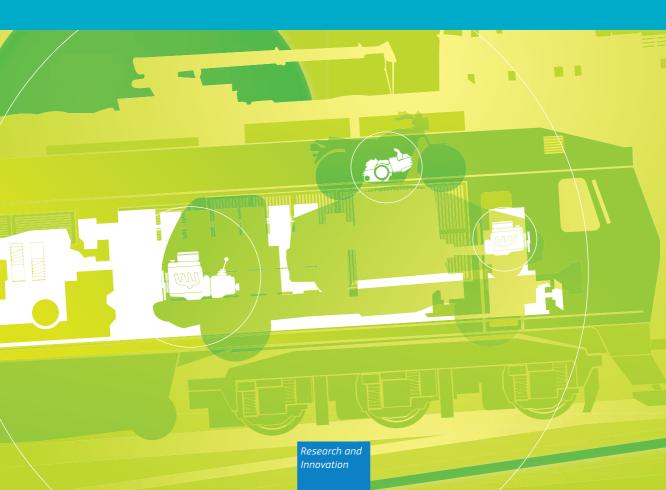


More efficient – less polluting

How 20 years of EU research cleaned up the internal combustion engine, and made it drive better



EUROPEAN COMMISSION

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How 20 years of EU research cleaned up the internal combustion engine, and made it drive better

Directorate-General for Research & Innovation

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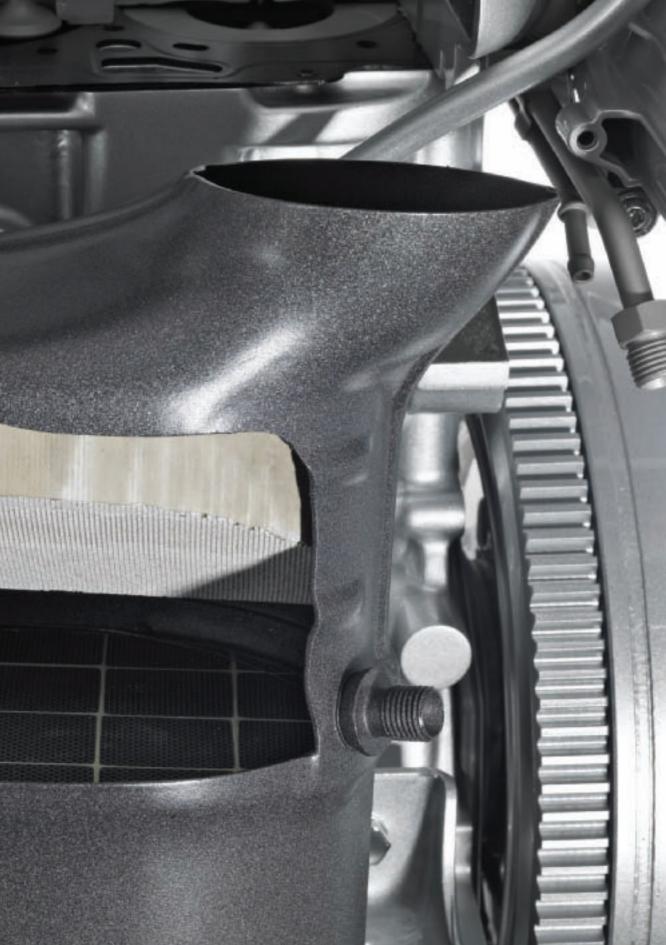
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1. Introduction

Only 50 years ago, most people had few concerns about the internal combustion engine (ICE) — except how to make it more reliable, and how to develop more power. The first fuel crisis of 1972 was barely on the horizon, and it was only scientists and policymakers who took notice of the growing problem of air pollution in Los Angeles in the United States.

The search for the green engine

In the 21st century however, attitudes have changed drastically. Along with other concerns such as climate change and energy security, today air quality in cities is a major issue worldwide. Since the early 1990s, these issues have been at the top of European policymakers' agendas, and this focus has been given greater emphasis in light of increasing awareness of the effects of climate change and the worldwide financial crisis. (Fig. 1.1)

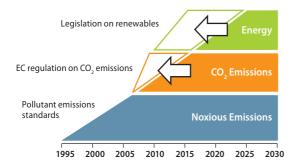


Figure 1.1 Evolution of power train technology and the effects of legislation.

As a consequence, in recent years much of the innovation in ICE and power train technologies have been driven by the progressive tightening of EU emissions limits. These were introduced for the first time in the 1970s for cars powered by spark ignition (SI, i.e. gasoline) engines, and in the 1980s for cars powered by compression ignition (CI, or diesel) engines.

As of 1993, subsequent emissions limits (Euro 1, 2, etc.) were set to deal simultaneously with pollutant emissions (carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x) and particulate matter (PM)) from SI and CI cars. Since the late 1990s, reducing carbon dioxide (CO₂) emissions has been a key global priority due to the contribution these emissions make to rising greenhouse gases (GHG). That's why today's ICEs are often defined as 'clean' when they comply with both pollutant and CO₂ emissions limits, even though strictly speaking, CO₂ is not a pollutant.

After a voluntary commitment to reduce fleet average CO_2 emissions to 140 g/km was not met by the car industry, in 2009 a regulatory limit on CO_2 emissions from passenger cars was defined for the first time (EC regulation 443/2009). This limit is expected to be further tightened to 95 g/km by 2020, a process that will spur further innovation in ICE and power train technologies for European passenger cars as well as major research into alternative fuels.

Passenger cars first

Policymakers began with a focus on the passenger car because it was perceived as the most polluting transport medium, due to highly variable operations in terms of engine speed and load, and the sheer quantity of traffic affecting air quality in European cities.

Limits on pollutant emissions for heavy duty (HD) engines were first introduced in 1988. Then, starting from 1992, subsequent steps (Euro I, II, etc.) dealing in particular with the most harmful pollutants (NO_x and PM), were introduced. Pollutant-emission regulations for rail and waterborne transport engines, which tend to spend most of their working lives close to maximum load, were adopted even later, being defined for the first time in 2004 (Directive 2004/26/EC).

As far as CO_2 emissions are concerned, once again the private passenger car market, where less attention had been paid to fuel consumption, was targeted first. The commercial sector and its HD engines were already sensitive to fuel economy; fuel represents a larger part of total operating costs, and maximising fuel efficiency has always been an important factor.

In order to help the industry meet these ever-tightening emissions targets, 20 years of research, from the Third Framework Programme for Research (FP3) to the Seventh Framework Programme for Research (FP7)⁽¹⁾ have been devoted to making the passenger car cleaner and more fuel efficient. Techniques employed range from downsizing the engine for greater efficiency, to implementing an array of technologies to develop flexible engine-control technologies and clean up exhaust gases using exhaust after treatment systems. At the same time, improved performance (the socalled 'fun-to-drive' factor⁽²⁾) was needed to justify the increased cost for customers (Fig. 1.2). This literally 'explosive' mix, coupled with market competition between CI and SI engine types, has resulted in some of the most impressive technological advances in mechanical engineering. And often, it is European projects that are behind these advances.

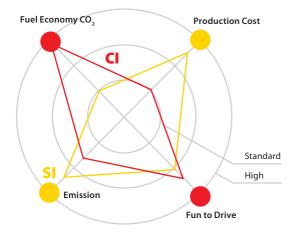


Figure 1.2 Comparison between compression ignition (CI) and spark ignition (SI) passenger cars in Europe against the market drivers: fuel economy/CO₂, production cost, pollutant emissions and fun-to-drive factor. The circle in the inner part of the diagram indicates the minimum acceptable threshold.

² The fun-to-drive factor is linked to the car accelerations at different vehicle speeds: lower acceleration time, better fun-todrive index.



¹ The full titles of the projects as well as the acronyms and the abbreviations mentioned in the brochure can be found in the Appendix.

The rise of diesel

In recent years, radical developments in diesel-engine technology have driven an expansion of the diesel-driven car market. This competition was made possible because of the more gradual application of emission-control measures for diesel engines in the EU, in particular for NO_x emissions, one of the most powerful factors working against CO₂ reduction (although lower fuel consumption produces less CO₂, it is usually associated with higher NO_x⁽³⁾).

In the United States, where fuel-neutral emissions limits were adopted from the start, diesel-engine development for cars was nipped in the bud. In Europe, newer and cleaner diesel cars are gradually meeting fuel-neutral emissions standards (expected for Euro 7), i.e. the same level of NO_x emissions as for gasoline cars; clean-diesel European technologies are coming into use worldwide.

In the early 1990s, the indirect injection (IDI) diesel engine could not compete with the traditional SI engine for passenger cars because of low power density and high PM and NO_x emissions (even though its fuel economy was better than with the SI engine). At the same time, the highly efficient direct injection (DI) diesel engine had a hard time improving its noise, vibrations and harshness (NVH) behaviour, and was only adopted in a limited number of models.

However, 1997 saw a technological breakthrough that changed diesel engine prospects. Whereas earlier injection systems had limited control capacity and depended on high engine speed to get sufficient pressure to the injectors, the new common rail injection (CRI) for the diesel engine has a 'common rail' high-pressure (> 40 MPa) fuel reserve that is always available through a high-pressure pump system and electronically controlled fuel injectors. The development of CRI was supported by the EU research project NOFISDI⁽⁴⁾, and from 1992 onwards, the project clusters ADDI and D-ULEV. By separating the production of fuel pressure from the actual injection process, a fully flexible system has been generated (Fig. 1.3).

For the market, the common rail diesel engine was the perfect development. Not only did it deliver improved fuel economy and lower CO₂ emissions, it also offered a significant increase in performance (low-end torque). In other words, it gave greener diesel-engine cars that important fun-to-drive factor that makes them attractive to consumers, and consequently new diesel-engine cars quickly penetrated the market.

Despite these advances, diesel-engine technologies still need further development if they are to match SI engines in terms of pollutant and noise emission levels. One constraint is the cost of the whole diesel power train, which is higher than that for gasoline (by up to 100 % for smaller vehicles). These costs — due to greater complexity (reinforced structure, turbocharging, injection and aftertreatment systems, etc.) — could make diesel engines uneconomical if cheap aftertreatment solutions are not developed, a factor that poses another challenge for researchers.

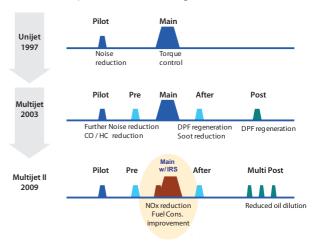


Figure 1.3 The common rail system evolved from the Unijet (a Fiat trademark, like the following ones), which had two separate injections to reduce noise and improve torque control, to the Multijet which was capable of multiple, smaller injections (including post injection when needed for regeneration, i.e. to burn particles accumulated in the diesel particle filter). The last evolution is the Multijet II, which could both change the quantity of fuel during the injection IRS (injection rate shaping) and enable multiple small post injections to reduce substantially NO_x emissions and to reduce the phenomenon of oil dilution by unburned fuel during regeneration.

 $^{^3}$ The term NO $_x$ (oxides of nitrogen) is used to describe nitric oxide (NO) and nitrogen dioxide (NO). Formation occurs through a chain of high-temperature reactions (greater than 1 600 °C) between atmospheric nitrogen and oxygen. NO is therefore not a combustion product but the result of unwanted secondary reactions. The higher the combustion temperatures, the higher the NO is levels in the exhaust, and the higher the energy extracted from the fuel.

⁴ In the project NOFISDI, VW also developed the unit injector for passenger cars (previously used exclusively on heavy-duty engines). This technology was also an important contribution to the rise of Diesel. For an explanation of acronyms, please see the lists of projects and acronyms at the end of the text.

Gasoline strikes back?

While the diesel engine was making such startling progress, for a while the SI engine only demonstrated some small technological advances that had little effect on fuel consumption or the fun-to-drive factor. It has now been marginalised in the upper passenger car market segment, but still retains a larger share of the medium and lower segments where it maintains some strategic advantages: this is due to low-cost emissions-control technologies (three-way catalysts) and the intrinsic cost advantage over diesel, which will be further increased whenever CI engines are fitted with NO_x aftertreatment to meet the new Euro 6 emissions limits.

European research has supported several key innovations in SI power train technologies too. Around 2000, two project clusters started developing the concept of low-cost variable valve actuation (Fig. 1.4), leveraging on the know-how gained during the common rail development (in ADIGA), and the concept of downsizing (in GET CO₂) respectively. Other projects enabled the development of the DI gasoline engine, first introduced with the GADI project in 1997 and put on the market a few years later as FSI (fuel stratified injection)⁽⁵⁾.

More and more of these technologies are now available to mass market consumers (or soon will be), something that could soon lead to an SI engine 'revival': they will be thriftier yet more fun to drive.

Yet it is clear that for all sectors other than the passenger car market, diesel power trains dominate (with the exception of buses, where SI engines burning compressed natural gas (CNG) are gaining importance). From HD road vehicles to ships, from earth-moving machinery to locomotives, the diesel engine prevails.



Figure 1.4 The variable valve actuation (VVA) system, controlling lift and timing of the engine valve by means of an electro-hydraulic system, enabled new combustion strategies of the gasoline engine.

