

# Future Emissions Trends and Technologies to Meet Them

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## ABSTRACT

This paper reviews the current trends in the main drivers for technical change – emissions legislation and CO<sub>2</sub> targets - and discusses technologies and countermeasures for meeting these trends in a cost-effective and profitable strategy.

**Key-words:** Emissions, Powertrain, Aftertreatment, Diesel, CO<sub>2</sub>, Gasoline, Profitability

## INTRODUCTION

At no time, in the approximately 100 year history of the automobile, have so many conflicting constraints been imposed upon engine engineers and planners. Engine technologies must satisfy or respond to many constraints including regulation, consumer demands and competitor offerings. In addition, the advent of new technologies and the enabling of old technologies by modern electronic control systems has created what is often a conflicting plethora of technology options. Selecting engine technologies for light duty vehicles has grown increasingly challenging. The variety of options has never been greater yet conflicting constraints imposed by regulations, competitors, globalization, and consumer preference increase the risk of making the wrong decision. The challenges associated with making technology selections are compounded by the need to reverse shrinking profitability in this business sector.

The development and selection of engine technologies is driven by MegaTrends. These are regulatory, market and business requirements that are undeniable and which are largely out of the direct control of any particular vehicle manufacturer. Figure 1 shows the most compelling MegaTrends that apply to light duty vehicle engines. These are broadly grouped into Environmental, Systems Integration and Product & Business factors. These MegaTrends establish the basic framework against which all products and technology advancements must be judged.



**Fig 1. – MegaTrends which drive product technologies in most global markets**

One of the most influential Megatrends in recent years has been environmental, with successive applications of ever tightening emissions control legislation. Such regulation has dramatically affected all segments of powertrain application, for light to heavy duty and both on and off-highway. It has led to evolution and revolution in powertrain technology that has spun-off other benefits of refinement and performance. It has undeniably quickened the pace of development. This pace of development is not slowing, neither is the trend of tightening emissions control. Emissions of NO<sub>x</sub>, Particulate, HC and CO have received much of the attention, but with rising concerns over Global Warming, CO<sub>2</sub> emission has taken on a more urgent priority.

## EMISSIONS LEGISLATION TRENDS

In all sectors of our industry and in all nations and economic regions, legislation is regulating lower emissions. This regulation is lead by the USA, European Union and Japan. Each region has its own particular history and agenda, based on local

requirements and currently dominant technologies. The USA has very tight light-duty NOx legislation that favours gasoline over diesel. This is due to air-quality problems in cities, such as Los Angeles. In the USA, fuel is relatively low-cost and fuel consumption is not such a major issue with customers. Alternatively, in Europe, where fuel consumption is a big issue, diesel vehicles have been given a NOx derogation to promote their inherently lower CO2 emission. In Japan, LD diesel has never been popular as diesels have always been embarrassingly noisy. This generalized global picture is changing. The world is a smaller place and what effects one person, affects his neighbour. The USA is concerned over fuel consumption and fuel dependency. Europe is concerned over local air quality and diesel particulate. Japan is still concerned about all of this, but now, diesels are quiet – the technology has changed. Changing technology leads to changing consumer patterns, which leads to changing emphasis on regulations.

As part of this global effect, we can observe that some level of emissions harmonisation is a trend. Not only is it clear that emission legislation is harmonized across fuel types (as current in US passenger car legislation), it is becoming more of an objective to harmonise test cycles and limits across nations and regions. The outcome of this is deeply related to the political global situation. In the heavy-duty diesel segment, it may be advantageous to certify a loose engine to a global standard for use anywhere in the world. As developing regions adopt either US or EU legislation, the pressure to harmonise across light duty will only increase. Currently, there is some evidence, shown in Figure 2, to show approximately compatible levels of emissions between the US and the EU.

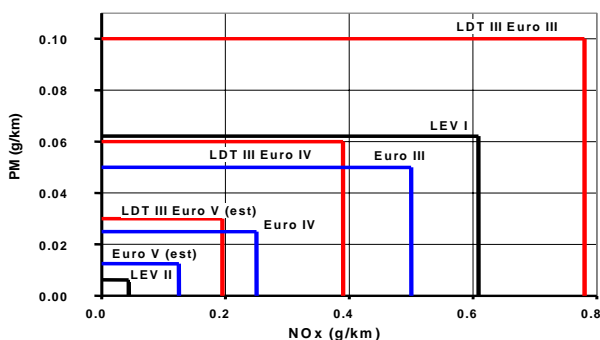


Figure 2 – European and US Emissions Legislation

However, the US still leads the EU in time-based severity. The goal of harmonization should be to drive commonisation of powertrain and vehicle technology for the global market. However, for at least the 2010 horizon, the USA will demand a different technology pack to that of Europe, and harmonization is not likely to progress.

**LIGHT DUTY** - It is clear that the most aggressive limits are those proposed for LEV II in the US. This represents a significant challenge for the diesel engine

but many programmes are underway to address this issue [1]. The US legislation also leads the way with the trend towards additional test cycles to encompass more real-world driving, e.g. US03 and US06 Supplementary FTP cycles.

The trend in emissions legislation has generally been year on year reductions. However, one of the key challenges for limits in discussion for 2008-2010 will be the ability to reliably measure vehicle tailpipe emissions and differentiate from background or ambient levels. Significant work is also underway to characterise particulate size distribution and it is possible that particle size/number may become an important issue [2]. In recent years, the focus has been on optimisation of combustion and aftertreatment systems to reduce NOx and Particulate emissions. However, control of HC and CO emissions to future engineering targets has become a significant issue and will become a key driver in emissions control system design.

For Europe, the major issue of the time is Euro5 – its levels and introductory date. For diesel passenger cars, there have been many discussions and recommendations, ranging from minimal NOx change to continue to promote lower CO2, to gasoline Euro IV equivalence of 0.08 g/km. Particulate regulation may also be set low enough to force the application of diesel particle filters (DPF's) on most, if not all, light duty vehicles.

To reach such low NOx levels with the application of DPF will result in some level of CO2 and cost penalty. It is the responsibility of our industry to quantify these penalties to guide the legislative bodies. Clearly, some balance must be drawn if our global priorities include reduction of Global Warming, air quality and economic growth and stability.

**HEAVY DUTY** – The same trends can be seen with HD legislation. However, there are more obvious moves towards addressing global harmonisation and off-cycle emissions. Europe has adopted a new transient cycle (European transient cycle – ETC), whilst US legislation has adopted element of the existing European steady-state cycle (ESC). In both cases, legislation considers limits over most of the engine operating range, in areas described as the “not-to-exceed” zone. In this off-cycle region, emissions must not exceed a certain factor of legislated emissions. In the case of US FTP, this factor is 1.5 times. This forces the application of emissions control technology over the entire operating range of the engine, regardless of application. Table 1 shows a comparison between US and EU emission legislation.

