potential of exhaust after treatment and engine technologies to meet future emissions limits

Background information for CONCAWE Report No. 99/55.

Prepared for the CONCAWE Automotive Emissions Management Group, based on work carried out by the Special Task Force on gasoline/diesel after-treatment devices (AE/STF-13):

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ABSTRACT

In view of the European Auto Oil Process (AO2) a CONCAWE study reviewed literature (up to 9/1998) and in-house information on improved exhaust after treatment and engine technologies to reduce emissions from gasoline (stoichiometric, lean-burn, G-DI) and diesel vehicles (light and heavy duty). Engine features include advances in engine combustion, fuel injection equipment, exhaust gas recirculation systems and management systems/strategies. The various technologies are summarised with regard to their application, advantages, disadvantages, fuel implications, fuel consumption and their likelihood to emerge on the European market.

Based on the knowledge available at the time of the study, CONCAWE's experts assessed the potential of different technologies to contribute to meeting the year 2005 emissions limits. While it is concluded that vehicle technologies already exist to meet such limits even with current fuel quality, for conventional gasoline vehicles, no current light duty diesel vehicle achieves these limits. For light and heavy duty diesel vehicles, several technologies exist (traps, de-NOx) which will be further developed, and fuel quality will depend on the conversion efficiency and durability needs of such catalyst technology to meet 2005 limits and beyond. The SCR (urea de-NOx) system would be expected to be sulphur tolerant and applicable for heavy duty engines. Continuous regenerative traps (CRT) should operate satisfactorily with the 2005 sulphur level (50 mg/kg). De-NOx catalyst systems required for gasoline direct injection systems (G-DI) are under rapid development and improvements in their sulphur tolerance could be expected. In the Fuels Directive 98/70/EC fuel sulphur has been specified to enable new technologies to meet future emission limits.

KEYWORDS

After treatment devices, new engine technologies, gasoline vehicle technologies, diesel vehicle technologies, exhaust emissions reduction potential, catalysts, traps, de-NOx, fuel sulphur influence

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EXECUTIVE SUMMARY

This is the CONCAWE view based on literature available up to September 1998.

To meet the indicated year 2005 emissions limits a combination of improved exhaust after-treatment and engine technologies will be required. The after-treatment advances include improvements in current systems and the introduction of novel technologies. Engine design features used to meet future emission limits will include advances in engine combustion, fuel injection equipment, exhaust gas recirculation systems and management systems / strategies.

About 65% of the gasoline vehicle models homologated in Germany during 1997 already meet the 2000 (Euro 3) limits and about 15% have the potential to meet the limits for 2005 (Euro 4). These low emissions vehicles represent wide ranges of vehicle technologies and engine capacities with many vehicle manufacturers being represented. Thus, we conclude that the vehicle technologies and fuel quality already exist in Europe to achieve the 2005 limits for conventional gasoline vehicles.

The introduction of lean-burn gasoline vehicles, including gasoline direct injection (G-DI) engines, to gain fuel economy and CO_2 benefits is increasing pressure for further reductions in gasoline sulphur content. Vehicle and catalyst manufacturers claim that a sulphur content of less than 50 mg/kg is required for G-DI engines with NOx storage catalysts to achieve the 2000 emissions limits. OEMs have recently reported improvements in the sulphur tolerances of these catalyst systems. Through these improvements, improved thermal management, and the use of SOx traps OEMs will launch Euro 3 direct injection gasoline vehicles capable of operating on Euro 3 sulphur levels. However, lower sulphur levels will give better fuel economy and will be mandatory at 50 mg/kg in 2005. Considerable fuel economy and CO_2 benefits may be achieved without having to use a lean-burn approach: improved transmission, Variable Valve Timing (VVT), stoichiometric direct injection and hybrid technology are all promising technologies for CO_2 reduction.

The 1997 German homologation data indicate that a small proportion (6.5%) of current light duty diesel vehicle models can achieve the 2000 emissions limits with current quality diesel. No current light duty diesel vehicle achieves the limits for 2005.

As a result of the expected advances in diesel engine technologies, such as advanced fuel injection equipment and active de-NOx catalysts, it is considered that only oxidation catalysts will be required to meet year 2000 emission limits for most light duty diesel vehicles. Exceptions are heavier sports utility vehicles (SUVs) and light commercial vehicles (>2000 kg) which may require NOx conversion efficiencies of up to 40% using active de-NOx catalysts.