The heart of technology advances

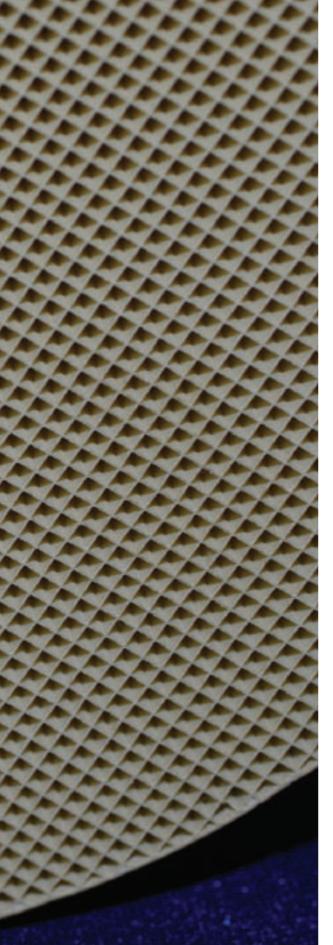
The concept of flexibility has characterised many of the advances in technology made over the 20 years of EU research from FP3 to FP7, both in terms of technology characteristics (e.g. advanced fuel injection and variable valve actuation (VVA)) and in engine-control strategies on a cylinder-by-cylinder and stroke-by-stroke basis.

Take, for example, the three-way feedback-controlled catalyst introduced at the end of the 1970s for gasoline engines. 'This technology became the $DeNO_x$ catalyst needed for diesels only when a suitable control strategy, capable of alternating lean operation with rich combustion to remove the accumulated NO_x , allowed the trap to start working again,' says Dr Bernd Krutzsch, in charge of combustion and emission control at Daimler, 'and this work is not yet complete, since achieving longer life for the $DeNO_x$ catalyst requires further research.'

At the time, the other dominant concept was downsizing, associated with turbocharging (also twostage), to improve fuel conversion ⁽⁶⁾ efficiency by operating SI and CI engines at their optimal, higher load. Reducing the engine size also delivers a sensible cost reduction; four-cylinder in-line engines, for instance, are replacing V6 engines and delivering better performance, improved fuel efficiency and lower costs.

⁵ Where the injected fuel creates a richer (i.e. with more fuel than required for the complete combustion) air-fuel mixture near the spark plug to facilitate ignition, and leaner (i.e. with less fuel) airfuel mixture elsewhere. This allows to reduce fuel consumption.

⁶ That is, the efficiency with which an engine transforms fuel energy into mechanical work.



EU funding for engine technologies and fuels

Between 1998 and 2002 alone, the EU invested approximately EUR 320 million in surface transport technology research, with a significant part of this funding allocated to clean engine research. The initial approach delivered funding to component level projects, which resulted in fruitful cooperation between groups of stakeholders throughout Europe, followed by several projects focused on the engine.

Between 2002 and 2006, under the EU's Sixth Framework Programme for Research (FP6), the focus shifted to the power train level, with bigger projects looking at the technologies needed to advance each engine type in a more holistic way, as with the complete aftertreatment system or electric components that can make up a full hybrid. The whole road transport sector benefited from research on engine efficiency (new combustion-control systems), but also on basic energy needs (development of alternative fuels and their use in innovative engines), sustainable development (new designs for clean vehicles), and a range of projects on supporting technologies such as intelligent materials, production methods and information technology.

Due to the sheer number of research projects on the go throughout FP6, the support of dedicated coordinated actions such as PREMTECH and ULYSSES was essential. These 'meta-level' initiatives both helped the EC consolidate the results and extract trends, and keep each project consortium informed of other projects' results. From 1992, all the main areas were covered:

- aftertreatment with 25 projects;
- components with 13 projects;
- control with 6 projects;
- fuels (inclusive of biofuels) and lubes with 4 projects and 1 Integrated Project (IP), (including 4 sub-projects);
- HD engines with 7 projects and 1 IP (including 4 sub-projects);
- light duty (LD) engines with 13 projects and 2 IPs (including 8 sub-projects);
- hybrids with 1 IP (including 5 sub-projects);
- modelling with 7 projects;
- natural gas application to LD and HD vehicles with 5 projects and 1 IP (including 6 sub-projects);
- new combustion concept with 4 projects (this area was also explored in engine projects);
- rail transport engines with 1 IP (including 8 subprojects) and 1 sub-project of the HD engines IP;
- waterborne transport engines with 3 IPs and 2 projects.

Future perfect

ICE research in all transport sectors marches on. While the technologies developed in the previously mentioned Fifth Framework Programme for Research (FP5) and FP6 projects (VVA, common rail, FSI, CNG for buses, etc.) are already being installed in vehicles on the road today, the latest EU collaborative research programme, FP7, is driving research towards meeting even lower GHG emission targets.

FP7 was launched in 2007 and covers the period until 2013. ICE research under this latest banner is taking a distinctly 'global' approach to the clean engine, examining new areas that might contribute to further reductions in GHGs.

The 'European Green Car Initiative' (EGCI), for example, is driving research into new breakthrough areas such as electric vehicles, while maintaining a focus on conventional engines for cars, HD vehicles, maritime and rail applications. A total of some EUR 80 million has already been earmarked for the period leading up to 2011.

ULYSSES The future propulsion as ONE system

The ULYSSES Coordination Action (CA) follows similar activities carried out during FP3, the Fourth Framework Programme for Research (FP4) and FP5 by the thematic networks PREMTECH I and II. ULYSSES aimed to provide a platform for information exchange and strategic planning for EU-funded research projects on new ICE fuels, including improved-fuel blends, alternative and renewable fuels, and hybrid-engine technologies. Although the focus is on road vehicles, relevant research into rail and water transport systems is also being taken into account. The aim was to develop the full potential of ICE technologies by analysing the total power train (including engine, gearbox and transmission systems) and treating it as one system. Project partners include large companies such as Fiat, Daimler, Volkswagen and OMV, a small enterprise (META-Ricerche), and research centres such as AVL, FEV and IFP.

Coordinator:	CRF — Fiat Research Centre (Italy)
EU funding:	EUR 1.2 million
Start/end:	01/06/2006-30/11/2013
Website:	http://cordis.europa.eu/fetch?CALLER=FP6_PROJ
	&ACTION=D&DOC=1&CAT=PROJ&QUERY=0129ad
	e261a5:4aee:21c44155&RCN=79976





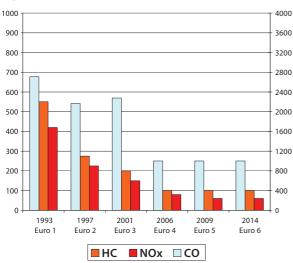
2. Road transport – Cars and light commercial vehicles

Until 2000, the main driver of engine and power train development was the increasing severity of pollutant emission regulations (see emission limits for SI and CI cars, indicated by Euro classes in Arabic numerals, in Fig. 2.1 and 2.2 respectively). After 2001 however, with climate change increasingly prominent on the global political agenda, regulators added the strategic target of CO₂ reduction to emissions limits.

EU research projects focused on several areas to help the engine industry meet these combined targets, taking into account the introduction of new fuels as well⁽⁷⁾:

COLimits

- 1. improving engine components;
- 2. cleaner combustion processes;
- 3 treating exhaust gases.



HC, NOx Limits

Figure 2.1 Pollutant emission limits of spark ignition (SI) engines cars from Euro 1 (1993). The ratio between emission levels in 1970 (the start of the process to limit emissions) and 1993 is about 10. A particulatesemission limit for SI vehicles is to be introduced by September 2014.

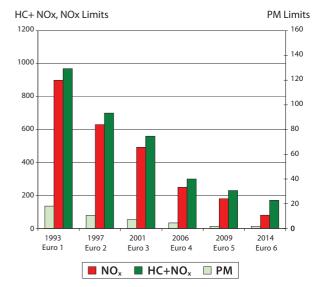


Figure 2.2 Pollutant emission limits of compression ignition (CI) engines from Euro 1 (1993). The ratio between emission levels in 1984 (the start of the process to limit emissions) and 1993 is about two. A particle number emission limit of 6×10^{11} km⁻¹ becomes effective at the Euro 6 stage in addition to the particle matter (PM) mass emission limit.

Improving engine components

Many EU projects that were carried out as part of the FP3-to-FP5 research programmes concentrated on the development of more innovative components, such as fuel injection and valve control systems, turbochargers and materials. The CRI system developed in the 1990s was one of the most important advances for the ICE in recent decades.

After being trialled as part of the NOFISDI project (1992– 1995) by FIAT, who patented the concept, Bosch licensed and industrialised it before beginning production in July 1997. That same year, from September onwards, Mercedes and Alfa Romeo started equipping models with the system (Fig. 2.3, page 18). Within a few years, IDI diesel engines had all but disappeared.

⁷ See chapter on alternative fuels.

Second-generation common rail systems came about thanks to work carried out as part of two project clusters (Fig. 2.3, page 18): ADDI in 1997 and D-ULEV in 2001. These clusters were able to make considerable performance improvements compared with earlier systems: a peak injection pressure higher than 200 MPa, temporal variation of the injection rate, and multiple injection to both modulate the combustion process and drive the exhaust-gas aftertreatment.

Engine manufacturers also made considerable efforts to develop variable valve control, particularly important for providing optimal airflow in and out of SI engines. Dr Andrea Ferrari, coordinator of the ADIGA project (Fig. 2.4, page 18) and head of engine development at Fiat Powertrain Research comments: 'All mechanical solutions are normally based on the valve lift variation through complex mechanisms, combined with a cam phaser to allow control of both valve lift and phase. The major limitation of mechanical systems is linked to the low flexibility level, since to maintain costs and complexity within reasonable levels, all cylinders of an engine bank are actuated simultaneously and no selective actions on a specific cylinder are possible. On the opposite side, electro-magnetic and electrohydraulic camless solutions offer the full flexibility in management of intake and exhaust valve lift event, but at the moment they suffer from intrinsic problems due to power consumption in moving the valves at high speeds, safety, NVH control and costs.'

Why is VVA important? While the control of diesel combustion is based on the quantity of injected fuel, SI combustion is controlled via the load of fresh air in the cylinders, which determines the air-fuel ratio. In fact, in conventional gasoline engines, the air mass trapped in the cylinders is controlled by keeping the intake valves constantly open and regulating the flow of air upstream through a throttle valve — this means the engine wastes about 10 % of the fuel's energy in pumping the air charge. With VVA technology, the quantity of air for the charge is determined at the cylinder inlet by controlling the intake valves. In case of a very low load or even cylinder deactivation, multiple valve opening (multi-lift) can be used to enhance both thermodynamic and combustion efficiency.

The ADIGA project developed an intermediate electrohydraulic solution allowing full control over valve lift and timing (Fig. 1.4, page 10) that can be considered as a bridge between mechanical devices and fully flexible camless systems: it offers adequate flexibility in valve control with relative simplicity, low power requirements, intrinsic fail safe nature and low cost. From 1997, when ADIGA started, the electro-hydraulic control was developed in a number of projects until its production in 2010, under the trade name of Multiair.

Some projects examined the benefits of turbocharging in more detail, such as the 'Variable compression ration for co₂-reduction of gasoline engine' (VCR) project, for example, that aimed to run a gasoline engine at part load with high thermal efficiency, while avoiding the engine-knock^(®) problems common at full load with high compression ratios. The result was a method of optimising compression ratio for each load/speed combination; this enabled an engine with a VCR to always operate at peak efficiency resulting in the maximisation of both efficiency at part-load operations and performance at full load.

Other projects examined how lightweight materials can be applied to valves in order to reduce the energy consumption of VVA systems, in particular electromagnetic ones where the movement of the valves is achieved using 'precious' electric energy: the 'Lightweight valves for high efficient engines' (LIVALVES) project aimed to develop advanced technologies for the mass production of valves weighing 50 % less than conventional components.

⁸ Knocking occurs when combustion in the cylinder of SI engines starts off correctly in response to ignition by the spark plug, but one or more pockets of air-fuel mixture explode outside the envelope of the normal combustion front. The cylinder pressure increases dramatically, while the shock waves following the explosion create the characteristic metallic 'pinging' sound, with effects that can be destructive.



NOFISDI

Novel concept fuel injection systems for DI diesel engines for passenger cars

Until the 1980s and 1990s, diesel-engined vehicles were notoriously underpowered and polluting. The NOFISDI project aimed to tackle this problem by researching the efficiency of the new fuel injection system for diesel engines, focusing in particular on DI systems with variable nozzle geometry, unit injectors⁽⁹⁾ and common rail. Since then, the CRI system has become the standard for all diesel engines, and it is now applied to road vehicles, rail engines and large-bore marine power plants.

Coordinator:	CRF – Fiat Research Centre (Italy)
EU funding:	EUR 1.753 million
Start/end:	01/12/1992-30/11/1995

VCR

Variable compression ratio for CO₂ reduction of gasoline engines

The VCR project investigated different designs of VCR engines, in single-cylinder and four-cylinder designs, to test the theory that small turbocharged (TC) VCR engines can offer significant fuel efficiency and exhaust emission improvements compared to conventional engine designs.

The single-cylinder engine was designed, manufactured, built and tested with different VCR solutions. Selected VCR mechanisms were then transferred into larger four-cylinder engines which were installed into demonstrator vehicles of different sizes and curb weights.

Depending on the VCR system used and the degree of downsizing in engine capacity, fuel consumption improvements of up to 27 % were measured. Without any reduction in engine size, fuel consumption improvements of around 8 % were obtained by determining the optimum compression ratio alone.

Coordinator:	FEV (Germany)
EU funding:	EUR 2.7 million
Start/end:	01/01/2000-31/05/2003
Website:	http://cordis.europa.eu/search/index.
	cfm?fuseaction=proj.document&PJ_LANG=EN&PJ_
	RCN=4862515&pid=0&q=D3FD30A680DF8813A4D
	69366DF2527FB&type=sim

⁹ Another type of injector which included in a single unit the high-pressure pump and the injector, one per cylinder.

Cleaner combustion processes

Research into increasing fuel conversion efficiency has benefited gasoline engines as well as diesels. In addition, for gasoline engines, the concept of DI played an important part in the realisation of a lean combustion process (Fig. 2.4). This started in 1994 with the GADI project on gasoline DI, followed by two clusters of projects: ADIGA in 1996, and GET-CO₂ in 2001.



