance in unsteady flow conditions and correlation criteria between steady and transient performance

Within its participation to the project NICE, UNIGE develops specific know-how on transient turbocharging system performance. Starting from the state of the art, theoretical and experimental methodologies will be developed to assess unsteady turbine behavior and correlation criteria with steady flow performance. Moreover, the engine exhaust system optimization will be extended to a subsystem level, including the effect of different valve control strategies on turbocharger transient behavior.

These results will improve academic standards and research and will provide an operational tool for automotive industry to enhance engine-turbocharger matching.

14. Simulation of radial turbine performance usable in 1-D codes and tools for evaluation of turbine parameters at engine in operation

JBRC has developed specific procedures for radial turbine performance simulation based on quasi-steady 1-D model. It is useful for turbine features extrapolation. In the framework of NICE it was adopted to be used in calibration procedures based on specific testbed or engine measurements. The prediction was used in simulations of SP A2, TP 3 (turbocharged diesel engine with massive EGR). The predicted turbine map can be tested at engine in operation using unsteady pressure measurements and comparing predicted and achieved mean parameters of turbine. For this aim the other specific code was developed and tested by simulated results.

15. Stratified lean combustion system for CNG direct injection engine (AVL)

The developed combustion concept enables charge stratification with a richer mixture cloud around the spark plug and ideally pure air around. The combustion system represents a wall-guided system. The method enables a very lean global operation far outside the normal lean ignition limit. The dethrottling effect reduces pumping losses, the isolation effect of the air around the burnable cloud reduces the wall heat losses. This leads to a significantly better combustion efficiency, reducing fuel consumption.

An introduction into the market will strongly depend on the progress made on catalyst technology to cope with the relatively low exhaust gas temperature caused by this ultra lean operation.

16. Guidelines on CNG injector sprinkler-head design through 3D numerical investigation of gas-jet flows, their capabilities of air entrainment and of mixture formation (PT)

A contribution was given to basic knowledge concerning the influence of flow properties (upstream, downstream pressure and temperatures), as well as of nozzle hole geometric data (length h, diameter D), on gas jet features (cone angle and penetration) issuing from single-hole and sprinkler-head multi-hole nozzles in an open environment.

The mixture formation capabilities of the gaseous-fuel jets were analysed both in an open environment and in a cylinder-like closed volume, using a novel mass-averaged quantity, i.e., the mixture mass fraction, f_m.

17. Basic aspects of high-pressure supersonic gas-flow injection in an open environment and its dependence on wall to nozzle tip distance, through 3D flow simulation inside the injector and spray (PT)

Basic knowledge was provided to the design of CNG direct injection engines through the 3D computational analysis of jet flow field, methane concentration distribution and injected mass-flow rate and their dependence on the following parameters:
- computational mesh structure and size;
- upper wall distance from the nozzle cartridge tip.

18. Design of cylinder head

Specific knowledge of cylinder head conception with 0-degree valve shape. Renault improved its know how concerning the thermo mechanical calculation and fatigue strength assessment of such type of component

19. Design of intake manifold

Specific Knowledge to design a manifold with Variable Swirl flap. Renault improved its know how concerning the aerodynamic calculation and validation assessment of such type of component.

20. Design of LP EGR Loop

Specific Knowledge to design LP EGR Loop components. Renault improved its know how concerning GT power calculation and packaging of such type of component.

21. Design of H_WAB piston for HCCI combustion

Specific Knowledge to optimize a piston bowl for HCCI Engine. This know how could be used for future mass production engine.

22. Optimize Hardware for HCCI Combustion

Optimize Hardware for HCCI Combustion with high injection pressure level and pizo direct

23. Design for Variable valve lift VVA system to implement internal EGR and control of effective compression ratio

Design of a VVA system to implement internal EGR that operates by creating a modulated secondary exhaust valve opening during the intake stroke.

Design of a VVA system that controls effective compression ratio by altering the timing of intake valve closing.

Design of the cylinder head details required to package the VVA systems , design of covers and actuators for integration and control of the VVA systems for test bed operation and later installation in a vehicle.