For Euro 4, most light duty diesel vehicles (<1500 kg) will not require advanced exhaust after-treatment. These vehicles will be equipped with advanced fuel injection equipment, cooled exhaust gas recirculation (EGR) and oxidation catalysts. Vehicles above 1500 kg will require 40% NOx conversion, which can be provided by advanced fuel injection equipment and active de-NOx catalysts. Only the heavier SUVs (>2000 kg), of which only six models are currently marketed, will require >40% NOx conversion. This can be achieved with selective catalytic reduction (SCR - urea). The two most likely after-treatment options discussed above (active de-NOx catalysts and SCR-Urea) are fairly insensitive to sulphur and therefore do not require sulphur levels below those specified for year 2000 (Euro 3).

Although Euro 3 Heavy Duty (HD) engines are not currently available in the market, it is understood that currently available technology will allow the production of Euro 3 HD diesel. These engines will require no exhaust after-treatment. HD engines for Euro 4 will use advanced fuel injection equipment, with rate shaping and pilot injection, and advanced engine management systems.

In order to comply with the recently published Common Position proposal (December 1998), Euro 4 HD engines will also require a combined NOx/Particulate reduction strategy including after-treatment technology[1]. Several options seem to be possible, such as SCR technology (urea) and combinations of cooled EGR and particulate traps. Depending on the strategy, not even the mandatory 2005 low sulphur would always be required.

The proposed Euro 5 (2008) NOx limits will require further reduction of NOx, but are expected to use the same strategies, though at higher conversion efficiencies, which again are not considered likely to require sulphur levels below the 2005 level.

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[1] The assessment for HD engines was made by the CONCAWE Task Force in February 1999 on vehicle technology information then available.

1. INTRODUCTION

A review of current and future vehicle technology options for emissions control has been performed. It is based on information available up to September 1998 and was prepared in view of the European Auto Oil Process (AO2).

A total of 33 technologies covering gasoline, light duty (LD) diesel and heavy duty (HD) diesel applications, available up to September 1998, have been assessed. In view of the Council Common Position proposal on HD engines published in December 1998, the Task Force reviewed their earlier assessment for HD engines given in **Section 2.3**. The emissions performance, likelihood of market penetration and fuel implications (particularly sulphur content) of these technologies are reported for each technology. Tables summarising the above technology issues, detailed descriptions of the assessed technologies and overviews are contained in the main report. The overviews present CONCAWE’s current view (February 1999 with regard to HD engines, otherwise September 1998) on the technologies that will most likely be used to achieve the 2000 and agreed or proposed 2005 emissions limits, and highlights the fuel quality requirement for such technology.

Since CONCAWE is not involved in the development of engine and after-treatment technology and had no access to prototype designs, information available to CONCAWE is derived essentially from publications and in a few cases from discussions with consultants. The latter should explain why in some cases general assessments are not always referenced.

1.1. DEFINITION OF SUMMARY TABLES

Each row of the table describes a single technology that has been reviewed and has been indexed (far right hand column) to a technology review.

The sulphur sensitivity of the technologies were considered to be a key issue.

Technologies have been defined as either;

- Insensitive
- Sensitive but no “enabling” level required
- Sensitive and “enabling” level required

The second category "Sensitive but no “enabling” level required" defines those technologies that are sensitive to sulphur but reductions in sulphur content are not required to "enable" its use in 2005.

The third category "Sensitive and “enabling” level required" defines those technologies which require an “enabling” sulphur level. An “enabling” sulphur level has been established in the Fuel Directive 98/70/EC for 2005 at max. 50 mg/kg.[1]

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[1] It is claimed that sulphur levels below 50 mg/kg are required for NOx storage catalysts. The rapid development of this technology has to be closely monitored and resulting performance then further investigated to establish to what extent lower sulphur levels could enable further improvements (e.g. in fuel economy).

"Availability/Current" shows whether or not the technology under review is currently in use in Europe. The "Availability/ Technical" and "Availability/Market" columns give CONCAWE current views (September 1998) on whether the technology will be technically available by 2005 and the extent to which the technology will be used in the European market by 2005. This assessment considers both the emissions reduction potential and probable cost for the described technology.