Figure 2.3 ADIGA (1996–1999) helped develop the gasoline DI injection in the VWLupo 1.4 FSI engine.

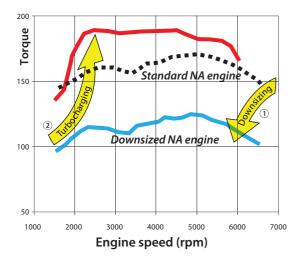
Besides starting the research on VVA technology, the ADIGA cluster continued this approach by using the concept of FSI developed by Volkswagen under the GADI project. The cluster explored the possibility of deactivating cylinders (i.e. temporarily transforming a four-cylinder engine into a more efficient two-cylinder one) in low load conditions as a means of improving fuel economy in city driving. Successive initiatives (i.e. GET) focused on how strong engine downsizing affected performance, fuel consumption and emissions levels.

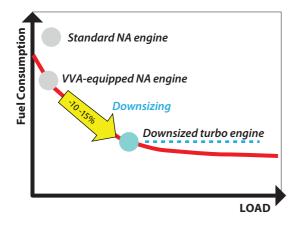


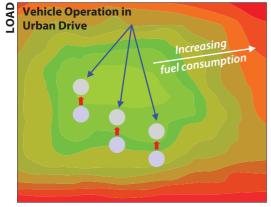
Figure 2.4 GET (2001–2004) applied gasoline engine downsizing exploiting advanced turbo charging.

As shown in Fig. 2.5 (page 19), efficiency improvements from radical downsizing are a result of using the most efficient area of operation (where throttle⁽¹⁰⁾ and mechanical friction losses are lower) by shifting the most common engine operation points to a higher load with a given power. What the GET team achieved was the development of a successful variable-geometry high-pressure turbocharger, enabling higher torque density (e.g. 200 N·m/litre instead of 120 N·m/litre) at lower engine revolutions due to reduced engine displacement. Following the same principle, an additional way of achieving downsizing benefits based on engine operation at higher load, is to reduce engine speed to have lower mechanical friction, the so-called downspeeding, i.e. can offer additional benefits by further moving operating points towards higher efficiency areas of the engine map. As a result of these developments, today's cars often have a 20-30 % smaller engine than only 10 years ago, and the trend continues, going below the 1 litre bar and, in the future, even smaller engines replacing 1.2–1.5 litre engines, and four-cylinder 1.8 litre engines replacing six-cylinder engines above 2 litres.

¹⁰ The effort needed to suck air into the piston through the restriction caused by the throttle.







Engine Speed (rpm)

Figure 2.5 The three graphs show the rationale for downsizing. The top one shows how downsizing normally lowers (1) the torque curve of the basic Naturally Aspirated (NA) engine, and therefore a turbocompressor (2) is needed to restore or even improve the drivability of the vehicle. The centre graph shows the effect on fuel consumption, with a 10-15 % reduction achieved by moving the points representing the average urban driving conditions at higher engine load. This is further explained in the third graph, where the typical engine working conditions in city driving move up and therefore towards the area of maximum efficiency of the engine, represented in green. Internal combustion engines (ICE) are in fact quite inefficient at low loads (the red areas), with a specific fuel consumption up to three times worse than the best possible.

The need to limit NO_x emissions was the motivation behind several studies of the internal combustion (IC) process for both diesel and gasoline engines operating at part load, such as the homogeneous charge compression ignition (HCCI) system for diesel engines, and the controlled auto-ignition (CAI) system for gasoline engines.

The defining characteristic of HCCI is that ignition occurs at several points in the fuel-air mixture at the same time in a homogeneous way (instead of explosive high temperature combustion that normally takes place), which makes the mixture burn at a lower combustion temperature. HCCI engines have been shown to achieve extremely low levels of both NO_x and PM because of the homogeneous charge. However, such a NO_x-PM reduction is accompanied by some increase in CO and HC, and it is difficult to achieve at higher loads.

CAI is a lean compression-ignited gasoline combustion process that produces lower peak temperatures and significantly lower levels of NO_x . However, achieving CAI's potential in the real world, particularly at part-load and sustained high-load operation, is still a challenge researchers are devoting much attention to.

LeaNOx I

Nitrogen oxide removal from diesel & lean Otto engine exhaust

Launched in the early 1990s, LeaNOx I was one of the first EUfunded research projects to investigate the use of lean-burn engine technologies, catalytic materials and processes to reduce the NO_x emissions from vehicles. The project work embraced:

- basic research on the elementary stages of lean-burn NO_x catalysis;
- formulation and experimental pre-selection of catalyst samples from various groups of catalytically active materials;
- application-oriented screening of samples from various catalyst manufacturers;
- bench tests on the activity of catalytic converters;
- system testing on a lean-burn Otto engine, a swirl-chamber diesel engine and a DI diesel engine in cars, and a DI diesel engine for trucks.

 Coordinator:
 Volkswagen (Germany)

 EU funding:
 EUR 1.46 million

 Start/end:
 01/11/1992–31/12/1995

LeaNOx II LeaNOx development for lean burn cars and diesel trucks

The follow-up LeaNOx II project further researched the use of emissions from lean-burn engines originally tuned for the Euro 2 emission-control regulations for the more demanding Euro 3 standard. The research involved some leading European universities (Leuven, Reading, Mulhouse, Bochum, Lund and Åbo) and helped to develop a platform for further development in the vehicle industry. The results were implemented in three pilot vehicles (two lean-burn cars and a truck engine).

Coordinator:	Volvo (Sweden)
Start/end:	01/01/1996-31/12/1998
Website:	http://cordis.europa.eu/fetch?CALLER=FP6_
	PROJ_BRITE&ACTION=D&DOC=17&CAT=PRO
	J&QUERY=0127cbd8e185:6dea:2d0f8378&R
	CN=30954

LEVEL Low emission levels by engine modelling

LEVEL consisted of a cluster of three projects that modelled the fuelinjection systems of both petrol and diesel-powered road vehicles. D-LEVEL focused on 'Diesel low emission levels by engine modelling', G-LEVEL covered 'Gasoline direct injection — Low emission levels by engine modelling', and I-LEVEL dealt with 'Injector flows-low emission levels by engine modelling'.

D-LEVEL considered a wide range of engine operation conditions, investigating the effects caused by different injection rate profiles on heat transfer and by exhaust gas recirculation (EGR). Validation of the models was carried out in carefully designed experiments in high-pressure diesel combustion chambers as well as in welldefined engine experiments, with direct participation from automotive-industry partners in developing demonstrator vehicles.

Coordinators:	Volvo and Daimler (Sweden and Germany)
EU funding:	EUR 3.65 million (total for the three projects)
Start/end:	2000–2002
Website:	http://cordis.europa.eu/search/index.cfm?
	fuseaction=proj.document&PJ_LANG=EN&PJ_RC
	N=4603379&pid=0&q=F14E0752122F56DFB523
	32E7582838A8&type=adv

SNR-Technique

Reduction of NO₂ in lean exhaust by selective NO₂-recirculation

Particular compounds like perovskites are able to adsorb large amounts of NO_x and can therefore be used in the first step of selective extraction of NO_x from the exhaust and temporary storage. In the second step, the stored NO_x is desorbed and fed back into the intake air. Thus the NO_x is selectively re-circulated back into the combustion chamber of the engine and decomposed by the combustion process itself.

The first aspect of the project was devoted to the development of NO_x adsorbents able to store large quantities of NO_x under lean conditions (synthesis of powders, surface characterisation and reaction dynamics, development of coating methods). The second aspect consisted of the study of NO_y decomposition in the combustion process.

Coordinator:	Daimler (Germany)
Start/end:	01/02/1996-31/01/1999
Website:	http://cordis.europa.eu/fetch?CALLER=FP6_
	PROJ_BRITE&ACTION=D&DOC=8&CAT=PROJ&QU
	ERY=012c1730163d:6fb6:5646c418&RCN=30951

Several other EU projects carried out modelling work on the fundamentals of the IC process. LEVEL, a cluster of three projects, modelled both diesel and gasoline-engine combustion processes, including a study of injector flows. The modelling activity has evolved into a models-based control of the engine that was first examined through large-scale FP6 and FP7 IPs. Particularly during transient operations, cold start, warming-up or aftertreatment regeneration events generate multiple and sometimes conflicting requirements that can be addressed through real-time computing capability devoted to engine control: this is beneficial to both the vehicle user and the environment.

Treating exhaust gases

Exhaust aftertreatment systems were initially developed in order to reduce emissions from harmful compounds, in relation to the different limits for SI and CI engines. In the first case, the three-way catalyst efficiently took care of HC, NO_x and CO simultaneously, except in the cold start phase, where the catalyst is not warm enough to work.

Unfortunately, lean combustion engines such as diesels (but also some gasoline engines developed over the last 10 years) cannot use this efficient and simple technology, because it requires a stoichiometric⁽¹¹⁾ air-fuel mixture in the cylinder, while the term 'lean' means that there is less fuel. Moreover, they produce huge quantities of ultrafine soot particles (this is the reason for introducing a particle number (PN) limit in EU regulations) which occur as a result of injecting fuel directly into the cylinder, where the fuel burns while diffusing into the air. In fact, in the coldest areas of the combustion chamber, some of the diffusing fuel is not able to combine efficiently with air and therefore burns incompletely. This is exacerbated in newer engine designs due to their higher injection pressures, which lead to even smaller, nanometre-sized particles, although older engines show more of the visible (and less harmful) black soot.

Another typical phenomenon of lean-combustion systems (both Cl and lean Sl engines) is the production of high NO_x concentrations as a result of the strong oxygen concentrations at high combustion temperatures, which oxidise the nitrogen in the air and represent a major obstacle to the wider use of Dl diesel and gasoline engines, which otherwise show exceptional potential for reducing fuel consumption.

A relatively simple solution, used both in SI and CI engines, is called EGR. The process uses a duct to bring exhaust gases back into the combustion chamber, thus reducing both oxygen concentration and temperature. This limits the temperature peaks that generate NO_x but also makes the combustion more difficult to control, so it cannot be used beyond a certain air/exhaust gas ratio.

¹¹ If exactly enough air is provided to completely burn all of the fuel, the air-fuel ratio is known as the stoichiometric mixture. In such a case, theoretically the exhaust gas would consist solely of nitrogen, water and $CO_{2^{\prime}}$ with no unconsumed oxygen or fuel remaining. When more fuel is added than required for stoichiometry, this is called 'rich' combustion; and when less fuel is added, 'lean' combustion.

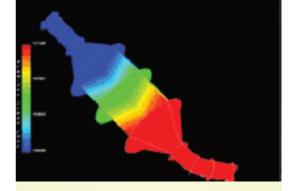
EU research into further reducing NO_x by means of catalytic converters began in 1992 with the LeaNOx I project, which was followed in 1996 by LeaNOx II. In 1996, another project, SNR-Technique, tried developing the selective NO_x recirculation (SNR) process which was expected to be more effective than EGR, and made a fundamental contribution to the development of NO_x adsorbents able to store large quantities of NO_x under lean conditions. Major European vehicle manufacturers were involved in these projects, in collaboration with research institutes specialising in the fields of materials/catalysis and engine technology.

The research led to a better understanding of the parameters affecting NO_x absorption in aftertreatment systems. However, finally the competitive selective catalytic reduction (SCR) system⁽¹²⁾, originally developed for HD vehicle applications (see project LOTUS of the TRUETEC cluster), was the first such system applied to passenger cars.

The less efficient (up to 60% instead of 80% or more for SCR) but lower cost NO_x adsorber represents an interesting alternative approach for low-to-medium–segment cars. The market share of these systems might increase with the advent of the future Euro 6 emissions limits.

Other projects such as PAGODE tried to keep the previously mentioned CO and HC increase (due to the HCCI and, more generally, to the low temperature combustion) under control, through the development of an advanced diesel oxidation catalyst addressed to CO/HC low-temperature oxidation.

Some European research projects approached the problem of PM emissions by adding particle traps, and in particular a diesel particulate filter (DPF), a device that captures more than 99.99% of the millions of billions of sub-micron particles a diesel engine emits every kilometre. Several geometries were tested, and the so-called wall-flow closed filter emerged as the winner, but two main technologies were developed that allow the collected soot to be burned from time to time to unclog the filter (the so-called regeneration). In both cases, additional fuel



PAGODE Post-treatment for the next generation of diesel engines

The aim was to provide a comprehensive, system-oriented view on new potential aftertreatment processes that will be required for the next HCCI combustion systems, taking into account the next fuel generation, by working on:

- a study of fuel effects and oxidation mechanisms in advanced homogenous combustion processes;
- the formulation, development, test and optimisation of an advanced new diesel oxidation catalyst (DOC) formulation for CO/HC low-temperature oxidation;
- emerging flexible low-temperature oxidation technologies, such as cold plasma;
- system synthesis for next-generation power trains.

Coordinator:	PSA (France)
EU funding:	EUR 1.6 million
Start/end:	01/11/2006-31/10/2009
Website:	http://cordis.europa.eu/fetch?CALLER=FP6_PROJ
	&ACTION=D&DOC=13&CAT=PROJ&QUERY=011c2
	89d7cf2:2801:02a5cf49&RCN=81508

 $^{^{12}}$ SCR is a means of converting NO, with the aid of a catalyst into diatomic nitrogen N2 and water. Å reductant, typically ammonia or urea, is added to a stream of exhaust gas and absorbed into a catalyst. When urea is used as the reductant, then CO₂ is also produced.

needs to be injected to burn the soot, and a catalyst allows this to happen at a lower temperature to minimise overconsumption.