24. Spray-guided Combustion System with Turbocharging

FEV has built up a new SprayGuided Turbo SGT engine with enhanced specifications. The turbocharged engine is modified into a spray-guided combustion system with central Piezo injector location. Main achievements: improved fuel consumption, improved charge dilution capability, improved cold start and warm-up capability. Higher specific power and torque levels are solved by specific design and cooling solutions. The engine is developed based on FEV's charge motion design (CMD) process and single cylinder investigations. The engine control unit has a modular basis and is realized using rapid prototyping hardware. Additional fuel consumption potentials can be achieved with high load EGR, use of alternative fuels and a hybrid powertrain. The CO_2 targets of the EU (130 g/km in the NEDC) can be obtained with a mid-size vehicle by the technologies presented in this paper.

25. Combustion System Development for CNG-Direct Injection to reduce CO2 emission (Daimler)

The developed combustion system will combine gasoline typical full load performance and high efficiency due to the higher CR which can be used because of CNG‘s knock resistance. Further advantage is given by easier conversion of future DI gasoline engines.

26. HCCI combustion

Jet visualization, mixture formation, flame propagation and CFD analysis of several multiple injection strategies. Single cylinder engine tests to select cooled high EGR rates, injection parameters and boost pressure.

27. Mechanical Variable distribution

Use of exhaust valve reopening to reduce HC/CO emissions in HCCI combustion. Strategy to be used and consequences have been shown. Comparison with HP EGR showed similar results confirming the simulation which proved exhaust reopening could be used to replace a part of EGR.

28. Double turbocharging management strategy

Simulation of the double turbocharger system behavior and switching from high pressure turbo to low pressure turbo at the right engine revolution /load. Results have been cross checked with separate testing of the two turbochargers. Benefits in emissions, power and consumption have been highlighted.

29. Engine management strategy

Definition of two combustion types states, choice of the right use of the right combustion type depending on engine revolution /load. Management of the transitions between the two states.

3.4 Dissemination of knowledge

The dissemination activities of this section include past and future activities maintained by the coordinator of the IP NICE in cooperation with the core group and the partner responsible for the related result.

Planned/ actual Dates	Type	Type of audience	Countries addressed	Size of audience	Partner responsible / involved
After the end of the project	congresses	professional audience	worldwide		FEV
After the end of the project	Academic lessons	students	worldwide		RWTH/VKA
Regular	C&I I Meetings	Engine OEM's	Europe and overseas		AVL
After the end of project	Presentations for customers	Customers Engine OEM's and subsystem suppliers	Europe and overseas		AVL
After the end of project	Publications	Customers, Engine OEM's and subsystem suppliers	Europe and overseas	1000	AVL
After the end of project	AVL Sales and marketing meetings	Customers, Engine OEM's and subsystem suppliers		100	AVL
13.06-15.06.2005	AVL-AST International User-Meeting	Research , Automotive Industry	Europe and overseas	150	AVL (1)
22/23 September 2005	Conference	Research and industry	International	200 (est.)	DC (2)
2008	Scientific congress	Research and industry	World	200	IFP (3)
07.03.2005	Seminar (Master at University of Naples)	Higher education	Italy	15	IM-CNR (4)
15.9.2005 (cancelled)	conference	International		100	IM-CNR (5)
September 2005	Conference	Research and industry	International	150	UNIGE (6)

Planned/ actual Dates	Type	Type of audience	Countries addressed	Size of audience	Partner responsible / involved
April 2006	Congress	Research and industry	International	200	UNIGE (7)
13-15.9.2006	Thiesel Conference, Valencia, Spain	Research and industry	World	200	Volvo (8)
Lisbon, 6-10 October 2005	Mediterranean Combustion Symposium, Conference	Research	International	200+	UCAM (9)
At project end	Conference	Research & car industry	World-wide	about 200 people	IFP
17/18 Mai 2006	Conference	Research and industriy	International	200 (est.)	DC (10)
April 2008	Publications	Research and industry	International		UNIKA (11)
July 2006	Conference	Research & industry	International	100	IM-CNR (12)
6-9 September 2005	Conference	Scientific & Research audience	International	>200	KU (13)
10-13 September 2006	Conference	Scientific & Research audience	International	>100	KU (14)
After the end of the project	Publications at conferences, congresses, AVL FIRE user meetings	Research and industry	worldwide	150	AVL
14.9.2005	Conference	Research and industry	International	100	UNIGE (15)
17 and 18.5.2006	Conference	Research and industry	International	150	UNIGE (16)
22-27.10.2006	Congress	Research and industry	International	>200	UNIGE (17)
October 2007	Thesis	Research and industry	International		DC (18)
September 2007	Conference	Research & industry	International	100	IM-CNR (19)
30.05.2007-01.06.2007	Congress	Research and industry	International	150	UNIGE (20)