Date	Cycle	NOx	HC	CO	PM	
<b>Euro 3</b>	<b>2000/1</b>	<b>ESC</b>	<b>5.0</b>	<b>0.66</b>	<b>2.1</b>	<b>0.10</b>
<b>Euro 3</b>	<b>2000/1</b>	<b>ETC</b>	<b>5.0</b>	<b>0.78</b>	<b>5.45</b>	<b>0.16</b>
<b>Euro 4</b>	<b>2005/6</b>	<b>ESC</b>	<b>3.5</b>	<b>0.46</b>	<b>1.5</b>	<b>0.02</b>
<b>Euro 4</b>	<b>2005/6</b>	<b>ETC</b>	<b>3.5</b>	<b>0.55</b>	<b>4.0</b>	<b>0.03</b>
<b>Euro 5</b>	<b>2008</b>	<b>ESC</b>	<b>2.0</b>	<b>0.46</b>	<b>1.5</b>	<b>0.02</b>
<b>Euro 5</b>	<b>2008</b>	<b>ETC</b>	<b>2.0</b>	<b>0.55</b>	<b>4.0</b>	<b>0.03</b>
<b>Euro 6?</b>	<b>2010-2013</b>	<b>ETC</b>	<b>1.0</b>			<b>0.02</b>
Highest probability option						

Date	Cycle	NOx	HC	CO	Pm
-----[g/bhp.h]-----					
<b>1998</b>	<b>FTP-Trans</b>	<b>4.0</b>	<b>1.3</b>	<b>15.5</b>	<b>0.10</b>
buses:0.05					
<b>2002/4</b>	<b>FTP-Trans</b>	<b>2.5 (NOx +NMHC)</b>		<b>15.5</b>	<b>0.10</b>
plus: SET<1*FTP limits & NTE<1.25*FTP buses:0.05					
<b>2007</b>	<b>FTP-Trans</b>	<b>0.2</b>	<b>0.14(NMHC)</b>	-	<b>0.01</b>
(50% of fleet)					
<b>2010</b>	<b>FTP-Trans</b>	<b>0.2</b>	<b>0.14(NMHC)</b>	-	<b>0.01</b>
(100% of fleet)					
plus: SET<1*FTP limits & NTE<1.50*FTP					
<b>FTP-Transient Test:</b> 1200s mixed speed and load test, including motoring.					
<b>SET:</b> "Supplementary Emissions Test"- 13-mode steady-state test					
<b>NTE:</b> "Not To Exceed" Zones, where emissions can be checked for compliance					

Table 1 – Summary of US and EU HDD legislation

In all cases, the low levels of NOx expected from future legislation will call for highly developed combustion systems and possible sophisticated NOx exhaust aftertreatment systems. The legislated PM levels expected will promote, if not mandate, the universal application of DPF technology on all diesels. As the diesel PM legislation will most likely be less than 0.01g/km, new measurement technologies must be adopted to consider particle number density and sizing. The remainder of this paper considers the emissions trade-off situation with CO<sub>2</sub> and the technological solutions to meet these trends.

## CO<sub>2</sub> SITUATION AND TRENDS

Oil is the major source of world-wide energy supply and as a consequence the primary source of fossil based carbon dioxide. As a general rule, combustion of 1 litre of gasoline will produce 2.4 kg of carbon dioxide. Transport in general produces about 20% [2] of overall man-made carbon dioxide. In response to the Kyoto protocol, the EU has negotiated an agreement with the vehicle manufacturers that supply to the European market to reduce fleet average fuel consumption to 140 g/km by 2008 based on the New European Drive Cycle (NEDC) [4]. Further reductions are being discussed for 2012. Government funded studies and reports have also set future targets (Figure 3) [5]:

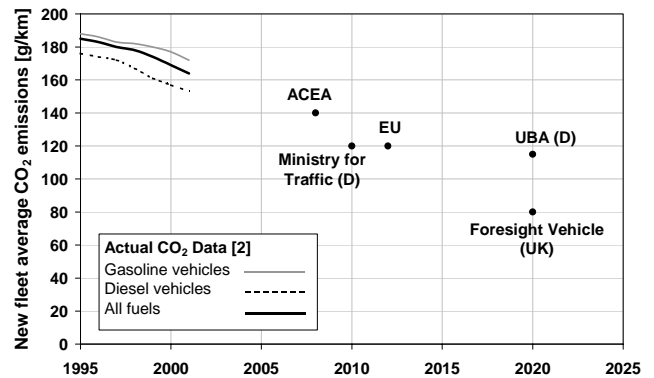


Figure 3 - Fleet Average CO<sub>2</sub> emissions and Proposed Future Targets

Currently these targets are not legislated by the EU. The US has the Corporate Average Fuel Economy (CAFE) system, which is a more formal corporate control. However, the significant achievements in Europe have not required legislation of any kind.

Fleet Fuel consumption and CO<sub>2</sub> targets are mainly applied to light duty vehicles as fuel consumption is seen as one of the major priorities of the heavy duty sector and needs no other external pressures to minimize it. Fuel consumption translates directly into fleet running cost that is first and foremost in the minds of HD fleet operators. An obvious consequence of this is that ~100% of the HD fleet is direct injection diesel. Further to this, it will be the demands of fuel consumption that will ultimately decide on the HD technology pack to meet future emissions.

Thermodynamically, there is a direct trade-off between fast and hot efficient combustion (low CO<sub>2</sub>) and low NOx emissions resulting from slower, cooler combustion. Therefore, the technologies targeted at lowering NOx will undoubtedly have a negative (or at best, neutral) effect on CO<sub>2</sub> (or vice-versa). Good examples of this are injection timing retard for diesel and direct injection technology for gasoline. Due to this trade-off situation, other aspects of development must be considered to minimize CO<sub>2</sub>, whilst reducing NOx. Such approaches aim at reducing parasitic losses, such as compression ratio reduction and downsizing.

The further trends of reducing CO<sub>2</sub> emission will drive technology further away from hydrocarbon fuels, towards the "Hydrogen Economy". However, the use of hydrogen for CO<sub>2</sub> reduction must be considered on a "well-to-wheels" basis, as all forms of H<sub>2</sub> production require energy. If this energy generates CO<sub>2</sub>, then there is limited benefit to Global Warming reduction.

Hydrogen has been promoted as an attractive future automotive fuel for a number of reasons. It does not

release any carbon when consumed, exhibits a wide flammability limit for use in combustion engines and is also compatible with fuel cells. However, unlike oil based or bio fuels, hydrogen is not a primary energy source but an energy carrier. Although it is the most widespread element in the universe, free hydrogen does not occur in nature. It needs to be “extracted” from compounds such as hydrocarbons and of course water, and requires an energy input. Unless produced from renewable energy sources, this results in CO<sub>2</sub> emissions depending on the source of that energy and the efficiencies of the conversion process.