However, while in one type of system on the market the catalyst is mixed with the fuel, in the other it is coated on the walls of the filter itself. The FP5 DEXA-cluster projects helped develop the latter idea, which is now widely adopted, and also set up the basis of the Particle Measurement Programme (PMP) working group for UN-ECE GRPE (United Nations – Economic Commission for Europe Working Party for Pollution and Energy). This organisation proposed a measurement method for PNs, which in turn allowed the Euro 6 standards (which limit the number of particles) to be adopted.

In the subsequent FP6 programme, other projects like IPSY (page 24) developed innovative geometries to improve these filters by further reducing the overconsumption related to regeneration; they aimed to combine all diesel aftertreatment into a single component, instead of two or three 'bricks' as is currently the norm. According to Dr Athanasios Konstandopoulos, Director of Aerosol & Particle Technology Laboratory, 'by using a filter topology that recovers heat from the exhaust flow through a heat exchanger, we achieved a 45.2% reduction of the energy needed to achieve filter regeneration on the New European Driving Cycle.'

The continual growth of the global vehicle market combined with an increasing awareness of environmental concerns are in conflict with the limited supply of precious metal used in aftertreatment systems. Nearly all aftertreatment projects on PM and lean NO_x reduction technology have devoted some attention to cost-effective material alternatives. The possibility of finding alternatives to precious metals like platinum will become increasingly important in the future because of the improvement of fuel quality (with less and less sulphur, which poisons catalysts), and advances in aftertreatment control systems.



DEXA Diesel engine exhaust aftertreatment

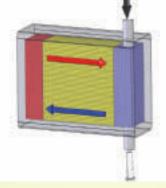
The DEXA cluster consisted of four projects:

- the component technology integration aspect (ART-DEXA led by CRF);
- the system design aspect (SYLOC-DEXA led by AVL;
- the quality assessment/measurements aspect (PSICO-DEXA) led by the Aerosol & Particle Technology Laboratory (APTL) of CPERI/CERTH, who also served as cluster coordinator;
- the development of simulation tools for optimisation of foamstructured diesel particulate filters (STYFF-DEXA led by Graz University of Mining and Metallurgy in Austria).

The most important results of DEXA included the development of:

- advanced DPF control technologies and their integration into two demonstrator vehicles;
- a user-friendly simulation toolkit for the computer-aided design and engineering of integrated diesel exhaust aftertreatment systems;
- novel particulate size and composition measurement methodologies;
- simulation tools for computing the details of the filtration and regeneration processes inside foam filter materials.

Coordinator:	APTL (Hellas, Greece)
EU funding:	EUR 6.67 million
Start/end:	01/02/2000-30/06/2005
Website:	http://ec.europa.eu/research/infocentre/export/
	success/article_701_en.html



IPSY

Innovative particle trap system for future diesel combustion concepts

The project worked on the development of a multifunctional reactor (MFR) combining heat recovery with a multifunctional catalyst for particulate and gaseous emissions treatment. Compared to state-ofthe-art catalysed DPFs, the MFR demonstrated increased (up to four times) soot oxidation activity, increased filtration efficiency while keeping a comparable pressure drop. The developed technology demonstrated the potential to significantly lower the required filter regeneration temperature, and in turn to lower the fuel penalty associated with filter regeneration.

Coordinator:	FEV (Germany)
EU funding:	EUR 1 million
Start/end:	01/01/2007-31/12/2009
Website:	http://cordis.europa.eu/search/index.
	cfm?fuseaction=proj.document&PJ_
	LANG=EN&PJ_RCN=9596212&pid=0&q=C692A4
	83125EDE390D5472160D1D87C1&type=sim



NICE New integrated combustion system for future passenger car engines

The main objective of NICE was to develop a new integrated combustion system that, independent of the type of fuel, could achieve the highest fuel conversion efficiency of 43 %, while complying with a zero-impact emission level. The new integrated combustion system was the heart of an innovative fully flexible power train able to use newly designed bio and/or alternative fuels and natural gas. Four sub-projects were included: A1'Enlarged HCCI-Diesel combustion process under transient operation', A2'Compressed / Spark-Ignited variable engine', A3 'Future gas Internal Combustion engines with diesel equivalent fuel consumption', and B1'Improved CFD tools and modelling'.

Innovative Diesel- and Otto-cycle engine technologies, including the definition of new Engine Control Unit (ECU) - algorithms, realtime models and software tools for automatic validation, hardwarein-the-loop tests and calibration were developed. The results also included advanced control systems for mixture preparation and combustion, and a numerical modelling tool to describe new, lowemission and highly efficient combustion processes.

Coordinator:	Daimler (Germany)
EU funding:	EUR 14.5 million
Start/end:	01/01/2004-31/12/2007
Website:	http://ec.europa.eu/research/transport/projects/
	view_item_road_en.htm?Page=2

Any lessons learned?

Early research projects on engine components, the combustion process and aftertreatment significantly contributed to the development of highly efficient power trains. In 2004, the baton was passed from FP3-to-FP5 projects to NICE — the first large-scale IP under FP6. Coordinated by Daimler, two engine routes, Diesel and Otto-cycle, were pushed towards converging into a new flexible combustion system capable of reducing both CO₂ and NO₂ emissions (Fig. 2.6).

The Diesel route, thanks to progressive improvements in CRI technology, was able to significantly reduce NO_x while maintaining lower CO_2 emissions (25% better) in terms of the gasoline engine. The introduction of catalytic converters for diesels and the improved combustion technologies developed under NICE further reduced NO_x emissions, but came with a moderate loss in the CO, advantage.

For Otto powertrains, lower CO_2 emissions were made possible combining technologies from previous projects on lean combustion, cheap VVA, and engine downsizing, which were offset in some cases by an increase in NO_x . The continual improvement of the NICE combustion process means CO_2 emissions from the Otto engine are being lowered further, while at the same time, NO_x levels are kept under control. Yet the best NO_x/CO_2 trade-off was achieved with CNG engines that were also developed as part of the project (see paragraph on alternative fuels, page 41).

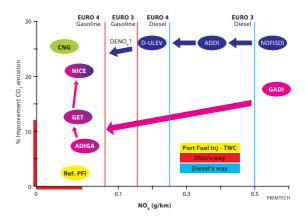
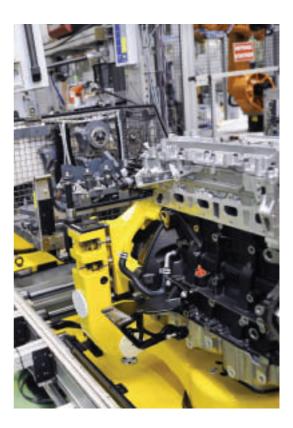


Figure 2.6 The graph shows how a series of EC-funded projects from FP3 to FP6 (1992–2006) supported the evolution of gasoline and diesel engines in terms of improved CO_2 and pollutant emissions in comparison with the standard gasoline engine, with port fuel injection (PFI) and a three-way catalyst, represented in the bottom left corner.





3. Road transport – Heavy commercial vehicles

Research into HD diesel engines for larger commercial vehicles began with a drive to improve engine components, before focusing on engine architecture in the same way as previous studies on LD vehicles had done. However, compared to the passenger car sector, initially little attention was paid to exhaust-gas treatment, as early emissions limits (in Latin numerals in Fig. 3.1) were simply met with engine improvements.

For heavy commercial vehicle operators, achieving optimum fuel efficiency has always been a top priority. As concerns grew about air-quality regulation and levels of NO_x and PM emissions, engine developers had to try and find the best compromise between reducing these emissions and improving engine efficiency.

Projects HEDE and SORPTEC, led by Daimler and started in 1997 and in 1998 respectively, laid the groundwork for the following developments:

- basICE parameters for combustion optimisation based on increasing in-cylinder peak pressure, the use of EGR (Fig. 3.2) and advanced air-to-air intercooling;
- NO_x storage catalyst (NSC) combined with continuously regenerating soot trap where soot formed under rich conditions is stored in the trap, before being subsequently regenerated via the chemical reaction of nitrogen dioxide (NO₂) with the carbon load.

Three different fuel injection systems (common rail in CRICE project, unit injector in FUNIT project, and pumpline-nozzle in PICE project) were studied between 2000 and 2004 for the heavy commercial sector; the fact that these were studied when they had already been adopted for LD diesel vehicles highlights the research gap between HD and LD applications.

SORPTEC Sorption technique for the removal of NO_x in exhaust gases of heavy-duty vehicles

As a follow-up to the SNR-Technique project applied to cars, the SORPTEC project developed a DI HD diesel engine equipped with a NSC combined with a continuously regenerating soot trap (CRT). Under lean conditions, NO_x is stored in the NSC unit. When the filter is saturated the engine is briefly operated under rich conditions to convert the stored NO_x and let the trap start absorbing again. The soot formed under these conditions is stored in the particle trap, which is in turn cleared of its carbon load via a chemical reaction with NO_x .

The NSC-CRT system was realised using engine management measures without any fuel consumption penalties.

Coordinator:	Daimler (Germany)
Start/end:	01/01/1998-31/12/2000
Website:	http://cordis.europa.eu/fetch?CALLER=FP6_
	PROJ_BRITE&ACTION=D&DOC=140&CAT=PR
	OJ&QUERY=0127ca3bd37e:d1d7:31bcf318&R
	CN=38806

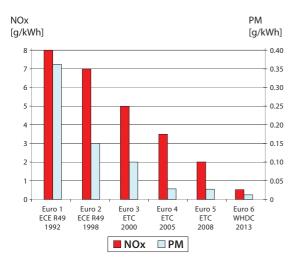


Figure 3.1 Evolution of pollutant emission limits (g/kWh) for HD engines starting in 1992 with Euro I. The ratio between emissions levels in 1988, at the start of the emissions-limits process, and 1992, was about two. A particle number (PN) limit (in addition to the current PM mass one) will be introduced with Euro VI.

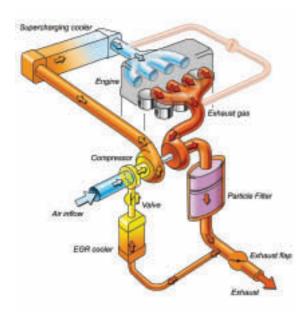


Figure 3.2 NO_x reduction using EGR to reduce in-cylinder gas temperature.

However, research into exhaust-gas treatment using SCR and urea injection (seen in the LOTUS project) became instead the reference point for both HD and LD vehicle applications.

In 2000, the results of HEDE and SORPTEC were fed into the eight-project cluster TRUETEC, which moved HEDE's original research forward in different directions. Involving nearly all of Europe's HD vehicle manufacturers, TRUETEC looked at:

- advance engine control;
- fuel-injection systems;
- exhaust-gas treatment development;
- electrical turbocharging to reduce turbo-lag.

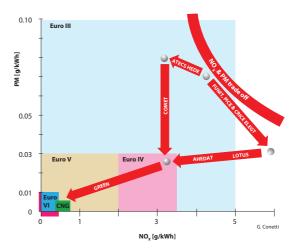
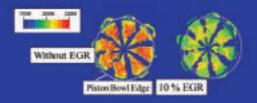


Figure 3.3 EC-funded HD engine projects from FP4 to FP6 in view of low NO_x and PM as requested by the emission limits of Euro III (2000), Euro IV (2005), Euro V (2008) and Euro VI (2013).





HEDE High fuel-efficient diesel engine with significant increased peak pressure

The aim of HEDE was to achieve Euro IV emission standards as well as a 15 % fuel consumption reduction with respect to 1997-model diesel engines, by increasing peak injection pressure by approximately 8 MPa. The reduced losses caused by the walls heating up (3 %) and improved exhaust gas turbocharging (4 %) also helped to achieve the target.

The project demonstrated that emissions and fuel consumption improvements can be achieved using only internal engine measures based on peak-pressure increase, and that further research was necessary to meet 2005-to-2008 emission limits without compromising on the very low CO_2 level of HD diesel engines at the time.

Coordinator:
Start/end:
Website:

Daimler (Germany) 01/08/1997-31/07/2001 http://cordis.europa.eu/search/index. cfm?fuseaction=proj.document&PJ_ LANG=EN&PJ_RCN=2552928&pid=2&q=E551AE 3D13EB5E4140544517B63CD74D&type=sim TRUETEC was followed up in 2005 by the GREEN project. As shown in Fig. 3.3 (page 28), by moving on the NO_-PM hyperbola expressing the NO_/PM tradeoff for a given technology level with improved fuel injection systems (projects FUNIT, PICE and CRICE) or turbocharging (ELEGT), it is possible to reduce PM and to improve fuel conversion efficiency at the expense of a NO₂ increase. NO₂ can, however, be reduced via SCR and NO₂ adsorption technologies (developed in the LOTUS and AHEDAT projects respectively). On the other hand, there is another possibility: by increasing peak combustion pressure (HEDE) and improving the engine control system (ATECS), NO, can be reduced, but the PM increases. Therefore the COMET project looked into alternative particulate filter technologies for HD applications.

Moreover, GREEN initiated research into another important technology to improve energy efficiency of trucks. While today's truck engines convert into mechanical energy around 40 % of the energy in the fuel, the rest is dispersed in the environment as waste heat through the radiators and hot exhaust gases. The project started looking at how to re-use it, and concluded that this could lead to improving fuel conversion efficiency by between 8 % and 12 %, a subject to be further addressed in FP7 projects.