Technologies have been defined as follows:

- High - likely
- Medium - limited
- Low - unlikely

1.2. DEFINITIONS OF FUEL IMPLICATION IN TECHNOLOGY REVIEWS

The review was conducted up to September 1998 in support of the AO2 activities. In Working Group 2 (Vehicle Technology) one of the tasks was to identify “enabling” fuel properties. With regard to fuel sulphur, the CONCAWE Task Force evaluated the respective fuel implications by taking the current (1998) sulphur level (max. 500 mg/kg) for gasoline and diesel fuel as the reference.

2. SUMMARY

2.1. GASOLINE SUMMARY

2.1.1. The Current Situation

Technologies to meet the Euro 4 emission limits for gasoline vehicle models are already marketed in Europe. About 15% of the gasoline vehicle models which were homologated in Germany during 1997 would meet Euro 4 regulations and 65% would meet Euro 3. These emissions have been achieved using pre-2000 quality gasolines. Those vehicles meeting Euro 4 represent a cross-section of the entire European car parc, with all technologies, vehicle sizes and engine capacities being present. Most current vehicles operate under stoichiometric conditions and are equipped with Three Way Catalysts (TWC). The best emissions reported are 0.04 g/km HC + NOx and 0.07 g/km CO, far below Euro 4 (see **Section 3.1**). Thus, it is clear that current gasoline quality is adequate to meet Euro 4 limits with current vehicle technology.

However, increasing interest in improvements in fuel economy and CO_2 emissions may result in the launch of new gasoline engine technologies, such as lean-burn G-DI[1], stoichiometric G-DI, hybrids and advanced transmission systems. Mitsubishi has been the first to launch a lean-burn G-DI in Europe and claimed a 20% benefit in fuel consumption along with Euro 2 and German D3 emissions performance with current quality fuels. Mitsubishi also claims that Euro 3 emissions performance is possible without major alteration to this vehicle. There will be pressure on the OEMs to achieve these fuel economy benefits together with the Euro 4 emissions requirements.

2.1.2. Strategies to Meet Euro 4 and Euro 5

2.1.2.1. The base case : Stoichiometric + TWC

There are many technology options which can be implemented to improve, where necessary, conventional technology to Euro 4 with a moderate cost. Reduction of the light-off delay of the TWC is the most efficient way, and can be combined with an advanced air/fuel control and the use of improved formulations of the TWC. There are several ways to reduce light-off delay including close coupled catalysts, electrically heated catalysts, exhaust gas ignition and engine management cold start strategies. All have been developed, but not all are currently in use in the market place. In some cases, there is a slight fuel economy penalty of up to 1%.

2.1.2.2. Improved fuel economy : including G-DI

Improved fuel economy and lower CO_2 emissions are driving the development of new gasoline vehicles. Vehicle technology options for reducing CO_2 emissions are lean-burn G-DI, stoichiometric G-DI, lean-burn MPI, hybrids and advanced transmission systems. The first vehicle in Europe with a lean-burn G-DI engine was launched in October 1997 by Mitsubishi. Mitsubishi claims that its vehicle can deliver a fuel economy benefit of up to 20% over the European test cycle and achieve the Euro 2 and D3 emissions standards. Volvo has recently launched a G-DI, based on

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[1] Abbreviations are explained in the Glossary (**Section 5**)

Mitsubishi's engine and catalyst technology, but only claims a 10% fuel economy benefit. The Mitsubishi Carisma G-DI uses an iridium based de-NOx catalyst upstream of a conventional TWC. It has been claimed by Mitsubishi that this formulation is tolerant to sulphur at levels up to 440 mg/kg S. Mitsubishi claims that it will launch a Euro 3 vehicle in 1999 based on this vehicle and catalyst technology. NOx storage catalysts may provide the only NOx control option for future Euro 4 G-DI vehicles, however it is claimed by OEMs that such catalysts are extremely sensitive to sulphur (see **Section 2.1.3**) There are, however, serious concerns about the thermal durability of NOx storage catalysts and as yet the durability of this technology has not been demonstrated for European applications even with low sulphur.

Considerable fuel economy and CO_2 benefits may be achieved without having to use a lean-burn approach. For Euro 4, these technologies can therefore use conventional TWCs rather than the sulphur sensitive NOx storage catalysts. It is believed that stoichiometric G-DI engines can provide up to 15% fuel economy benefit and increased power by 10%. A vehicle equipped with variable valve timing (VVT) and an advanced transmission system may provide up to 25% benefit compared to conventional MPI vehicles. The more costly option of a gasoline/electric hybrid may give up to 50% fuel economy benefit.