Planned/ actual Dates	Type	Type of audience	Countries addressed	Size of audience	Partner responsible / involved
05-08.08.2007	Congress	Research and industry	International	>200	UNIGE (21)
21.7.2006	Publication via AVL News letter	Customers	International	>300	AVL
20.9.2006	Publication in magazine Automobil-Revue	International	International		AVL (22)
10-13.09.2006	Congress	Research and industry	International	>250	KU (23)
20-23.05.2007	Congress	Research and industry	International	>350	KU (24)
April-June 2005	Seminars to postgraduate and doctorand students	Higher education	Italy	10	PT (25)
28.8.-1.9.2006	Conference	Research and industry	International	> 200	AVL(26)
10.01.-11.01.2007	Colloquium (Conference)	International	International	> 200	AVL (27)
6th Symposium Towards Clean Diesel Engine - Napoli, June 20-22th 2007	Scientific congress	Research and industry	Italy (Napoli)	200	IFP, Renault, Delphi, Mechadyne (28)
SAE 2008 conference- Detroit, April 14th-17th 2008	Scientific congress	Research and industry	International	>200	IFP, Renault, Delphi, Mechadyne (29)
Aachen conference 2008	Scientific congress	Research and industry	International	200	IFP, Renault, Delphi, Mechadyne (30)
2007/08	Conference	Research & Industry	International	200	BU (31)
28-29.09.2006	Congress	Research and industry	International	>200	Siemens AG (32)
6-7.02.2007	Congress	Research and industry	International	50	Siemens AG (33)

Planned/ actual Dates	Type	Type of audience	Countries addressed	Size of audience	Partner responsible / involved
28.03.2007-30.03.2007	Congress (5. Dessauer Gasmotoren-Konferenz)	Research and Industry	International	>150	FEV (34)
9 June 2007	Conference	Research and Industry	International		EUCAR (35)
11.06-12.06.2007	AVL-AST International User-Meeting	Research , Automotive Industry	Europe and overseas	150	AVL (36)
16.-20.9. 2007	SAE - ICE2007	Research and Industry	International	150	DC (37)
June 2007	Congress	Research and industry	Germany	200	FEV (38)
2007/2008	Congress	Research and industry	International	50	JBRC (39)
2007/2008	Congress	Research and industry	International	50	JBRC(40)
28.-29. March 2006	Congress	Research and industry	Germany		NICE Co-ordinator (41)
12-15. June 2006	Congress	Research and industry	International		NICE Co-ordinator (42)
22.-23. November 2006	Congress	Research and industry	International		NICE DC Co-ordinator (43)
28.5.08	Congress	Research and industry	International		AVL (44)
Sep. 2008	Congress	Research and industry	International		AVL (45)
3-5 September 2007	Conference	Research and Science	International	80	CUT (46)
9-12 September 2007	Congress	Research and industry	International	>200	CUT(47)
20-21 September 2007	Conference	Research and industry	International	200	DC / AVL (48)
April 2008	Congress	Research and industry	International		PT/Daimler (49)
May-December 2006	Thesis	Research and industry	International		PT (50)
Regular	Academic lessons	students	worldwide	40	PT

Planned/ actual Dates	Type	Type of audience	Countries addressed	Size of audience	Partner responsible / involved
17. – 18. 9.2008	Congress	Research and industry	International		VDO + Siemens AG(51)
08.-10. October 2007	Congress	Research and industry	International	400	FEV (52)
Volume 227 , Issue 10 (May 2008)	Publication in Journal of Computational Physics	Research and industry	International	>200	CORIA (53)
April 16-19, 2007	SAE 2007 Congress	Research and industry	International	>200	Daimler, UNIKA (54)
FISITA September 2008	Congress	Research and industry	International	>200	IFP, Renault, Delphi, Mechadyne (55)
TRA Ljubljana 21st-24th April 2008	Conference	Research and industry	International	72	Renault (56)
April 2008	SAE Technical Paper Series Paper 2008-01-0206	Research and industry	International		JBCR, AVL, VW (57)

(1) The intermediate status of the Eulerian spray model and of the ACCI code-coupling interface has been presented at the forthcoming AST-User Meeting. At this meeting an audience of actual and potential FIRE users as well as people interested in recent CFD development from industry as well as from universities and research laboratories will take part. Presentations by participants as well as from AVL stuff on actual progress in simulation methodologies will be given. This included as well include a presentation on the status of the novel Eulerian spray model.