TRUETEC Truck engine technology

TRUETEC aimed at developing new diesel engine technologies conforming to the Euro IV and Euro V standards; formed by the majority of European truck manufacturers, TRUETEC was a cluster of several research projects:

- 'Common rail based improved combustion for low emissions' (CRICE) led by CRF;
- 'Future unit injector technology' (FUNIT) led by Volvo;
- 'Advance truck engine control system' (ATECS) led by FEV;
- 'Low temperature active urea based selective catalytic reduction of N0,' (LOTUS) led by Volvo;
- 'Pump-line-nozzle-based improved combustion for low emissions' (PICE) led by Daimler;
- 'Advanced heavy-duty engine aftertreatment technology' (AHEDAT) led by AVL;
- 'Coated sintered metal trap' (COMET) led by Daimler;
- 'Electrical exhaust gas turbocharger' (ELEGT) led by IVECO.

Coordinators: see above

EU funding:	EUR 14 million	
Start/end:	01/02/2000-31/01/2003	
Website:	http://cordis.europa.eu/search/index.	
cfm?fuseaction=proj.document&PJ_		
	LANG=EN&PJ_RCN=5075260&pid=0&q=511260	
	7C40259C61B5EC97C0A1E7EF4C&type=sim	



GREEN Green heavy-duty engine

The main objective was to develop an intelligent and flexible dieselengine system able to achieve maximum fuel conversion efficiency of 45 % while complying with regulated emissions levels. The second objective was to develop innovative diesel and gas engines for rail use. GREEN developed systems for reducing both NO_x and PM in diesel engines, while one sub-project developed a heavy-duty natural gas (NG) engine able to achieve very low emissions (see Chapter 6 on alternative fuels on page 41).

Future GREEN engines will offer flexible components, a new combustion process, closed-loop emission control, higher performance, the ability to use alternative and renewable fuels, and integrated exhaust-gas treatment systems. These advances will enable Europe to maintain its lead in HD ICEs from 2012 to 2016, at the same time that the development of the integrated combustion system in an innovative power train is completed.

Coordinator:	Volvo (Sweden)
EU funding:	EUR 10 million
Start/end:	01/03/2005-28/02/2008
Website:	http://green.uic.asso.fr/introduction.html





4. Rail transport

Although the first EU emission-control regulations for road vehicles began to be implemented in the 1970s (LD vehicles) and 1980s (HD engines), those for the rail transport sector came along somewhat later with the adoption of EU Non-Road Mobile Machinery (NRMM) Directive 2004/26/EC. However, voluntary emission limits (e.g. UIC I or UIC II⁽¹³⁾) for the European rail market have been in place since the 1990s. Stricter emissions regulations for diesel-driven locomotives and railcars are beginning to take effect, and the aim is to achieve a PM limit of 0.025 g/kWh and a NO, limit of 2.0 and 4.0 g/kWh for railcars and locomotives respectively by 2012 (stage IIIB). Besides NO, and PM, HC emissions represent further problems in terms of engine idling, due to the length of time a train can remain stationary, for instance in an underground station or at the depot.

More stringent emission limits will be examined in 2013 in light of the introduction of NO_x aftertreatment technology based on SCR for the rail transport network.

The different NO, limits of stage IIIB for railcars and locomotives are due to the fact that engines for railcar application with a power output lower than 560 kW are usually derived from HD engines, and technology transfer is relatively easy to realise; locomotive engines with a typical power output of between 1000 kW and 3 000 kW are not derived from truck engines, and transfer to rail engines is more difficult. Another limiting factor is the sheer longevity of the engines concerned. While road-vehicle engines have a shelf life of about 20 years, after which the whole vehicle is scrapped, locomotives and rail cars can last for over 50 years. This means it can sometimes be difficult to replace an old engine with new cleaner technology in the same vehicle, particularly due to space and weight limitations. The first project that studied rail technologies was conducted jointly by truck and train engine manufacturers as part of the FP6 project GREEN, while under FP7 a specific project (CleanER-D) on train applications has been launched.

As far as rail is concerned, GREEN aimed to develop an IC process that meets stage IIIB regulation. Therefore, various combustion technologies from road applications were analysed and their adaptation to rail applications was evaluated. Two promising concepts were investigated by single cylinder experiments: EGR and a combined homogeneous/heterogeneous combustion. It was shown that EGR has the potential to achieve NO, compliance with stage IIIB regulation, but sufficient cooling of the re-circulated exhaust gases has to be ensured. This impacts the cooling system of IIIB-compliant diesel locomotives, since either the efficiency of the cooling system or the dimensions of the coolers has to be increased. In comparison, the investigation of the combined combustion process revealed that EGR rates can be reduced at low engine loads, but not at full engine load. Since the locomotive operates partially at full load in many rail applications - where most heat is rejected - there is no significant benefit of the combined combustion process in rail application regarding the stage IIIB regulation.

Based on these results, a stage IIIB-compliant diesel engine has been developed. Emissions of NO_x are reduced by an EGR combustion process and the emissions of particulates are reduced by a DPF. The results of the GREEN project (Fig. 4.1) provided important input for the CleanER-D project.



Figure 4.1 MTU (series 4000) V8 engine at the test bench and a typical locomotive application.

The main goals of this project are to demonstrate the feasibility and reliability of railway rolling stock powered with diesel engines in service, which are compliant with the requirements of stage IIIB of the abovementioned Directive. To ensure the success of the project, three operational sub-projects have been established. Two of them focus on re-powering existing diesel vehicles (a railcar and a locomotive) through a low-emission engine. The third operational sub-project deals with the installation of a stage IIIB engine in a newly designed locomotive. The scientific subproject focuses on investigating existing and potential emission reduction technologies for integration into different rail applications, and evaluating the energy-saving potential of onboard energy-storage system concepts. Much attention is given to the influence of fuel type and quality on emissions, evaluating diesel DPF strategies, and assessing emerging aftertreatment technologies using stage IIIB emissions levels as a baseline, but also researching the suitability of these solutions beyond IIIB. The future environmental responsible solution of the diesel applications is the hybrid system. The Hybrid Solutions sub-project intends to make use of an optimised overall system approach considering the latest state-of-the-art energy storage technologies. In addition, the best solution for the electrical drive system is found after considering all aspects of drive technologies, energy storage technologies, harmonised duty cycles and operational concepts.



Clean European Rail-Diesel

The CleanER-D project aims to develop, improve and integrate emissions-reduction technologies for diesel locomotives and railcars to fulfil stage IIIB emission limits and beyond. CleanER-D technology will enable European manufacturers to offer competitive rail vehicles to the market in order to boost the rail industry.

There are a number of main goals:

- delivering enhanced environmental performance for new and re-manufactured rail diesel vehicles in a fast and cost-effective manner;
- establishing an industry knowledge base on the essential interfaces for exhaust systems and exhaust treatment technologies;
- encouraging engine suppliers to give new low-emission technologies serious consideration in their product development plans;
- envisaging innovative solutions for the rail sector, including hybrid technologies, with a potential for further reduction of pollutant emissions, while aiming at a breakthrough in energy consumption and CO, emissions.

Coordinator:	UNIFE (Belgium)
EU funding:	EUR 7.98 million
Start/end:	01/06/2009-31/05/2013
Website:	http://www.cleaner-d.eu/





5. Waterborne transport

Even though it is a very efficient mode of transport, total emissions from shipping and inland-waterway vessels have traditionally been quite high. In 2000, for example, EU-flagged ships emitted almost 200 million tonnes of CO_2 , significantly more than the corresponding emissions from EU aviation⁽¹⁴⁾. And it is estimated that by now, sulphur dioxide (SO₂) emissions from ships in European waters account for 75 % of all emissions from EU land-based sources⁽¹⁵⁾.

In 2002, the EU adopted a new strategy to reduce atmospheric emissions from seagoing ships. The strategy reported the magnitude and impact of ship emissions in the EU and proposed a number of actions to reduce the contribution of shipping to acidification, ground-level ozone, eutrophication, health, climate change and ozone depletion.

Similar to the rail transport sector, the entry into effect of EU Directive 2004/26/EC introduced a first stage of emissions limits for CO, HC + NO_x , and PM. These regulations also took effect starting from 2007 (and from 2009 for vessels on inland waterways).

Polluting emissions are also covered by Annex VI of the Marine Pollution Convention, MARPOL 73/78, of the International Maritime Organization (IMO)⁽¹⁶⁾. This contains provisions on sulphur oxides (SO_x) and NO_x emissions standards for ships' engines.

Since 1 July 2010, when the 2008 amendments to MARPOL Annex VI entered into effect, ships operating in the Emission Control Areas (ECAs)⁽¹⁷⁾ have been required to use fuel not exceeding 1 % sulphur. And by 2016, according to Tier III of the MARPOL regulations, NO_x emissions⁽¹⁸⁾ within the ECAs will be the same as those for rail transport.

- ¹⁴ Source: Ship emissions assignment report, p. 160 (2005).
- ¹⁵ Source: Europa Summaries of EU legislation.

POSE²IDON Power optimised ship for environment with electric innovative designs on board

The POSE²IDON consortium aims to investigate the potential for the commercially effective application of electric ship technology.

The project is developing a working guide on how to improve efficiency and reduce the environmental impact of the combined European commercial shipping fleet; the consortium also aims to enhance the electric ship concept so that it can be applied to a wider range of vessels than is currently the case.

The principal barrier to adoption of the electric ship concept in smaller merchant ships is the size of the generating equipment and propulsion motor. The POSE²IDON consortium will therefore focus on achieving size reduction through the development of new technologies across all aspects of marine electrical engineering. A key element will be the application of high-temperature superconductivity (HTS) technology that will allow for smaller electrical drive components and an increase in efficiency. Additionally, electric auxiliaries, wireless technology and fail-safe power distribution will be studied.

Coordinator:	BMT Defence Services Ltd (United Kingdom)
EU funding:	EUR 20 million
Start/end:	01/01/2009-31/12/2012
Website:	http://www.poseidon-ip.eu/index.php

TEFLES

Technologies and scenarios for low-emissions shipping

The overall goal of TEFLES is to cut ship oil consumption so as to lower emissions and costs. It will achieve this through a combination of novel technologies and impact models that allow owners to evaluate the emissions and cost implications of fitting different technologies to their boats. The project will focus particularly on reducing emissions during port operations such as docking, loading and unloading.

Coordinator:	Inova (Spain)
Total budget:	EUR 3.1 million
EU funding:	EUR 2.26 million
Start/end:	01/02/2011-31/01/2014
Website:	http://cordis.europa.eu/fetch?CALLER=FP7_
	PROJ_EN&ACTION=D&DOC=3&CAT=PROJ&QUERY
	=012ebe1d4137:fdf6:53c04c06&RCN=97753

¹⁶ MARPOL (MARine POLution) is an international convention for prevention of the pollution of the sea from ships. It establishes rules for the protection of the environment for international shipping sailing under the flag of an IMO (International Maritime Organization) member country or in their waters.

¹⁷ More stringent emissions limits are applied to Emission Control Areas (ECAs) — Baltic and North Sea regions, and in future US West Coast, Mediterranean and Japan — which can extend to 322 kilometres (200 miles) from the coast line.

¹⁸ Tier III NO_x limits depend on the engine speed n: 3.4 g/kWh for n lower than 130 rpm, for n between 130 and 1 999 rpm and 2.0 g/kWh for engines having an engine speed n higher than 2000 rpm.

Although regulation was slow in coming through, some manufacturers of large marine-diesel engines for shipping did at least conduct studies on how to implement emission-control technologies in their designs relatively early. For example, in 1994 an FP3 project led by MAN Diesel studied the elimination of material-related problems due to NO, reduction by injecting a reducing agent into the cylinder and by exhaust-gas recirculation. In 2002, engine manufacturers MAN Diesel and Wärtsilä, through the HERCULES project, conceived a long-term strategic (research and development (R&D)) plan, joining forces to make ship engines cleaner and more energy efficient. Between them, the 2 companies are world leaders, supplying about 90 % of the market for ship engines, so the project outcomes are of relevance to ship owners worldwide.

The HERCULES team set itself the ambitious goal of cutting fuel consumption (and hence CO_2 emissions) by 10 %, NO_x emissions by 70 % (relative to IMO 2000 standards) and other emissions (such as PM and HC) by 50 %, all by 2020. The first phase investigated a range of technologies designed to meet these goals; the most successful were then chosen for further development in the second phase, HERCULES B, launched in 2008.

A favoured NO_x control strategy is the Miller cycle, which involves early closing of inlet valves and decompression of the charge air. This technology, initially developed for large marine engines, can help inspire similar developments in rail and road engines. Likewise, with multi-stage turbocharging being an important enabler of the Miller valve timing, such a development can make an important contribution to two-stage turbocharging, now a feature of rail and road engines. Another leading technological innovation for large engines is heat recovery with a combined steam cycle, which allows a substantial increase of fuel conversion efficiency (an approach that, as seen above, is now also taken for trucks).

The technology choices for meeting IMO Tier III NO_x emissions in low-speed, 2-stroke engines are urea-SCR, EGR (high-pressure loop with scrubber, 40 % EGR rate), water-in-fuel emulsions and/or water injection.

While most ships are still directly powered by diesel, some, like cruise ships, warships and ferries, need to be able to change their speed frequently. Theoretically, diesel-electric propulsion is by far the most efficient solution for such applications. Yet most designers stick to pure diesel propulsion because of the size, weight and cost of the equipment involved in electric propulsion, and also because diesel engines are a known quantity.

One project, POSE²IDON, is at the forefront of efforts to overcome such barriers. Part of the research is devoted to simply identifying the kinds of ships that have the most to gain by going electric. At the same time the project team is working on a new approach — the development of HTS technology — to bring down the size and cost of electrical propulsion systems.