Assuming that energy will always be an expensive commodity, particularly any renewable supplies, energy conversion and transmission efficiencies will also be maximized. It is likely that the majority of renewable energy will be in the form of electricity produced by wind, wave, hydro, photovoltaic or even nuclear generators. The most efficient way to distribute this power is via AC power lines at high voltage to minimize losses, often less than 10% overall. If this electricity is converted directly to hydrogen, efficiencies of around 50% at best are likely and a significant proportion of our expensive renewable energy will have been lost. If this hydrogen is then used in a fuel cell vehicle with 50% overall efficiency, about 75% of the original renewable energy will have been lost from the effective “well” to wheels [6].

## DIESEL TECHNOLOGY

Fundamentally, most of the future technology for diesel emissions reduction is applicable to both light and heavy-duty applications. Low NO<sub>x</sub> requires cooler, slower combustion [7] and lower PM emissions benefit from higher injection energy and improved atomization. The application of exhaust gas recirculation (EGR) to reduce NO<sub>x</sub> has been applied to LD and HD engines. Key enablers for this are advanced fuel injection equipment, air handling systems and improved electronic control systems. Aftertreatment systems are also fundamentally common, with applications of oxidation catalyst and DPF already appearing on both LD and HD applications [8][9]. Advanced NO<sub>x</sub> after-treatment, such as lean-NO<sub>x</sub> traps (LNT) (or NO<sub>x</sub> storage catalyst) and UREA SCR has also been applied to both LD and HD applications.

**LIGHT DUTY** - Major international research programmes are underway to lower NO<sub>x</sub> emissions. In this respect a variety of calibration strategies, alternative fuels and advanced combustion concepts have been proposed for compression ignition engines [10]. Fundamental to these strategies is the objective of increasing pre-mixed combustion and reducing combustion temperatures. Such strategies have been shown to lower both NO<sub>x</sub> and soot emissions but are

limited to light load operation. Furthermore, the operation is challenged by excessive products of incomplete combustion (HC and CO).

Many researchers have proposed early injection strategies but such an approach is greatly limited by fuel impingement on the cylinder wall and a resulting increase in fuel-in-oil dilution. However, Kimura et al. [7] have demonstrated the benefits of injecting the fuel during the ignition delay period and applying Exhaust Gas Recirculation (EGR). The operating range of this strategy was enhanced by promoting increased ignition delay and mixing characteristics and presents the most practical approach to reducing NO<sub>x</sub> emissions. Figure 4 shows an example of single cylinder engine results compared to a baseline engine that achieves Euro 4 emissions legislation.

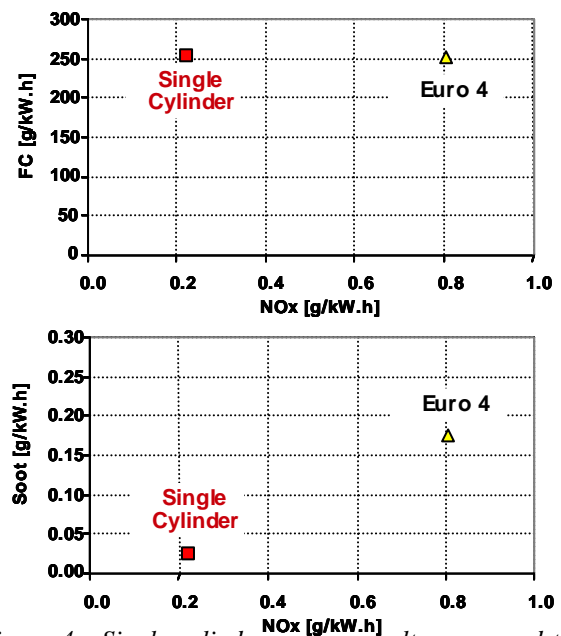


Figure 4 - Single cylinder engine results compared to Euro 4 baseline engine at 1500 rev/min, 6.3 bar IMEP.

To achieve such low NO<sub>x</sub> and soot emissions requires a combination of combustion system design, air/EGR system and calibration modifications. In particular the reduction of compression ratio enables reduced compression pressure, compression temperature and increased ignition delay. Through the application of high rates of EGR and reduced air/fuel ratio, NO<sub>x</sub> emissions can be significantly suppressed. Although such results can be demonstrated on single cylinder engines, the critical challenge is to deliver driveable vehicles.

Legislative demands will therefore force a trend towards increasingly pre-mixed and reduced temperature combustion. This has been described as “alternative combustion” but it is the authors’ opinion that there is a progressive roadmap of technologies which will enable this trend. Ricardo have termed this roadmap “ACTION” - Advanced Combustion

Technology for Improved engine-out NO<sub>x</sub> [11]. An integrated approach is recommended which combines air/EGR, cooling, fuel injection and control system developments. Such an approach enables increased control of combustion whilst minimising the cost of meeting legislative demands. The ACTION roadmap produces a synergistic effect, resulting in reduced emissions and high performance engine output at moderate peak cylinder pressure levels. The overview of ACTION is shown in Figure 5 below:

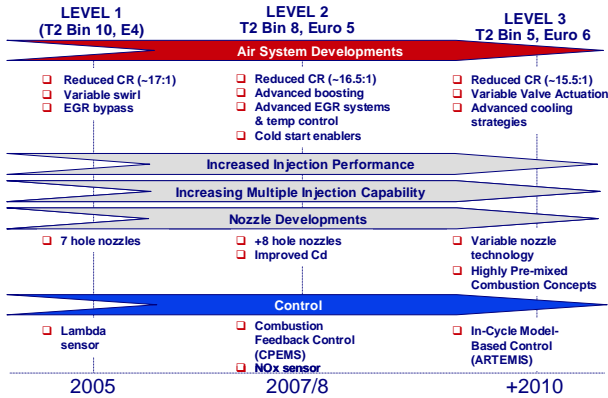


Figure 5 – ACTION technology roadmap

The development of the levels of ACTION is an on-going research commitment. Recently, Level 1 ACTION has been demonstrated on many passenger car programs (Figure 6). This early demonstration of relays on close attention paid to development of the combustion system [12], which tolerated increased levels of cooler EGR. Engine-out levels of ~0.08 g/km NO<sub>x</sub> were demonstrated. Particulate emissions were controlled with a catalyst-coated DPF (CDPF). This early demonstration resulted in a significant fuel consumption penalty c.f. Euro III baseline. This penalty was attributed equally to the combustion system and DPF pressure drop. At this time, this demonstration is not compatible with production requirements as it was based on a very precise calibration that could not be realized without developments in adaptive control systems, discussed later in this paper. Current developments of ACTION, using more advanced FIE, EGR and control systems are exhibiting lower engine-out NO<sub>x</sub> without a measurable detriment in fuel consumption.