(2) The presentation with the title “Is Quasi Constant Speed Exhaust Gas Turbocharging for Passenger Car SI Engines Possible?” was given at the “Aufladetechnische Konferenz” in Dresden on 22/23 September 2005. The content of the lecture was the principle concept of the “Delay Optimized Turbocharging” and the technical approach.

(3) IFP intends to publish and present its work within subproject B1 at the SAE World Congress 2008.

(4) 07.03.2005 Seminar at University of Naples about methods to improve efficiency of SI engines.

(5) Cancelled: Paper “Perspective and problems of SI Engines downsizing” (paper accepted but not presented)

(6) (7) UNIGE Participation to the following events:

- Paper for the 7th International Conference on Engines for Automobile, organised by SAE-Naples Section – September 11-16, 2005 – Isola di Capri, Italy.
- Paper for SAE 2006 World Congress – April 2-6, 2006 – Detroit (USA).

(8) 13.-15.9.2006. Presentation and Publication of a paper at the Thiesel Conference (Thermo- and Fluid Dynamic processes in Diesel Engines) in Valencia, Spain, entitled: "Simulation of soot formation for diesel engine like conditions and comparison with experimental data".

(9) Paper presenting CMC method for autoignition and validation against experimental data.

(10) The presentation with the title “Using the Centrifugal Compressor as a Cold Air Turbine” was given at the 8th International Conference on Turbocharging and Turbochargers in London on 17/18 Mai 2006. The content of the lecture was the principle concept of the “Delay Optimized Turbocharging”, the technical approach, CFD simulation and testing results.

(11) The publications planed during the year 2006 are postponed. One publication is currently in progress. In cooperation with DC this publication will present the the UNIKA progress variable model, its implementation into a CFD code and the results of these CFD calculations using the progress variable model.
Participation to the following event is planned:

- Paper proposed for SAE 2008 World Congress – April 14-17, 2008 – Detroit (USA).

(12) Presentation of a paper titled “Downsizing of SI Engines by Turbo-Charging” at ESDA2006 - 8th Biennial ASME Conference on Engineering Systems Design and Analysis July 4-7, 2006, Torino, Italy, paper ESDA2006-95215.

(13) 31st International Scientific Congress on Powertrain and Transport Means, 6-9 September 2005, Polanica, Poland – W. Mitianiec “IGNITION AND COMBUSTION PROCESS IN HIGH CHARGED SI ENGINES WITH DIRECT INJECTION OF CNG” – conference on new technologies and research works on combustion engines in transportation. The paper is published in Journal of KONES, vol.12, No 1, ISSN 1231-4005

(14) 32nd International Scientific Congress on Powertrain and Transport Means, 10-13 September 2006, Naleczow, Poland – W. Mitianiec “STUDY OF STRATIFICATION OF CNG MIXTURE IN A HIGH CHARGED SI ENGINE” – conference on new technologies and research works on combustion engines in transportation. The paper was published in Journal of KONES vol.13 No 2, ISSN 1231-4005

(15) 14.9.2005: Presentation of the paper “Transient performance of automotive turbochargers: test facility and preliminary experimental analysis” – SAE paper 2005-24-66 – 7th International Conference on Engines for Automobile (ICE 2005), Naples.

(16) 17-18 May 2006: Presentation of the paper “Turbocharger turbine performance under steady and unsteady flow: test bed analysis and correlation criteria” – 8th International Conference on Turbochargers and Turbocharging - Institution of Mechanical Engineers, London.

(17) 22-27 October 2006: Presentation of the paper "Unsteady flow behaviour of the turbocharging circuit in downsized SI Automotive Engines" – FISITA 2006 World Congress, Yokohama (Japan).

(18) The thesis of Markus Müller with the title „Der Radialverdichter im Kaltluftturbinenbetrieb – Auf dem Weg zur drehzahlstationären Abgasturboaufladung" was published in October 2007. The content of the thesis will be the principle concept of the "Delay Optimized Turbocharging", the technical approach, CFD simulation and testing results.

(19) Paper proposed for 8th International Conference on Engines for Automobile - ICE2007 Capri (Naples- Italy), September 16th - 20th, 2007.