Currently most ships run on diesel, but EU-funded researchers are actively investigating ways of making use of cleaner alternatives. The HELIOS project is developing an engine that runs on compressed or liquefied natural gas (CNG and LNG respectively) instead of the conventional heavy fuel oil. Among others, the technology should almost eliminate sulphur emissions, cut carbon emissions by over 20 %, NO_x emissions by up to 15 % and PM emissions by as much as 70 %.

Another method of cutting shipping emissions is through the use of aftertreatment systems that remove pollutants from the exhaust. The TEFLES project is developing and integrating novel aftertreatment and other technologies with a view to reducing emissions both at sea, and in and around ports. In addition to aftertreatment solutions, the team is looking into the application of other technologies in areas such as shore power connection, power generation and propulsion, that offer the potential for deep emissions cuts.



HERCULES-B High efficiency R&D on combustion with ultra low emissions for ships — Phase II

HERCULES-B is phase II of the HERCULES programme to develop the future generation of efficient and clean marine diesel engines. Its research objectives focus on drastic reduction of CO₂ emissions from diesel propulsion systems which today power 99% of the world fleet.

The principal aim of HERCULES-B is to reduce fuel consumption of marine diesel engines by 10 %, thus achieving a fuel conversion efficiency of more than 60 % (from the present level of 51 % – 52 %), with a substantial consequent CO_2 emissions reduction. An additional aim is to move towards ultra-low exhaust emissions (70 % reduction in NO_x, 50 % reduction in particulates) from marine engines by the year 2020.

To achieve this target, the project is focusing on diesel combustion and advanced exhaust-gas treatment methods. The total power train, and the interaction of the engine with the ship, as well as the use of combined cycles in overall system optimisation, are all being taken into account.

 Coordinator:
 Karlsruher Institut Fuer Technologie (Germany)

 EU funding:
 EUR 15.0 million

 Start/end:
 01/09/2008–31/08/2011

 Website:
 http://www.hercules-b.com/



HELIOS High Pressure Electronically controlled gas injection for marine two-stroke diesel engines

The objective of HELIOS is to develop a marine low-speed two-stroke gas/diesel-engine research platform that is realistically sized for direct-drive marine propulsion.

The potential of the HELIOS project is further enhanced by the possibility of retrofitting gas diesel technology onto existing inservice ships, since less component modifications are needed and engine removal or reinstallation is not necessary. The research platform will form the basis for a new generation of high-pressure gas injection engines operating on CNG and/or LNG, using diesel type and partly pre-mixed combustion principles. The new generation of engines will be fully electronically controlled and have power ratings from 5 000 kW to 100 000 kW.

Coordinator:	MAN Diesel & Turbo (Germany)
EU funding:	EUR 2.98 million
Start/end:	01/09/2010-31/08/2013
Website:	http://cordis.europa.eu/fetch?CALLER=FP7_
	PROJ_EN&ACTION=D&DOC=1&CAT=PROJ&QUERY
	=012ce990e6e1:5867:398f1d4e&RCN=97022



6. Alternative fuels

After the EU had established emission-control regulations for passenger cars and commercial vehicles, the next area to receive attention was fuel quality, with particular emphasis on diesel fuel. The first visible sign of these regulations taking effect was the introduction of sulphur-free diesel fuel (less than 10 ppm) into the market in 2005.

This also specified a reduction of another major source of PM emissions, heavy aromatic HCs. In turn this increased cetane number of modern diesel fuels which brought other advantages in terms of ignition, reducing HC and NO_x emissions. Furthermore, the legislation mandated a lower final boiling-point, thus reducing soot fouling of injector nozzles and PM formation. This advanced sulphur-free diesel had fully penetrated the EU markets by 2009.

A strong push to introduce quality targets for fuels began to appear in many EU research projects, such as the FP5 project on diesel fuels, CLEAN, which started in the 1990s. In addition, many of the projects focusing on the development of exhaust-gas treatment systems required low-sulphur diesel fuels in order to allow the use of catalysts.

Compressed natural gas – the clean fuel?

Natural gas was probably the first real alternative to refined crude oil as a fuel for ICEs. As CNG, it has been in use across Europe as a vehicle fuel for many years, and remains attractive for city public-transport applications because of its low emitting nature. In fact, NG is a clean fuel; there are no toxic compounds such as sulphur in its exhaust fumes, or potentially toxic ones such as benzene and higher molecular-weight HCs. Even highly reactive compounds such as olefins are absent. The compact molecule of methane, the main constituent of NG, allows for higher compression ratios and consequently higher engine efficiency, while its higher hydrogen-to-carbon ratio ensures a combustion process without carbon particles and 23 % lower CO₂ emissions than gasoline-fuelled vehicles.

In 2009, known world reserves of NG amounted to 185 trillion cubic metres — equivalent to 62.8 years' supply, compared to crude oil's 45.7 years'. The total quantity of NG resources is estimated to be more than 850 trillion cubic metres. Unlike oil reserves, that are for the most part concentrated in the Middle East, NG reserves are spread far more widely throughout the world (Europe, Africa, America and Asia), and this makes NG attractive because of the improved security of energy supply.

European research into use of CNG as an alternative fuel started with projects concerning its application in:

- LD vehicles in METHACAR, a project that aimed to understand the combustion process of NG in a LD vehicle, and in BMW-led NG COMPONENTS AND FUELS, developing specific components to match the quality of NG in Europe;
- HD vehicles in projects EMING and IGIS that concentrated on developing the gas injection system, ignition, EGR and aftertreatment to meet the very low emissions requirements of enhanced environmentally friendly vehicles (EEVs).

Two types of combustion process were considered: stoichiometric (i.e. with exactly enough air provided to completely burn all of the fuel), and lean.

In the field of HD vehicles, the optimum in terms of the balance between fuel consumption and emissions was found to be the stoichiometric configuration, which is now used in the majority of CNG buses on the market. CNG and diesel are the two main competitors for inner city road transport. However, diesel-driven vehicles will have to use four catalysts to meet future Euro VI emissions limits (a catalyst to oxidise HC and CO, a catalysed DPF, a catalyst to reduce NO_x, and a clean-up catalyst to oxidise the remaining ammonia). CNG, by contrast, using a single three-way catalyst, is already able to meet even stricter emissions levels.

In the field of LD vehicles, there is still a debate regarding lean or stoichiometric combustion and its use, in light of some technological limitations that make it difficult to fully exploit its potential for high efficiency.

Despite the many environmental advantages NG offers, why don't we see more NG vehicles on our streets? Several obstacles have contributed to this slow uptake from the market, says Massimo Ferrera, Director of alternative fuel engines in the research and technology division of Fiat Research Centre & Powertrain Technologies, which is part of the Fiat Group: 'Firstly, today's gas engines have the heavy drawback of being developed as multi-fuel engines out of conventional gasoline-fuelled combustion engines, and are not designed and optimised for CNG only. In addition, gaseous fuels pose challenging storage requirements and vehicles have a shorter motoring range. With relatively few filling stations available, this is a deterrent to many consumers.'



Dr Ferrera is the coordinator of INGAS, a large-scale FP7 IP focusing on NG-fuelled cars. Its main objective is to develop LD vehicle engines which achieve both high fuel conversion efficiency and lower emissions. The project team is also investigating the quality of NG fuels, lighter gas-storage systems and exhaust-gas treatment systems designed specifically for CNG cars, since NO_x and methane catalysis are still problematic for non-stoichiometric combustion and require large quantities of precious metals such as platinum, driving the costs of this technology even higher. In fact, one of the key challenges is to develop a dedicated methane catalysts, with higher conversion efficiency than gasoline catalysts but at a similar or lower cost.

While the use of CNG can serve as an option for urban buses and fleets of municipality trucks within the city, today its use cannot be accepted for long-distance commercial vehicles: the unsustainable increase of the weight and size of the fuel tanks mean that the gas storage system would occupy most of the space and reduce the payload of a commercial vehicle. The use of LNG in commercial vehicles paves the way for its use as a replacement for oil-derived fuels. This technology can also be very useful when applied to waterborne transport, as shown by the HELIOS project. In the long term, NG could become an attractive fuel option for long-distance passenger and goods transportation, due to the availability of large worldwide reserves.



INGAS

Integrated gas powertrain — Low emissions, CO₂ optimised and efficient CNG engines for passenger cars and LD vehicles

INGAS aimed to develop LD vehicles with custom-designed engines and exhaust-gas treatment systems that would achieve, depending on which engine technology is adopted, a 20 % lower GWI (Global Warming Index) than that of today's corresponding gasoline vehicles (for the stoichiometric approach) or 10 % higher fuel conversion efficiency than that of a corresponding 2006 diesel vehicle (for the lean-burn approach), while complying with emission standards higher than Euro 6 limits. The project compares three main combustion technologies:

- a 1.4-litre engine using sequential multi-point port gas injection in a stoichiometric approach;
- a turbocharged DI 1.8-litre engine using direct gas injection and a stoichiometric/lean burn approach;
- a boosted lean-burn 1.9-litre gas engine using port gas injection, or low-pressure direct gas injection and ultra-lean combustion.

Coordinator:	CRF (Italy)
EU funding:	EUR 12.3 million
Start/end:	01/10/2008-30/09/2011
Website:	http://www.ingas-eu.org/

METHACAR Methane fuelled ultralow emitting cars

CNG has proved to be very clean as a fuel; however, its use requires specially fitted vehicles with sophisticated gas-injection systems, methane selective catalysts and light fuel tanks of innovative technology. The METHACAR project conducted research into which new fuel injection and exhaust-gas treatment technologies are necessary if CNG-fuelled vehicles are to reach their full potential.

METHACAR developed multi-point sequential gas-injection systems designed specifically for CNG fuels, and dedicated catalysts with high methane-oxidation efficiency for effective treatment of exhaust gases. Research techniques included computational fluid dynamics modelling of air/gas mixing and the combustion process, modelling of the three-way catalyst, integrated design of vehicles and fuel tanks for CNG storage, a study of system reliability and an environmental impact assessment.

Coordinator:	CRF – Fiat Research Centre (Italy)
EU funding:	EUR 2.15 million
Start/end:	01/05/1994–30/04/1997
Website:	http://cordis.lu/fetch?CALLER=MSS_IT_PROJ_EN
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	1e3771f:a869:6898dba8&RCN=22507



EMING & IGIS

Dynamic emission control for NZEV⁽¹⁹⁾ HD CNG engines & Integrated gas injectionand ignition-systems matched to advanced combustion processes for HD NG engines.

CNG for fuelling buses is an effective and immediate solution to reducing emissions from public transport within Europe's ancient inner cities. However the fuel consumption of current CNG engines remains rather high and newer diesel technologies with highefficiency particulate traps are fast catching up as an alternative.

The EMING & IGIS projects aimed to develop a CNG-fuelled engine with very low emissions and improved fuel consumption for HD use and industrial exploitation. Research focused specifically on developing a suitable EGR system with purpose-built control of waste emissions.

Coordinator:	CRF — Fiat Research Centre (Italy)
Start/end:	01/08/1997-28/02/2000 (EMING), 01/11/1997-
	31/05/2001 (IGIS)
Website:	http://cordis.europa.eu/search/index.
	cfm?fuseaction=proj.document&PJ_LANG=EN&PJ_
	RCN=2552878&pid=0&q=DB921AF573D63FA6C1
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	http://cordis.europa.eu/search/index.
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cfm?fuseaction=acro.document&AC_ LANG=EN&AC_RCN=2730813&pid=0&q=4A4B8 27BB68FCCEEC540768426CA279A&type=sim

Synthetic and bio-derived fuels

Alternative fuel made from specially processed crude oil could be a reality in the future. This fuel group encompasses fuels with oxygenates, which reduce soot but lower the heating value of the fuel. Fuel mixtures with water can reduce both soot and NO_x, but again the heating value drops in proportion to the water content. A key issue with this fuel type is the stability of the mixture at low temperatures. In addition, the weight rises with the amount of water, leading to higher fuel consumption.

Another alternative is synthetic fuel derived from NG, which has no aromatic or sulphur content. Generally speaking, the production process to create a synthetic fuel involves cracking the molecules of any carbon source, e.g. wood, gas, sunflower oil, or even coal, and creating the fuel out of the resulting gas.

There are three main types of process: GTL (gas to liquid), CTL (coal to liquid) and BTL (biomass to liquid). In terms of overall CO_2 reduction, BTL fuels are the most promising. The synthesis process can be utilised to define the desired molecular structure of the fuels, within physical and chemical boundaries. With this additional degree of freedom, the fuel can be optimised and further potential to lower CO_2 and pollutants can be realised. This adaptation of fuel properties can be compatible with the existing combustion systems, but another, even more attractive, option would be to design fuels for HCCI combustion systems, for example, to gain even greater benefits. This potential was evaluated in the IP NICE (page 24).

BTL fuels in particular will play a major role in the fuel market of the future, due to their potential to blend with conventional diesel and achieve high emission reductions as well as very low well-to-wheel⁽²⁰⁾ CO_2 emissions.

Among the biofuel options, biomethane has strong market potential, both for its conversion yield and for its independence from the food sector. By using biomethane, there is an additional reduction of CO_2 emissions, thanks to both the CO_2 closed cycle and the fact that it avoids the problem of direct methane emission into the atmosphere from landfills (Fig. 6.2, page 46), something that has an enormous effect on the ozone layer. One of the most important objectives of the FP7 INGAS project is to develop engines that can use, with minor modifications, biomethane and NG/hydrogen mixtures up to 30 % by volume, bringing a further 12 % CO_2 reduction with limited impact on vehicle range.