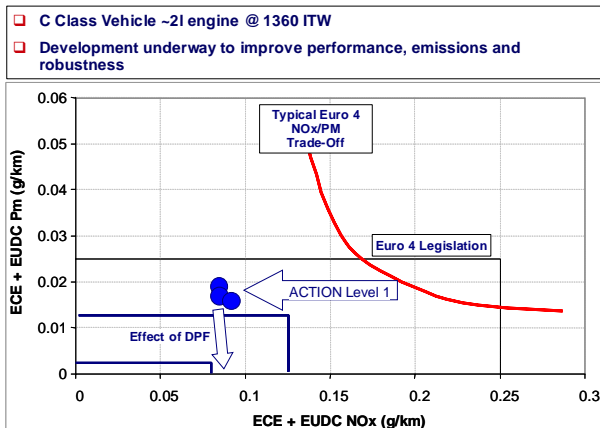


Figure 6 – ACTION Level 1 vehicle demonstration

The ACTION approach has demonstrated significant success in the reduction of engine-out and tail-pipe emissions. Continued development of this system-approach with state-of-the-art FIE and air-handling systems will provide the most cost-effective solution to meeting future LDD emissions. ACTION avoids the use of expensive aftertreatment systems for Euro 5 and beyond. Where NO<sub>x</sub> aftertreatment is seen as inevitable for US Tier II / US06 compliance, ACTION minimizes the engine-out emissions to levels that will facilitate service-fill UREA SCR. Figure 7 shows the cost-benefit analysis of the ACTION system.

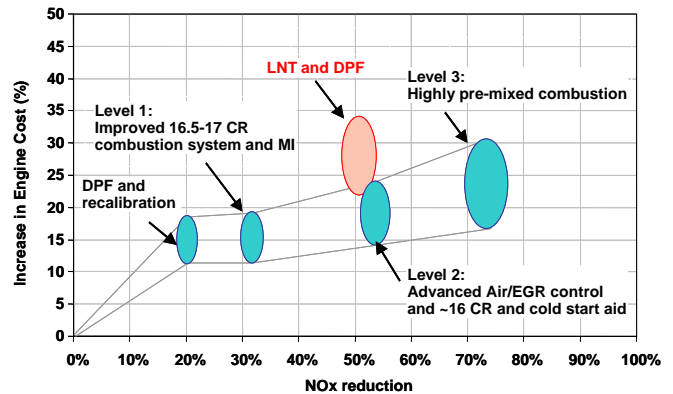


Figure 7 - Predicted Cost/benefit for ACTION technology

Development of the ACTION combustion system [11] on single and multi-cylinder engines has generated emissions feed-gas maps suitable for vehicle simulation and aftertreatment system specification. Figure 8 shows engine feed-gas maps for the combustion system scenario of 2010. Advanced achievement of such maps can be used to provide early definition of powertrain functional specification and selection of aftertreatment system. Using such feed-gas maps, aftertreatment application can be simulated to investigate total cost-benefit and ultimate development risk.

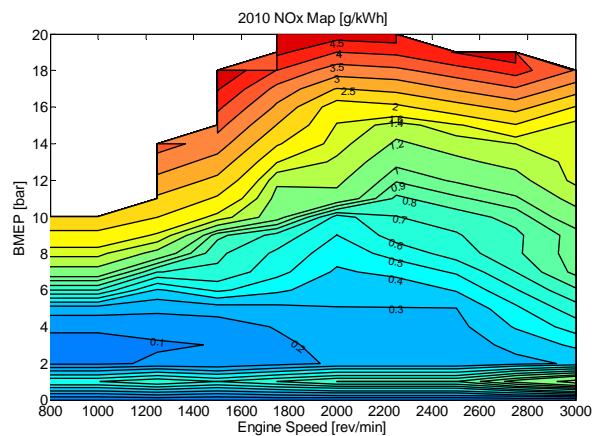


Figure 8 – 2010 NOx feed gas map measured from single- and multi-cylinder engine tests

Given low NOx feed-gas, the UREA SCR system may provide the optimum cost/risk solution for this emissions scenario.

Demonstrating low NOx combustion systems is interesting and helps the engineering community move forward. However, putting a low NOx combustion system into production is a completely new and severely challenging task. The enabling technology for this is control. Current production conformity issues and observed emissions durability will not be acceptable for the 2010 situation in Europe or the US. The level of variation acceptable at Euro 5 or Tier II will be beyond cost-effective production methods. To enable the mass-production of low NOx systems, the control system must be intelligent, predictive and adaptive. As well as controlling the effects of hardware tolerances, the low NOx combustion system itself will require adaptive feedback control to maintain a balanced operation at optimum settings during cooler, more pre-mixed combustion regimes. All this leads to a requirement for a model-based, feedback-controlled system. Critical enablers for this are the application of new sensor technology, and model based control strategies. This includes lambda and cylinder pressure sensors. In this regard, Ricardo is developing CPEMS (Cylinder Pressure based Engine Management Systems). This has been previously demonstrated on the part EC-funded AENEAS Project involving Ricardo, DaimlerChrysler and Kistler [13]. Ricardo is applying such an approach to diesel engines and results will be shown in subsequent papers.

HEAVY DUTY – Heavy duty technology has been developing along the same philosophy of minimizing engine-out emissions for the most cost effective solution. However, this approach will be compromised at Euro IV and beyond (and US 2007+) due to the requirement of NOx. Low NOx emission has caused a polarization of approaches. The engine-out approach has followed the LD technology path of application of EGR. Initially, this appears the favourable route. ER is self-contained and provides an effective NOx control at source, which must be the best way. However, the situation is significantly difference on the HD cycle. To control NOx, EGR must be present at full load. This is very rarely the case in LD applications where EGR is definitely a part-load phenomena. To drive EGR from the exhaust manifold to the inlet required a positive pressure gradient. This reverses decades of careful development of HD turbo-charging, which strove to gain as much net work from the turbocharger as possible. Remember that fuel consumption is everything to the HD fleet operator. EGR reduces the turbocharger efficiency dramatically. Additionally, as EGR displaces fresh air charge, the air-fuel ration inevitably reduces. This effect is tolerated at part load

conditions that otherwise run at highly excess air conditions. However, at full load, the luxury of excess air is not present. Air-fuel ratio must be maintained to avoid the inevitable increase in soot and particulate emission. To achieve this, the boost pressure ratio must increase with EGR applications. Therefore, with EGR applications the turbocharger takes more energy and does not give it back, as in a conventional HD turbocharged application. Table 2 below shows some comparative boost pressure ratio requirements.