(20) Paper proposed for EAEC 2007 11th European Automotive Congress – 30 May – 1 June 2007 – Budapest (Hungary), "Unsteady flow turbine performance in turbocharged automotive engines", written by Massimo Capobianco and Silvia Marelli, University of Genoa.

(21) Paper proposed for APAC 14th Asia Pacific Automotive Engineering Conference – 5-8 August 2007 – Hollywood, CA, USA, "Waste-gate Turbocharging Control in Automotive SI Engines: Effect on Steady and Unsteady Turbine Performance", written by Massimo Capobianco and Silvia Marelli, University of Genoa

(22) Article in the magazine "Automobil Revue Nr.38" – Title "Gas auf direktem Weg" – published 20.9.2006

(23) Presentation of the Paper "Study of stratification of CNG Mixture in high charged SI engine" at 32nd International Scientific Congress on Powetrain and Transport Means Eueopean Kones 2006 in Naleczow (Poland) – 10-13.09.2006

(24) Paper proposed for PTNSS Congress "The ignition problems of the stratified charge in SI engines with the CNG direct injection" – 20-23 May 2007 – Karkow (Poland)

(25) Cycles of Seminars were taken at Politecnico di Torino about methodologies to simulate both subsonic and supersonic transient gaseous flows inside injectors and sprays in both open and closed environments and to anlyse cause-effects relationships useful to an optimun design of Direct Injection innovative CNG SI engines.

(26) The status of the Eulerian spray model and of the ACCI code-coupling interface has been presented at the ICLASS-conference held at Kyoto (Japan) 29.8. – 1.9. 2006.

(27) 10.01.2007: Presentation of the paper: "The Potential of Bio Fuels and Synthetic Fuels in Conventional and Alternative Diesel Combustion Systems"; Session Emissions and Their Control (Part1), 6th International colloquium fuels, Technische Akademie Esslingen, Stuttgart/Ostfildern, Germany

(28) IFP, Renault, Delphi and Mechadyne published and presented the work within subproject A1 at scientific 6th Symposium Towards Clean Diesel Engine - Napoli, June 20-22th 2007 under the title "Reduction of HC and CO emissions at low load for HCCI Diesel combustion"

(29) IFP, Renault, Delphi and Mechadyne published and presented the work within subproject A1 at SAE 2008 conference-Detroit, April 14th-17th concerning the contribution of VVA to fit with Euro6 emission standard. Reference and title of the paper : 2008-01-0034, "Latest ways to lower HC and CO emissions in Diesel HCCI"

(30) IFP, Renault, Delphi and Mechadyne intend to publish the work within subproject A1 at Aachen conference under the title : "Comparative study in LTC combustion between a short HP EGR loop without cooler and a Variable Lift and Duration system".

(31) Brunel plans to publish and present some of its work from A1 at an international conference for engines during 2007 or 2008.

(32) 28-29.09.2006 Presentation with title "Key Components for gaseous Fluids from actual Demands to future Concepts" was given in Graz on "1st International Symposium on Hydrogen Internal Combustion Engines" published in VKM-THD Reports Volume 88 / 2006, published by Univ.-Prof. Dr. Helmut Eichelseder TU-Graz, Austria

(33) 6-7.Feb.2007 Presentation titled "System für die Erdgasdirekteinblasung (CNG DI) mit niedrigem Einblasdruck"(System for CNG-DI with low rail pressure) held on 5.Management Circle Fachkonferenz: "Start frei für Erdgasfahrzeuge" in Wiesbaden, Germany

(34) Contribution based on cognitions of the NICE A3 subproject for the 5th Dessau Gas Engine Conference.

(35) Presentation of the NICE project (current status and results) at the ACEA Board of Directors meeting in Venice on June 9, 2007. The presentation takes place within the frame of EUCAR and its projects.

(36) 11.-12.06.2007 The final status of the Eulerian spray model and of the ACCI code-coupling interface will be presented at the forthcoming AST-User Meeting to an audience of FIRE users as well as other particpants from industry and universities, Graz Austria.

(37) Presentaion and Paper at the SAE ICE 2007 meeting focusing on simulations and measurements of coupled Eulerian sprays in Diesel engines.