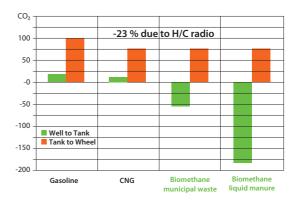


Figure 6.1 One of the most promising biofuels, according to the EC-funded well to wheel study (which includes GHG emissions in all phases, from extraction/production to the use phase in the engine) is biomethane. Burning methane already offers some global warming benefits due to its composition (hydrogen-to-carbon ratio equal to 4 for methane and $1.8 \div 2.0$ for gasoline and diesel fuel) since each carbon molecule corresponds to a CO₂ molecule after burning. However, methane is also a powerful GHG with a global warming potential of 25 relative to CO₂. Therefore when it is produced from waste materials it reduces the greenhouse effect by capturing gas which would otherwise be released in the atmosphere.

A major current research issue is the development of new second-generation biofuels, which do not compete with food production like first-generation ones, an area given particular emphasis in the VW-led RENEW IP. Meanwhile, several major vehicle manufacturers are becoming more and more interested in the potential of third-generation biofuels derived from sources such as algae. Initial laboratory testing has indicated that algae can produce up to 30 times more energy per acre than land crops such as soybeans can.

²⁰ A term which defines the emissions over the whole life cycle of the fuel, from its extraction from the well (or production, for nonfossil fuels) to its use.

With the days of oil-powered vehicles numbered, researchers looked also into hydrogen-fuelled engine systems that can take the lead in the transition from conventional fuels. As the only carbon-free fuel, hydrogen could play a large part in the energy landscape of the future. 'Hydrogen is the only renewable fuel which has the density of energy to power personal vehicles as we currently know them,' says Hans-Christian Fickel, coordinator of HY-ICE, 'HY-ICE was the first attempt to create an internal combustion engine purposely designed to run on hydrogen. We wanted to develop engine concepts that could beat both gasoline and diesel engines with respect to power density and efficiency at competitive costs,' says Mr Fickel. By using key components such as several types of hydrogen injectors and dedicated ignition systems, HY-ICE was able to overcome the major problem of hydrogen engines, i.e. the 20 % reduced power density compared to engines running on conventional liquid fuels.



- High CO₂ Avoidance Potential
- No Interference in the Food Chain
- High Hectare Yields

1st Generation

- Biodiesel (Rapeseed)
- Ethanol (Wheat, Sugar Beet)

2nd Generation (SunFuel®)

- Biomass to Liquid (Choren)
- Cellulose Ethanol (logen)

Another EU research project, CLEANENGINE (FP6), examined the ability of ICEs to use new biofuels and biolubricants. The project investigated a range of different engine-size categories, both automotive and not.

Figure 6.2 Another EU research from the first generation to second generation of biofuels.

RENEW Renewable fuels for advanced powertrain

Using agricultural land to grow biomass for fuels is highly controversial — with some claiming it is an energy-inefficient approach to producing fuel sources. The RENEW project set out to establish the truth of the matter, assessing various methods of biomass fuel production and Europe's potential to produce biomass material. The 31 partners from 8 EU Member States and Switzerland covered the automotive sector, the mineral oil industry, electricity producers, pulp and paper production, process engineering and universities.

Project results showed that there are 'multiple opportunities' in Europe for producing BTL, a type of biofuel made from lignocellulosic biomass such as wood, straw and energy plants. The researchers reached this conclusion after investigating BTL diesel, as well as two other options: methanol/dimethyl ether (DME) and bioethanol.

Coordinator:	Volkswagen (Germany)
EU funding:	EUR 8.23 million
Start/end:	01/01/2004-31/12/2007
Website:	http://www.renew-fuel.com

CLEANENGINE

Advanced technologies for highly efficient working engines with alternative fuels and lubes

This project focused on developing modern, clean ICEs that use liquid biofuels sourced from biomass (like biodiesel and bioethanol), and environmentally friendly and ash-free oils and/or lubrication concepts. Researchers evaluated the impact of biofuels and biolubes for both diesel and petrol engines, and sought to develop compatible materials (base materials and anti-corrosion, low-friction coatings), engine geometries and exhaust-gas treatment systems.

The project aimed to deliver optimised car, leisure boat and ship engines capable of running on high biofuel content blends and lubricated by optimised biolubricants, while achieving high fuel conversion efficiencies and very low emissions.

Coordinator:	CRF (Italy)
EU funding:	EUR 2.0 million
Start/end:	01/01/2007-31/12/2009
Website:	http://cordis.europa.eu/search/index.
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	LANG=EN&PJ_RCN=9595898&pid=0&q=D4FC4F
	B92A67199E5271D3966B396C9B&type=sim

CLEAN Optimum diesel fuel for clean diesel engines

Given the significant market share achieved by diesel engines because of their low $CO_{2^{\prime}}$ the CLEAN project aimed at developing new fuel blends optimised for diesel engines, thereby helping to reduce their pollutants emissions.

Initial fuel analysis data was used to adapt a high-pressureinjection single-cylinder engine, modifying the compression ratio, the bowl design, the EGR rate, the swirl ratio and the injection characteristics to obtain optimum burn efficiency. The results were used to recommend formulations for clean diesel fuels, and to help five vehicle manufacturers adapt their diesel-engine designs to optimise emissions and fuel consumption.

Coordinator:	Daimler (Germany)
Start/end:	01/01/2002-31/12/2004
Website:	http://www.ist-world.org/ProjectDetails.aspx?Proj
	ectld=08f7139a6887489daa777fe19939b425





HY-ICE Optimisation of hydrogen powered internal combustion engines

HY-ICE was an initiative for automotive hydrogen engine development that provides economically feasible and environmentally friendly solutions for increasing mobility demands. The goal of the project was to create the knowledge base needed to build a highly efficient hydrogen engine with a better specific power than gasoline and diesel at competitive costs.

One key component was the system applied to achieve the mixture formation. For the two most promising concepts, DI into the cylinder and cryogenic port injection (CPI), the necessary knowledge concerning design and application was established.

Subsequently, dedicated injectors capable of handling the new fuel with its specific characteristics were developed. The processes of mixture formation and combustion were studied and optimised using test engines as well as CFD calculations.

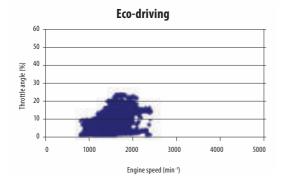
The supporting technologies, necessary for both engine concepts, were developed: an ignition system able to deal with the broad flammability limits of hydrogen, and CFD models adapted to hydrogen application.

Coordinator:	BMW (Germany)
EU funding:	EUR 5 million
Start/end:	05/01/2004-04/03/2007
Website:	http://cordis.europa.eu/fetch?CALLER=OFFR_
	TM_EN&ACTION=D&RCN=5577



7. Future perspectives

Despite the efforts of so many stakeholders to reduce ICE emissions over the years, EU policymakers recognise that air quality has not improved as much as had been expected. One explanation is the difference between emissions results obtained during typeapproval testing and those under real operating conditions (Fig. 7.1).



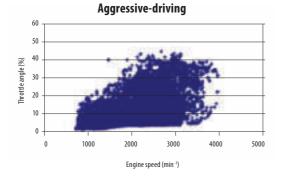


Figure 7.1 Different driving patterns and their effect on engine performance (the effect on emissions is similar) in the throttle angle (load) — engine speed map.

Integrated legislation

In order to avoid this effect, a new test cycle for passenger cars, the Worldwide Light-duty Test Procedure (WLTP), is now under development as part of an integrated legislation approach (Fig. 7.2), while one for trucks, the Worldwide Heavy Duty Certification (WHDC), has recently been adopted. The Portable Emissions Measurement Systems (PEMS) programme recently began development of a system to measure exhaust gases at the tail pipe. PEMS is intended to serve as a basis for testing and maintaining compliance with emission standards throughout the typical duration of an engine's life, thus helping to close the gap between test cycles and real emissions.

These developments are taken into account in the most recent FP7 projects such as POWERFUL, and will no doubt strongly influence all future engines, together with the expected tightening of CO_2 targets from the current 130 g/km to the 95 g/km expected by 2020. At the same time, CO_2 targets are being developed for LD and HD freight vehicles (where PEMS is already being applied to keep pollution in check), driving engine research further in these sectors.

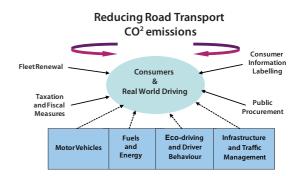


Figure 7.2 The integrated approach to reducing road transport CO_2 emissions.



Technology answers

The key challenges facing developers of future SI engines are how to radically reduce fuel consumption and CO_2 emissions while improving driveability and the fun-to-drive factor. At the same time, they have to ensure that add-on costs are no higher than those required by the diesel-driven competition.

Downsizing and turbocharging in combination with valve control and DI are regarded as key technologies enabling SI engines to meet these challenges. The present surplus on the EU gasoline fuel market compared to a relative shortage of diesel fuel (leading to higher fuel prices and CO₂ emissions, which diminish the benefit of buying diesel engines) is another factor pushing the development of SI engines. And because of their relative simplicity, SI engines remain the motive power of choice for smaller vehicles, where they represent the best compromise in cost/benefit ratio.

For diesel engines, the critical challenges are instead how to meet the expected severe Euro 7 NO_{x} limits at an acceptable cost, while maintaining or further improving diesel's low CO₂ emissions. On one hand SCR systems will be applied, while new technologies might need to be introduced (like VVA and new types of catalysts) in particular for smaller vehicles to reduce costs.

Some of this work is already under way in the latest research projects like the FP7 POWERFUL, which is working on advanced gasoline and diesel configurations to achieve the abovementioned targets by examining all the aspects and designing tightly integrated power trains.

Other areas where research might make important contributions look at other parts of the power train:

- flexible, on-demand use of engine auxiliaries (mainly by electrification) which would be powered only when needed and not, like today, at all times;
- integrated systems for energy management, in particular thermal management of the various systems which need to be cooled or heated, including the development of systems that recuperate useful energy from what is currently lost as heat in high-temperature exhaust gases (wasteheat energy recovery).

However, not all of these actions will improve on some intrinsic ICE limitations; in some cases they may even make them worse. Torque will still depend on engine speed (it tends to be particularly poor at low engine rpm), and with less cylinders, a possible consequence of downsizing, torque might oscillate, reducing the perceived'quality'of these smaller engines. The response to driver input might also be affected, as well as the precision with which the engine can be controlled.

While there are mechanical ways of dealing with these limits, they are likely to be fully overcome only with some hybridisation of the engine system, i.e. the use of electric motors to support the ICE. For example, they can deliver maximum torque at zero rpm, they are very smooth running, and they respond extremely fast and in a precise, controlled way.



POWERFUL Power train for future light-duty vehicles

A generation of new ICE technologies able to achieve a 50 % CO_2 reduction (compared to 2005 figures) for passenger cars and light commercial vehicles appearing on the market in 2020: this is the ambitious aim of this project. In particular, SI engines are to achieve 40 % lower CO_2 emissions with respect to the 2005 values, while a 20 % reduction is planned for CI engines.

Three different concepts are to be investigated:

- an ultra-downsized low-cost SI engine integrating VVA, advanced turbocharging and DI;
- a four-stroke Cl engine concept able to run on new tailored fuels and integrating the low-temperature combustion mode;
- a two-stroke CI engine concept running on diesel fuel and integrating the low-thermal homogeneous combustion mode.

These advanced engine concepts are accompanied by the development of:

- new simulation tools describing the strong interactions between combustion systems and engine architecture;
- means for reducing engine frictions and performing intelligent energy management;
- a PEMS approach, to ensure that real-life emissions are improved, not only those on the test cycle.

Coordinator:	Renault (France)
EU funding:	EUR 13.49 million
Start/end:	01/01/2010-31/12/2013
Website:	http://cordis.europa.eu/fetch?CALLER=NEW_
	PROJ_TM&ACTION=D&DOC=1&CAT=PROJ&QUER
	Y=0128610e2ec6:321c:187b2e64&RCN=93847

A hybrid future?

Hybridisation therefore represents the emerging technology for the ICEs of the future in many applications, enabling designers to fully exploit the key features of electric motors to simplify power train design and help reach technical (performance, driveability, and efficiency) and environmental targets both in LD (Fig. 7.3, page 53) and HD (Fig. 7.4) applications. An electrified IC-engined vehicle can:

- effectively use the electric motor as a very precise real-time torque metre, with clear advantages in terms of increased performance and emissions reduction (thanks to the electric drive's ability to precisely estimate the torque applied by the electric motor);
- use the electric motor's high-precision speed and position sensors to drive a 'self-restart' mode for the ICE;
- achieve high torque at launch.

The electric motor thus allows a re-optimisation of the ICE. For example, since the electric motor covers low-load operations, a hybrid diesel vehicle can:

- deploy the ICE at medium-high load when a sufficient gas temperature is available;
- use the higher performance of low-pressure EGR⁽²¹⁾ without any compromise in comparison to high-pressure EGR;
- decrease the compression ratio, e.g. from 16.5 to 15, for better engine starting and NO_x reduction.

In the case of hybrid SI engines (for gasoline or CNG vehicles):

- cylinder-deactivation can be pursued with no disadvantages;
- using the electric motor as a flywheel can strongly reduce NVH effects, particularly important in twincylinder four-stroke engines;
- low-end torque is boosted.

²¹ A low-pressure EGR, i.e. where exhaust gases are taken downstream of the turbine, allows higher exhaust-gas temperatures at the turbine inlet, and also a higher flow rate, while the air leaves the intercooler at a lower temperature, with a resulting strong increase in compression efficiency.