HD Boost Pressure Ratio	Peak Torque	Rated
Non EGR Engines - average rating	2.9	3.2
Non EGR Engines - high rating	3.1	3.5
15% EGR	3.2	3.5
20% EGR	4.1	4.3
20% EGR + Improved performance	4.8	5.0
SCR - current performance	3.2	3.5
SCR + High performance	4.8	5

Note: MD ~ 0.2 PR lower

Table 2 – Boost pressure ratio requirements for HD engines

The application of EGR leads to a fuel consumption penalty. The other route to low NOx is SCR. The injection of urea is not a new technology and has been demonstrated commercially on HD truck applications. Infact, many OEMs have stated publicly that this is their intended route to Euro IV. Although SCR is an exhaust aftertreatment system, it has demonstrated good durability and it has possibly the best NOx conversion potential. With the application of SCR there is an opportunity to actually improve fuel consumption by advancing injection timing, as NOx can be controlled adequately by SCR alone. In practice, this may be limited as most engines have injection retard to limit maximum cylinder pressures at full load. However, SCR should be a neutral fuel consumption option at worst. Figure 9 shows the technical approach to US07, showing the technology required for NOx/PM compliance with the associated fuel consumption penalty.

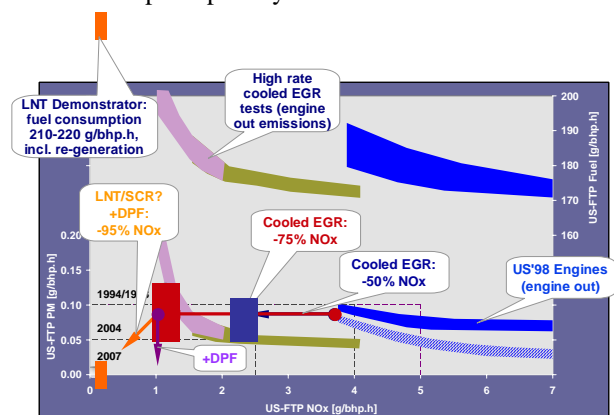


Figure 10 – Technical approach to US 2007

For the US, there is currently resistance from the EPA to clear the way for urea SCR. Therefore the technical approach favoured in the US is EGR and DPF.

Figure 10 shows the technical approach to Euro 5, where SCR is fully accepted as a primary route to emissions compliance with little or no fuel consumption penalty.

NO<sub>x</sub> reduction via LNT systems for US 2007 has been demonstrated [14] but with unacceptable fuel consumption penalty (Figure 11), caused by the necessity of regeneration. Additionally, the volume of LNT required for this demonstration would not suggest an economically viable solution with the present level of LNT technology.

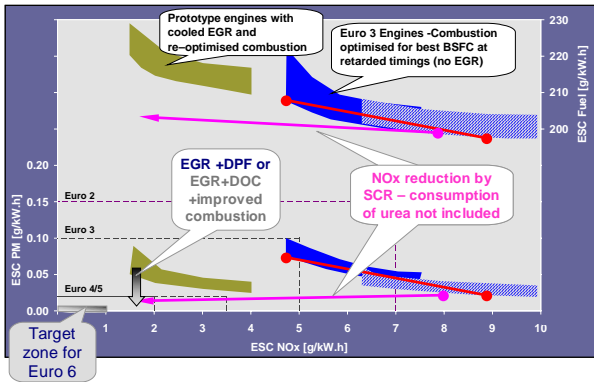


Figure 10 – Technical approach to Euro 5/6

DPF technologies have been successfully applied to HD applications. With SCR it is feasible to reach Euro 4 and interim US 2007 without DPF. However, as with expected LD Euro 5, the HD emissions levels of Euro 5 and US 2007+ will be such that forces the use of DPF. Catalysed DPF systems are favoured, as within the LD application. As an interim measure, some HD applications will use a “through-flow” catalysed DPF which is, effectively, a PM reducing oxidation catalyst.

**FUEL INJECTION EQUIPMENT** – Injection pressure is rising, as is speed of injector response and number of injections per cycle. Common rail (CR) systems are leading this flexibility with adoption of piezo technology. However, as injection pressure requirements rise above 2000bar (especially for HD application), the pressure capability of the electronic unit injector (EUI) is more attractive. Particularly in HD applications, there is still much debate over the superiority of CR versus EUI. The answer to this is that both systems are adopting the strengths of their opponents and soon both systems will be much alike in capability. EUI is adopting advanced switching and accumulator technology (Delphi E3 system) [15] which is enabling CR-like flexibility. Conversely, common rail systems are adopting intensifier systems capable of delivering 2500bar with the same flexibility as today’s advanced CR systems.

Ricardo has demonstrated that LD CR pressure requirements are unlikely to rise above 2000bar before

2010. More important to future emissions compliance is control of variability and in-life durability and adaptability to system aging.

## TECHNOLOGY FOR LD CO<sub>2</sub> REDUCTION

**CONVENTIONAL POWERTRAIN** - Conventional vehicles have achieved dramatic improvements in performance, emissions and fuel economy in recent years. Analysis of comparative vehicles over time has shown that newer products offer lower CO<sub>2</sub> emissions due to better detail design – a wide variety of factors including aerodynamics, friction, powertrain warm-up time and precision control. The underlying averaged trend is around 0.6% reduction per year due to continuous improvements by the automotive engineering community [4]. However, the ACEA agreement is based on improvements of approximately 2% per year. Vehicle fuel economy can be improved through improved aerodynamics and reduced rolling friction but the two main areas delivering most benefits are weight reduction and improved powertrain efficiency. In general, a 10% reduction in vehicle weight will deliver a 5% improvement in drive cycle economy. However, the demand for improved crash protection and feature content makes weight reduction and expensive route to improve fuel economy on its own. The most cost effective route to improved economy lies with the powertrain. The key areas for future fuel economy improvements in conventional powertrains are:

- Reductions in friction or internal losses
- Improvements in combustion efficiency
- Reductions in pumping losses or gas exchange
- Flexible efficient transmissions to operate the engine in more efficient areas

Reductions in friction or internal losses can be achieved through attention to detail in the design process and through “downsizing”. Improvements in specific power (power per unit displacement) have provided significant opportunities to maintain or even increase the absolute power of a conventional engine whilst reducing the swept volume of the engine and delivering lower friction through reduced piston and bearing areas. Downsizing has emerged as a key technology to improve fuel economy for both gasoline and diesel engines.