(38) Presentation of the Paper "Untersuchung des Ethanolmischkraftstoffs E85 im geschichteten und homogenen Magerbetrieb mit piezoaktuierter A-Düse" at 7. Tagung „Direkteinspritzung im Ottomotor", Haus der Technik in Essen (Germany) – 12-13.06.2007

(39) April 2008 SAE World Congress Detroit "Assessment of Different Layouts of EGR Systems Performance at CI Engines" – submitted by JBRC to Core Group for permission to publish

(40) 2008 FISITA Congress, Muenchen "VGT Turbocharger Control Optimization" – will be submitted by JBRC to Core Group for permission to publish

(41) Presentation of the NICE project by the co-ordinator on 28-29 of March 2006 at the Fuel and Powertrain Program Board Meeting in Hamburg, Germany

(42) Presentation of the NICE project by the co-ordinator on 12-15 of June 2006 at the Transport Research Arena in Göteborg, Sweden

(43) Presentation of the NICE project by the co-ordinator on 22-23 November 2006 at the EUCAR Conference 2006 in Brussels, Belgium

(44) Presentation at the congress "Transport Fuels: Crucial factor and driver torwards sustainable mobility" May 28th 2008, Vienna, focusing on Biogas with hybrid powertrains.

(45) Presentation and Paper at the congress Engine & Environment in Graz in September 2008 – Title to be defined.

(46) Presentation of the paper (CUT) "Ignition and Combustion of CNG with controlled gas motion", XX-th International Symposium on Combustion Processes, Pultusk, September 3-5,2007

(47) Presentation of the paper (CUT) "Theoretical and Experimental Study of Ignition Process in CNG Direct Injection SI Engine, International Scientific Congress on Powertrain and Transport Means – European KONES 2007, Warsaw, 9-12 of September 2007

(48) The presentation with the title "Potenziale des aufgeladenen monovalenten Erdgasmotors beim PKW" was given at the 11th conference "Der Arbeitsprozess des Verbrennungsmotors" in Graz on 20/21 September 2007. The content of the lecture was related to the potential of turbocharged mono-fuel CNG engines.

(49) Presentation of the paper "Multi-Dimensional Modeling of Direct Natural-Gas Injection and Mixture Formation in a Stratified-Charge SI Engine with Centrally Mounted Injector" at the SAE 2008 World Congress, Detroit, MI, USA, April 14-17, 2008.

(50) Thesis of Francesco Pesce entitled "Tecniche di fluidodinamica computazionale applicate all'analisi multidimensionale dell'efflusso supersonico di gas naturale da un iniettore piezoelettrico per motori ad iniezione diretta" has been published in December 2006. The content of the thesis was the influence of injection and environment conditions on jet shape, as well as the development and the first assessment of a CFD model with time-dependent needle lift and piston position.

(51) Presentation of the NICE CNG DI injector and ECU control strategy by VDO Automotive AG and Siemens AG at international congress: "Gasfahrzeuge - Die Schlüsseltechnologie auf dem Weg zum emissionsfreien Antrieb?"; 17.- 18.9.2008 in Berlin.

(52) Presentation of the Paper " Potenziale des strahlgeführten Brennverfahrens in Kombination mit Aufladung / Potentials of Spray-guided Combustion Systems in Combination with Turbocharging" at 16. Aachener Kolloquium Fahrzeug- und Motorentechnik 2007 in Aachen (Germany) – 08-10.10.2007

(53) Publication entitled "Three-dimensional boundary conditions for Direct and Large-Eddy Simulation of compressible viscous flows" in Journal of Computational Physics Volume 227 , Issue 10 (May 2008).

(54) Presentation and publication of paper entitled “3D-CFD Simulation of DI-Diesel Combustion applying a Progress Variable Approach accounting for detailed Chemistry” at the SAE Congress 2007.

(55) IFP, Renault, Delphi and Mechadyne intend to publish and present the work within subproject A1 at FISITA conference in September 2008 under the title “Two-stage turbocharging specifications for an automotive HCCI Diesel engine using a wave action model”.

(56) Renault presented the demo car and results obtained within subproject A1 in parallel to TRA conference Ljubljana to 72 European journalists.

(57) Publication in SAE Technical Paper Series Paper 2008-01-0206: “Comparison of Different EGR Solutions” - The published work compares in detail 4 different EGR solutions under both steady conditions and transient operation. The results are achieved by means of 1-D/0-D simulation tools using engine model which was calibrated by experiments on experimental single-cylinder engine.

3.5 Publishable Results

In the IP NICE different publications and papers have been publicized (see annex “Use and dissemination of knowledge”).