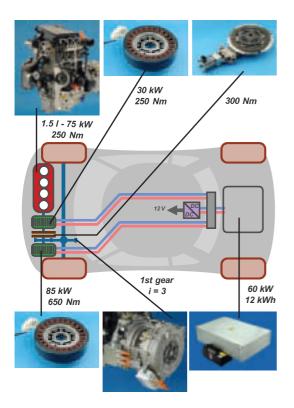


Figure 7.3 Twin drive plug-in at Volkswagen: front-wheel drive concept.



Figure 7.4 The BlueTec-Hybrid Citaro shows the benefits of electrifications in city buses: using four electric motors in the middle and rear wheels, for a total of 320 kW it can use a very downsized IC engine (form 12 to 4.8 litre).

Clearly, the progressive introduction of electric drives (electric motors and power electronics) will play an increasing role in satisfying environmental concerns, and several FP5 and FP6 projects have covered research in this area. As hybrid technologies advance, issues such as emissions of pollutants and CO₂, fuel consumption and noise reduction will become easier to tackle without sacrificing end-user demands for performance, driveability and comfort.

Depending on the class of the vehicle, more and more small micro-hybrid vehicles will start to appear, with stop/start and brake-energy recuperation (the generation of electric energy as the car slows down instead of just wasting it as heat on the brakes), and larger mild and full hybrids with increasing pure electric range.

A plug-in capability with the required infrastructure would increase the potential for running in cities without using the ICE at all, relying on the grid to supply energy to charge the batteries, while the ICE would be available for longer trips. But electric components cost money, and each additional component has to be developed in a way that integrates it with the vehicle's total hybrid power train (for instance, by eliminating some aftertreatment component). Since affordability is a major concern, (Fig. 7.5), such considerations (which strongly depend on fuel price) will drive the exact configuration of future power trains.

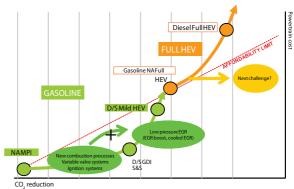


Figure 7.5 Cost/CO₂ emissions trade-off for different power trains (according to Renault). The affordability limit represents the maximum a customer is ready to pay for CO₂ and improved fuel economy.

The continuing challenges for any potential replacement for the ICE (limited range, battery durability and recharge for battery vehicles, cost, availability of hydrogen and efficient on-board storage for fuel cell vehicles) will, however, ensure a significant transition phase (Fig. 7.6) for traditionally driven vehicles, which will undergo increasing integration with hybrid components up to the point of complete electrification⁽²²⁾.

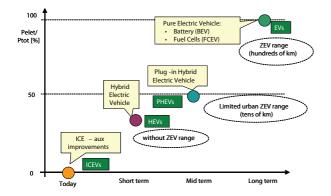


Figure 7.6 Powertrain electrification roadmap for mass production.

New research for the HD vehicle sector is also concentrating on advanced engine concepts. Emphasis is being placed on better combustion processes, but also on the intervention of intelligent control systems, alternative fuels and the use of recuperated waste energy from exhaust gases.

Finding further improvements in fuel consumption for the heavy commercial sector will almost certainly involve significant engine downsizing, while hybridisation will mainly be an option for some types of urban vehicles (buses, garbage trucks, etc.) Associated research will therefore focus on key components such as turbochargers, thermal management of the exhaust aftertreatment system and increased efficiency of SCR, as well as attention to the new PN limit. Rail and maritime engines will also follow these trends. Hybridisation could play an important role in rail propulsion, particularly for suburban railcars and switching locomotives that have a stop-start operating pattern, while aftertreatment and engine control solutions will be adopted from the truck sector. Maritime propulsion will instead improve efficiency by looking to new components such as diesel injection systems based on CRI technology and two-stage turbocharging, while exploring the potential of LNG as a future fuel, and the pros and cons of slower ship operation for engine efficiency.

The 'à la carte' vehicle

The ultimate power train configuration will, in the long run, make use of flexible components/subsystems, be managed cycle-by-cycle by advanced model-based control strategies, burn a mixture of fossil and renewable fuels, and be coupled with an electric motor.

To achieve this objective, researchers will need to harness all the advances already made in components (fuel injection system, VVA, sensors, etc.), integrated aftertreatment and new combustion processes for conventional and alternative fuels (Fig. 7.7). They will also need to find innovative ways of controlling these more complex machines and, even more importantly, of keeping production and operating costs at an acceptable level.

²² European Green Cars Initiative / Public-Private Partnership Multi-annual roadmap and long-term strategy Prepared by the EGCI Ad-hoc Industrial Advisory Group ISBN 978-92-79-19710-9

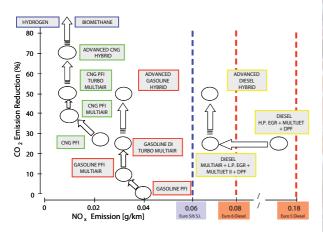


Figure 7.7 Fiat's roadmap for Diesel and Otto cycle mass-produced powertrains to comply with forthcoming emission limits. Multijet and Multiair are Fiat's trade names for VVA and CR systems.

Customers will also have more work to do, since choosing the best type of vehicle will be less straightforward. The multipurpose vehicles of the 1990s with gasoline or diesel engines will no longer be the norm; more highly specialised vehicles will emerge that are optimised for particular uses (e.g. city driving, commuting, long trips).

Such options will help match the specific needs of end users. Depending on drivers' specific driving behaviour or usage pattern (and of course, environmental awareness and spending power), the choice will be much wider than that of engine size and accessories, heading towards a real à la carte powertrain and fuels menu! Enjoy your driving!



8A. Appendix – Project titles

ADDI 'Advanced DI diesel with high pressure injection control' (1997–2000): a cluster with two other projects: 'Integrated aftertreatment system of DI diesel for cars' (DIDTREAT), and 'DI diesel noise and vibration control technologies' (DINOISE)

ADIGA 'Advanced DI gasoline engine' (1996–1999): a cluster with two other projects: 'Advanced valve control system' (ADVACO), and 'Integrated electronic system for dynamic emission control' (ELSEC)

AHEDAT 'Advanced heavy-duty engine exhaust-gas treatment technology' (2002–2005)

ATECS 'Advance truck engine control system' (2000–2004)

CLEAN 'Optimum diesel fuel for clean diesel engines' (2002–2004)

CLEANENGINE 'Advanced technologies for highly efficient working engines with alternative fuels and lubes' (2007–2009)

CleanER-D 'Clean European rail-Diesel' (2009-2013)

COMET 'Coated sintered metal trap' (2002-2005)

CRICE 'Common rail based improved combustion for low emissions' (2000–2003)

DEXA 'Diesel engine exhaust aftertreatment' (2000–2005): a cluster of four projects: 'Advanced regeneration technologies for diesel exhaust particulate aftertreatment' (ART-DEXA), 'Particulate size and composition measurements for diesel exhaust aftertreatment' (PSICO-DEXA), 'System level optimization and control tools for diesel exhaust aftertreatment' (SYLOC-DEXA), and 'Simulation tool for dynamic flow analysis in foam filters' (STYFF-DEXA) **D-ULEV** 'Low CO₂ ULEV diesel passenger cars' (2001–2004); a cluster with two other projects: 'Diesel injection for small engines' (D-ISELE), and 'Advanced diesel cycle development for mid-size engines with high pressure piezo common rail' (D-CYCLE)

ELEGT 'Electrical exhaust gas turbocharger' (2002-2006)

EMING 'Dynamic emission control for NZEV HD CNG engines' (1997–2001)

FUNIT 'Future unit injector technology' (2000-2003)

GADI 'The environmental friendly engine: joint research commitment on gasoline direct injection' (1994–1997)

GET-CO₂ 'Advanced gasoline powertrain for reduced fuel consumption and CO₂ emissions' (2001–2004); a cluster with two other projects: 'Advanced engine cycle development' (GET-ENGINE), and 'Driveability development of downsized, highly turbocharged gasoline engines' (GET-DRIVE)

GREEN 'Green heavy duty engine' (2005-2008)

HEDE 'High fuel-efficient diesel engine with significant increased peak pressure' (1997–2001)

HELIOS 'High Pressure Electronically controlled gas injection for marine two-stroke diesel engines' (2010–2013)

HERCULES 'High efficiency R&D on combustion with ultra low emissions for ships' (2004–2007)

HERCULES-B 'High efficiency R&D on combustion with ultra low emissions for ships — Phase II' (2008–2011)

HY-ICE 'Optimisation of hydrogen powered internal combustion engines' (2004–2007)

IGIS 'Integrated gas injection- and ignition-systems matched to advanced combustion processes for HD NG engines' (1997–2001)

INGAS 'Integrated gas powertrain — Low emissions, CO₂ optimised and efficient CNG engines for passenger cars and LD vehicles' (2008–2011)

IPSY 'Innovative particle trap system for future Diesel combustion concepts' (2007–2009)

LeaNOx Nitrogen oxide removal from Diesel & lean Otto engine exhaust (1992–1995)

LeaNOx II 'LeaNOx development for lean burn cars and diesel trucks' (1996–1998)

LEVEL 'Low emission levels by engine modelling' (2000–2002)

LOTUS 'Low temperature active urea based selective catalytic reduction of NO $_{v}$ ' (2000–2004)

METHACAR 'Methane fuelled ultralow emitting cars' (1994–1997)

NG COMPONENTS & FUELS 'Use of NG in passenger cars-components for bi-fuel vehicles and concepts to handle varying gas compositions' (1997–1999)

NICE 'New integrated combustion system for future passenger car engines' (2004–2007)

NOFISDI 'Novel Concept Fuel Injection Systems for DI diesel Engines for Passenger Cars' (1992–1995)

PAGODE 'Post-treatment for the next generation of diesel engines' (2006–2009)

PICE 'Pump-line-nozzle- based improved combustion for low emissions' (2001–2004)

POSE²IDON 'Power optimised ship for environment with electric innovative designs on board' (2009–2012)

POWERFUL 'Powertrain for future light-duty vehicles' (2010–2013)

PREMTECH 'Advanced propulsion systems and emission reduction technologies' (1997–2001)

PREMTECH II 'Efficient and low emitting propulsion technologies' (2001–2005)

RENEW 'Renewable fuels for advanced powertrain' (2004–2007)

SNR-Technique 'Reduction of NO_x in lean exhaust by selective NO_y-recirculation' (1995–1999)

SORPTEC 'Sorption technique for the removal of NO_x in exhaust gases of heavy-duty vehicles' (1998–2000)

TEFLES 'Technologies and scenarios for low-emissions shipping' (2011–2014)

TRUETEC 'Truck engine technology' (2000-2003)

ULYSSES 'The future propulsion as ONE system' (2006–2013)

VCR 'Variable compression ratio for CO_2 reduction of gasoline engines' (2000–2003)

8B. Appendix – Acronyms and abbreviations

BTL Biomass To Liquid **CA** Coordination Action **CAI** Controlled Auto-Ignition **CI** Compression Ignition **CNG** Compressed Natural Gas **CO** Carbon Monoxide CO, Carbon Dioxide **CPI** Cryogenic Port Injection **CRI** Common Rail Injection **CRT** Continuously Regenerating Soot Trap **CTL** Coal To Liquid **DI** Direct Injection **DME** Dimethyl Ether DOC Diesel Oxidation Catalyst **DPF** Diesel Particulate Filter ECA Emission Control Area **EEV** Environmentally Friendly Vehicle **EGR** Exhaust Gas Recirculation FP3 Third Framework Programme For Research FP4 Fourth Framework Programme For Research FP5 Fifth Framework Programme For Research FP6 Sixth Framework Programme For Research FP7 Seventh Framework Programme For Research FSI Fuel Stratified Injection **GHG** Greenhouse Gas **GTL** Gas To Liquid **GWI** Global Warming Index HC Hydrocarbons HCCI Homogeneous Charge Compression Ignition HD Heavy Duty HTS High-Temperature Superconducting HTS High-Temperature Superconductivity IC Internal Combustion ICE Internal Combustion Engine **IDI** Indirect Injection (Referred To Diesel Engines) **IP** Integrated Project **IRS** Injection Rate Shaping LD Light Duty

LNG Liquefied Natural Gas

MFR Multifunctional Reactor **NA** Naturally Aspirated NO, Nitrogen Oxides NRMM Non-Road Mobile Machinery NSC NO., Storage Catalyst **NVH** Noise, Vibration And Harshness **NZEV** Near-Zero-Emission Vehicle **PEMS** Portable Emissions Measurement Systems **PFI** Port Fuel Injection **PM** Particulate Matter **PN** Particle Number **PMP** Particle Measurement Programme **R&D** Research And Development SCR Selective Catalytic Reduction SI Spark Ignition SNR Selective NO, Recirculation **SO**, Sulphur Dioxide **SO**. Sulphur Oxides **TC** Turbocharged TWC Three-Way Catalyst **UN-ECE GRPE** United Nations – Economic Commission For Europe Working Party For Pollution And Energy VC Variable Compression VCR Variable Compression Ratio **VVA** Variable Valve Actuation WHDC Worldwide Heavy Duty Certification WLTP Worldwide Light-Duty Test Procedure



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European Commission

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Combining efficiency and reliability with sustainability is a major priority of the EU's Transport policy, and when it comes to the internal combustion engine (ICE) the EU has been at the forefront of efforts to clean it up and make it fuel efficient.

As awareness grew of the devastating effects emissions from the transport sector have on the environment, so too did innovation in ICE and power train technologies. 20 years of research, from the Third Framework Programme for Research (FP3) to the Seventh (FP7), have been devoted to helping the EU meet emissions targets, both for noxious substances and greenhouse gases.

Dealing with everything from new exhaust aftertreatment systems for passenger cars to alternative fuels and the challenges surrounding greening heavy commercial vehicles, this brochure provides a detailed overview of this journey and of the various EU-funded projects that continue to contribute to this effort.

Studies and reports