Improvements in combustion efficiency can be achieved through burning fuel in the engine at both optimum timing to produce the most work and at an air to fuel ratio that delivers maximum heat release without excessive combustion periods. In general, it is also desirable to operate at the highest useful compression ratio although it is difficult to obtain any real benefits in net fuel consumption beyond a fixed ratio of around 15:1. Many attempts have been made to design engines with variable compression ratio,

providing the opportunity to operate at part load with high ratios and at low ratios at full load. This approach can provide fuel economy benefits but it is difficult to realise in a cost effective robust package.

Much attention has been focused on reduction of pumping losses in gasoline engines in recent years. The move towards direct fuel injection systems has enabled operation with stratified charge and reduced the need to throttle the intake system to control load. Such engines show of the order of 15% reduction in part load fuel consumption. However, the need to provide good transient response and to control emissions has limited the overall drive cycle benefit to typically less than 10%. Variable valve actuation systems have also been developed to adapt gas exchange processes to the load demanded by the driver. Fully variable inlet valve actuation systems have also demonstrated benefits of up to 10% in drive cycle economy.

The majority of passenger car transmissions in Europe are manual systems. Automatic systems are generally an expensive option in all but premium vehicles and usually offer a deterioration in fuel economy. Automatic gear selection can improve fuel economy by allowing the engine to operate closer to optimum efficiency, which occurs typically at lower speeds and higher loads than a driver will select. However, higher engine efficiency is then generally offset by the relatively poor mechanical efficiency of conventional automated transmissions. Automated manual transmissions (auto change but with the efficiency of a manual) have been introduced in some classes of vehicle and fuel economy gains of 5-10% have been observed. This type of transmission introduces torque interruptions during gear changes and is therefore suited to vehicles with low power to weight ratio. More widespread introductions will be limited by the perceived driveability drawbacks. However, second generation automated powershift transmissions are being developed in a number of applications that can offer real benefits to the consumer in terms of good driveability with improved fuel economy.

In summary, some of the key powertrain fuel economy technologies and estimated benefits are listed in Table 3:

Characteristic	Technology/Solution	Potential Benefit (part load improvement)
Open cycle pumping loss	Wide range VVT	8%
	Direct Injection Stratified Charge	10-12%
	Cylinder Disablement	5-10%
Mechanical Loss	Downsized - Boosted	10-15%
	Fewer Cylinders (4 to 3)	3%
	Lower Speed (6000 to 4000)	3-5%
	Lower Cylinder Pressures (VCR)	3-5%
Combustion Efficiency	Higher Compression Ratio	2-3% per ratio
	Lean Burn	2%
	Combustion Period from 40° to 30° Cr	1%
Transmission	Automated Manual (torque interrupt)	c.f. manual 5-10%
	Dual Clutch Automated Manual	c.f. manual 4-8%

Table 3: Potential fuel economy benefits

Each of these potential benefits applies to the technology applied on its own. Many of the technologies or solutions overlap such that combining two technologies may result in substitutional and not additional benefits. The key to successful system engineering is to identify combinations of technologies that provide incremental benefits in the most cost-effective package.

The maximum thermal efficiencies of either gasoline or diesel engines is seldom more than 40% and on average considerably less than this. Around 1/3 of the fuel heat energy supplied to the engine will end up as exhaust heat at relatively high temperatures. As yet, it has proved very difficult to recover any of this energy in a practical operating system for a passenger car. However, research continues and the most likely solution is for direct electrical power using some form of semiconductor materials. Progress in recovering some of this energy will almost certainly extend the life of the combustion engine in relation to the alternatives.

**HYBRID SYSTEMS** - Hybrid systems are attractive in that it is possible to size the combustion engine closer to average power demand rather than peak power demand. As an example, with an aggressive driving style, a 1500 kg vehicle will require up to 100 kW to follow the US FTP drive cycle. However, the average power requirement is around 20 kW. If all of the energy generated during braking was recovered and then re-used during accelerations, the average power would drop to 4 kW. For a hybrid configuration, the vehicle could be fitted with a 50 kW combustion engine and a 50 kW electric motor. The combustion engine would be capable of meeting torque demand most of the time but with the electric motor available for peak loads. The motor will also provide a capability to recover braking energy.

Although there are now a number of battery electric hybrid vehicles on sale, these are relatively expensive to produce and will be limited to niche markets. Sales of the Toyota Prius have now reached 147,000 units worldwide [16] but this must be seen in context with the global market for light duty vehicles of about 50m units. For hybrid technology to make an impact on fleet average fuel economy, hybrid technology will need to be introduced to the mass market. This can only be achieved if the technology is cost effective. The weakest link in hybrid technology is almost certainly battery technology due to cost, life and technical limitations. Based on the incremental costs involved and the need to further develop energy storage and control systems, Ricardo believes that an evolutionary approach to the introduction of Hybrids is the most logical approach, introducing simple belt driven starter/alternators and lead acid batteries to existing engine architectures to provide start/stop function (Figure 11), extending to regenerative braking and torque assist as the technology develops into

practical and durable components. This approach would allow incremental increases in component volumes to deliver more acceptable unit costs [5].

- ❑ Stop/start, regenerative braking and potential for torque assist
- ❑ Belt driven 42V Integrated Starter Generator
- ❑ Gates Electro-Mechanical Drive (hydraulic tensioner system)
- ❑ Battery: 36V advanced lead acid
- ❑ DC-DC voltage converter



Figure 11: HyTrans – Mild hybrid light commercial vehicle

An interesting technology combination identified by Ricardo was downsizing with electrical assistance to enhance low speed torque (Figure 12). This was combined with the use of regenerative braking energy to power the vehicle ancillary systems. This system, defined as i-MoGen [17] consisted of a very highly rated 1.2 litre diesel engine with a rated power output of 74kW (100hp). The high rating allowed the engine to achieve good acceleration and top speed but the uprated boost system provided insufficient torque at engine speeds between 1,000 and 2,000 rpm. To overcome this issue, a 6 kW integrated motor/generator was coupled to the powertrain between the engine and the transmission. This added sufficient torque in this speed range to significantly improve low speed performance feel. At engine speeds above 2,000rpm, electrical assistance is no longer required which minimises the size of the motor and battery and minimises the power electronics specifications and costs, keeping the premium low enough to provide an attractive cost to benefit ratio in terms of fuel economy improvements. The vehicle was also fitted with intelligently controlled ancillaries such as the water pump, vacuum pump and air conditioning systems. These were coupled to a supervisor controller with a novel energy optimisation approach. The i-MoGen emissions control system included electrically assisted diesel particulate filter (DPF) regeneration and a passive de-NOx catalyst, so reducing the tail pipe emissions, potentially, to half of the Euro 4 diesel limits. The vehicle achieved a 28% reduction in drive cycle fuel consumption compared with a conventional diesel variant with equal performance. Over 2/3 of this fuel economy benefit was attributable to the downsized engine alone.

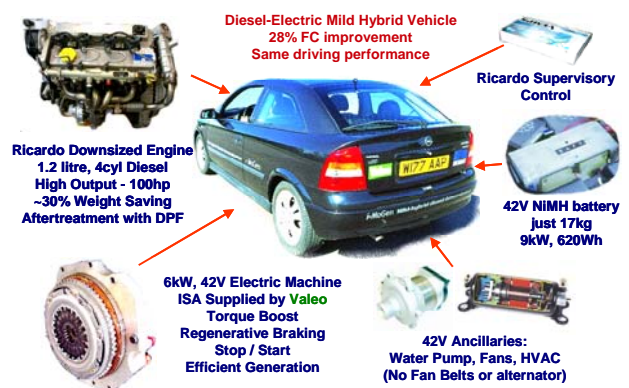


Figure 12: Ricardo i-MoGen Mild Hybrid Diesel Vehicle

## GASOLINE TECHNOLOGY FOR CO<sub>2</sub> REDUCTION

Lean Boost Direct Injection - In 1998, a concept analysis study at Ricardo designed to identify and rank technology combinations with maximum benefits and low risk identified the Lean Boost Direct Injection Engine as a potential future system. LBDI features a combination of downsizing, direct injection and lean operation throughout the operating envelope to deliver fuel economy improvements (Figure 13) [18]. The combination of direct injection and lean operation reduces full-load octane requirement, allowing operation at around 2 ratios higher than for a turbocharged port injected gasoline engine. LBDI requires no overfuelling for component and catalyst protection at full load. This enables excellent high load and motorway fuel economy whilst the exhaust temperatures are compatible with a diesel type variable nozzle turbocharger, providing a more flexible boost response and improved low speed torque. The lean exhaust conditions require a lean NOx trap for NOx control although engine out NOx emissions are relatively low due to homogeneous lean combustion. The engine operates with the combustion characteristics and speed range of a gasoline engine but the gaseous exhaust temperatures and characteristics of a diesel. Ricardo has built a vehicle demonstrator based on a 1.1 litre turbocharged direct injection with comparable performance and acceleration to a 1.6 litre naturally aspirated gasoline variant. However, the LBDI system delivers a 22% improvement in measured fuel economy.



Figure 13 - Ricardo Lean Boost Direct Injection Gasoline Vehicle

**Stroke/4 Stroke Switching Engine** - Following a similar theme of downsizing and boosting, another technology combination to provide a highly rated engine with excellent performance feel and driveability is to combine direct injection, turbocharging and supercharging with a switch from four stroke to two stroke operation to deliver higher torque when required. The primary advantage of two stroke operation at full load is to deliver higher specific torque without increasing peak in-cylinder pressures and adding to engine weight. This system is shown in Figure 14 and requires a flexible valve train and boosting system together with a combustion system capable of competitive operation in either two stroke or four stroke modes.

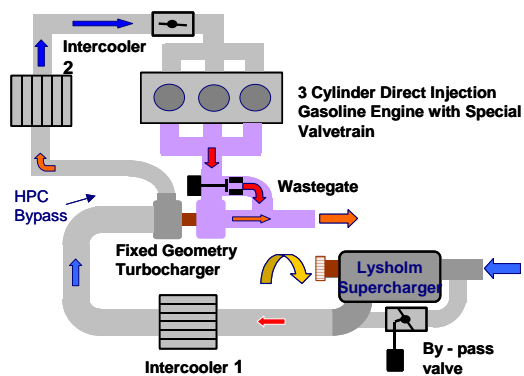


Figure 14: Ricardo 2/4 Stroke Switching Configuration

Work to develop this combustion system has been successfully completed at Ricardo whilst the focus is now on developing transient switching strategies to provide seamless changes from 2 to 4 stroke operation. This involves integration of both valve train and boost systems. Torque levels of 220 Nm/litre displacement have been achieved to-date in two stroke mode (Figure

15). Current estimates predict fuel economy benefits for this concept of around 25% compared with a conventional gasoline engine.



Figure 15 - Ricardo 2/4 Stroke Torque Characteristics

**FUEL CELL VEHICLE EFFICIENCY** - Fuel economy data for Fuel Cell vehicles is generally in short supply given that there are very few vehicles in existence and that when operating on Hydrogen, consumption must be re-calculated for comparison with gasoline or diesel fuelled vehicles. However, both Ford [19] and Toyota [16] have published data indicating that we should not assume that fuel cell vehicles will be more efficient than conventional IC engine hybrid systems (Figure 16). It is inevitable that Fuel Cell vehicle efficiency will improve but we must also compare this against the inevitable improvements that will be obtained with internal combustion engines and their hybrid configurations.

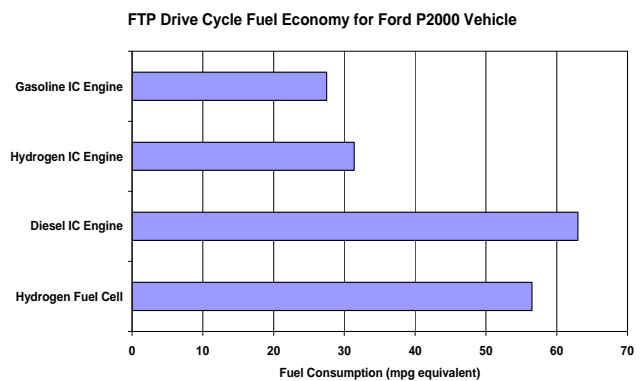


Figure 16 – FTP “Well-to-wheels” fuel consumption

Ricardo has recently carried out a study for the UK Department for Transport and Department of Trade and Industry, in which two step-wise technology routes from Carbon to Hydrogen based transport were studied in terms of their benefits, risks and likely on-sale costs [5]. This study compared two paths to the widespread use of Hydrogen for automotive use, a “revolutionary” fast transition and a more “evolutionary” approach taking smaller incremental steps in a logical sequence.

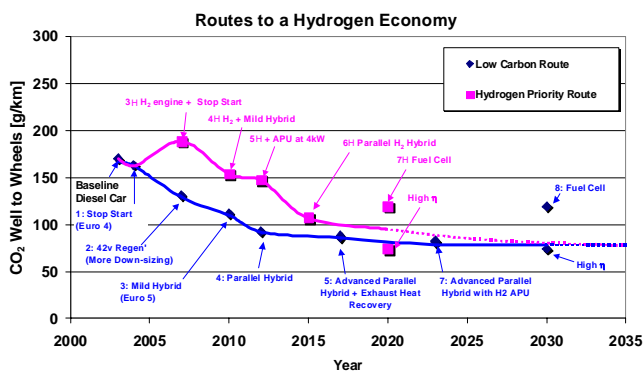


Figure 17 – Low Carbon v Hydrogen Priority Roadmap

The revolutionary approach:

- Requires renewable-derived Hydrogen to be quickly available; Hydrogen from fossil fuels would be required in the short to medium term
- Would make CO<sub>2</sub> emission worse during transition
- Represents exceptionally high investment risk and technical/commercial hurdles

The evolutionary approach:

- Represents a slower transition to Hydrogen or other zero CO<sub>2</sub> infrastructure
- Is Initially based on reduction of fossil fuel consumption, partial use of compatible renewable/alternative liquid fuels
- Offers a risk-managed transition for vehicle platforms, manufacturing, servicing & fuelling infrastructure
- Series of smaller (but very significant) technical / commercial hurdles, overcome via research initiatives & tax incentives

A comparison between the two routes in terms of CO<sub>2</sub> emissions are shown in Figure 17:

## CONCLUSIONS

There are many conclusions to be drawn from such a discussion paper. Firstly, the main conclusion is that there are technologies and countermeasures that will enable compliance to the toughest future emissions regulations. The caveat to this is that the technology package must be cost-effective and profitable. LD diesel is perhaps the most threatened area from future legislation. Ricardo has developed the ACTION approach for LD Diesel, demonstrating a cost-effective and a robust solution to foreseeable emissions legislation.

In all aspects of emissions reduction from 2005 onwards, the engine management system must take on a more adaptive function, which will not only enable control of advanced combustion mechanisms but will ensure manufacturing CoP and emissions lifetime durability.

Going forward to 2010, all diesel engines will probably require DPF aftertreatment. Where NO<sub>x</sub> aftertreatment is inevitable, in post 2010 US LD scenarios or HD applications, SCR appears to currently offer the best solution considering total cost and risk. However, for light duty, the SCR application is contingent on very low engine-out NO<sub>x</sub> levels.

CO<sub>2</sub> reduction will continue to rely heavily on application of conventional diesel powertrain. Downsizing will be the main area of diesel change for lower CO<sub>2</sub>. The main technological changes for CO<sub>2</sub> reduction will be seen in gasoline engine technology, hybridization and a slow evolution toward the hydrogen-powered fuel cell. However, when taken on a “well-to-wheels” basis, none of these technologies are superior to the direct injection diesel engine, which is here to stay, for at least three decades.

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## REFERENCES

1. “Ways to meet Future Emissions Standards with Diesel Engine Powered Sport Utility Vehicles (SUV)”, P. Zelenka, M. Egert, W. Cartellieri, AVL List GmbH, SAE 2000-01-0181
2. “ACEA Programme On Emissions Of Fine Particles From Passenger Cars”, ACEA Website, Dec 1999
3. Douaud, André, “Potential of Alternative Fuel Options, GHG performances and economics”, Surface Transport Technologies for Sustainable Development, Valencia, Spain, June 2002
4. Hodac, I (ACEA), Day, C (EC DG Environment) and Mingasson, J-P (EC DG Enterprise): “Monitoring of ACEA’s Commitment on CO<sub>2</sub> Emission Reduction from Passenger Cars (2001) - Final Report, 25 June 2002”
5. Gordon R.L., Owen N.J., and Greenwood D.G. "Carbon to Hydrogen" Roadmaps For Passenger Cars: Study for the Department for Transport and the Department of Trade and Industry, PPAD 9/107/19, Ricardo RD02/3280 (www.roads.dft.gov.uk/cv/power ), 2002
6. Bossel, Ulf., “We Need a Renewable Energy Economy, Not a Hydrogen Economy” The Hydrogen & Fuel Cell Letter Sept 2003

7. KIMURA, S.; AOKI, O.; KITAHARA, Y.; AIJOSHIZAWA, E. "Ultra-clean Combustion Technology Combining a Low-Temperature and Premixed Combustion Concept for Meeting Future Emission Standards", SAE paper 2001-01-0200
8. "An Integrated SCR and Continuously Regenerative Trap System to Meet Future NOx and Pm Legislation", A. Walker, G. Chandler, B. Cooper, J. Harris, J. Thoss, J. Warren, A. Uusimaki, Johnson Matthey plc, SAE 2000-01-0188
9. "Passenger Car Serial Application of a Particulate Filter System on a Common Rail Direct Injection Diesel Engine", O. Solvat, P. Marez, G. Belot, PSA Peugeot Citroen, SAE 2000-01-0473
10. THRING, R. H. "Homogeneous-Charge Compression Ignition (HCCI) Engines", SAE 1989-2068
11. "Advanced Combustion System Design, Control and Optimisation to Meet the Requirements of Future European Passenger cars" B. Cooper, N. Jackson, I. Penny, D. Rawlins, A. Truscott and J. Seabrook, THIESEL 9<sup>th</sup> September 2004
12. DOWNES, T.A., RAWLINS, D.J., "Development of HSDI Combustion Systems Using CFD Analysis Techniques", Fuel Injection Systems – I Mech E Conference Proceedings, November 2002
13. MOULIN, P., AKOACHERE, A., TRUSCOTT, A., NOBLE, A., MUELLER, R., HART, M., KROETZ, G., CAVALLONI, C., GNIELKA, M., VON BERG, J., "Benefits of a Cylinder Based Engine Management System on a Vehicle". Advanced Microsystems for Automotive Applications, Berlin 2002
14. WHITACRE, S., ADELMAN, B., MAY, M., McMANUS, J., "Systems Approach To Meeting EPA 2010 Heavy-Duty Emission Standards Using A NOx Adsorber Catalyst And Diesel Particle Filter On A 15liter Engine", SAE 2004-01-0587, 2004, 12pp
15. ROGERS, B., SUCH, C., BEST, C., "Investigation of a Two Valve Electronically Controlled Unit Injector On A Euro IV Heavy Duty Diesel Engine Using Design of Experiments", I.Mech.E. Conference on Fuel Injection Systems 26-27 November 2002
16. Takaoka T., Kotani, T., Abe, S., Ueda, T., "Study of the Optimisation between Engine and Hybrid System" - 12. Aachener Kolloquium Fahrzeug- und Motorentechnik 2003
17. Gordon, R., Fussey, P., and Streater, S., "Mild Hybrid Operation with a Downsized Diesel Engine – A Practical Approach to Outstanding Fuel Economy - Global Powertrain Congress, September 2002 (www.gpc-icpem.org); see also I-MoGen information at <http://www.ricardo.com/i-MoGen/default.htm>
18. Lake, T., Stokes, J., Murphy, R. and Osborne, R. "Turbocharging Concepts for Downsized DI Gasoline Engines" - 12. Aachener Kolloquium Fahrzeug- und Motorentechnik 2003
19. Tang, X., Kabat, D., Natkin, R., Stockhausen, W., Heffel, J., "Ford P2000 Hydrogen Engine Dynamometer Development" – SAE 2002-01-0242