2.1.3. The Sulphur Issue

There is no major issue of sulphur on vehicles equipped with TWCs. There is a short-term sulphur effect on current TWC performance, however, it is small and reversible. The effect of fuel quality on the long-term catalyst durability is considered insignificant. Although there is still some concern from OEMs regarding palladium containing catalysts, recent work indicates that this should not be a problem.

Sulphur could be an issue for gasoline vehicles which require lean de-NOx technology, particularly NOx storage catalysts. Lean-burn G-DI engines with NOx storage catalysts will provide the largest fuel economy benefit from the engine alone whilst meeting the Euro 4 emissions standards. However, it is claimed that NOx storage technology requires a low sulphur gasoline (< 50 mg/kg max. year 2005 sulphur level). More sulphur tolerant catalyst systems are being actively investigated by catalyst manufacturers. The use of a SOx trap or TWC upstream of the NOx storage catalyst or improved thermal management have been shown to reduce the sulphur sensitivity of NOx storage catalysts on the laboratory scale. The chances of developing them to marketable technologies appears high. There are some concerns about the thermal durability of NOx storage catalysts under typical European driving conditions, even with low sulphur (30 mg/kg). Another long-term option is the use of plasma after-treatment devices, which may give the required conversion and are thought to be insensitive to fuel quality.

The same fuel economy benefits of lean-burn G-DI for Euro 4 may be obtained with other technologies which only require conventional TWCs and not NOx storage catalysts, see previous section.

2.1.4. Other Fuel Implications

In stoichiometric engines, the excursions of the mixture strength during transient operation affect the emissions. These excursions are sensitive to fuel properties such as distillation and chemical composition and to the density. The use of transient adaptive learning and/or G-DI may reduce this sensitivity.

Other fuel related issues may be important in G-DI engines, such as the effect of composition on emissions, deposit formation, driveability, lubricity and octane number requirement increase. Little information is currently available on these issues.

Summary Table 1 Gasoline Technologies

Technology	Emissions Reduction Potential	Sulphur			Other Fuel implications	Fuel Consumption	Availability			Index
		Insensitive	Sensitive, but no “enabling” level required	Sensitive, and “enabling” level required1)			1998 market	Technical by 2005	Market by 2005	
Palladium containing catalysts	30% THC 30% CO 20% NOx		x		No	No	Yes	H	H	PDC
Catalyst formulation changes	Up to 70%		x		No	No	Yes	H	H	CFL
Close coupled catalysts	60% THC 9% CO 10% NOx		x		No	No	Yes	H	H	CCC
Catalyst physical design	25% THC 25% CO 12% NOx		x		No	No	Yes	H	H	CPD
Cold start spark retard and enleanment	Lower emissions, but no data available	x			No	No	Yes	H	M	CSS
Rich start and secondary air injection	Catalyst reaches light-off earlier	x			No	Small increase	Yes	H	L	RSA
Transient adaptive learning	Lower emissions, no data available	x			lower sensitivity to changes in fuel	No	Yes	H	M	TAL
Exhaust gas recirculation	50% NOx	x			No	Increase	Yes	H	H	EGR
Fast light-off lambda sensors	35% THC 65% CO 45% NOx		x?		No	Small decrease	Yes	H	M	FLS
On-Board Diagnostics	Improvement mainly due to better I&M of vehicles		x		None	Small	Yes	H	H	OBD
Electrically Heated Cat	>70% improvement over conventional catalysts	x			Small	ca. 1% increase	Yes	H	L	EHC
Gasoline Burner	>60% improvement over conventional catalysts	x			Small	ca. 1% increase	No	H	L	GBC
Exhaust Gas Ignition	ca. 80% improvement over conventional catalysts	x			Small	ca. 1% increase?	No	H	L	EGI

Summary Table 1 Gasoline Technologies

Technology	Emissions Reduction Potential	Sulphur			Other Fuel implications	Fuel Consumption	Availability			Index
		Insensitive	Sensitive, but no “enabling” level required	Sensitive, and “enabling” level required$^{1)}$			1998 market	Technical by 2005	Market by 2005	
HC Trapping Systems	>80% improvement on HC over conventional catalysts		x?		Tendency to produce light HCs in the engine-out exhaust would affect trapping efficiency	Small ?	No	H	L	HCT
Saab "Cold Start" Bags	Can achieve ULEV levels on current cleanest US engines	x			None	None	No	H	L	SCB
Indirect MPI Lean-burn	None (w / o cat)	x			Potential problem with oxygenates	10% typical reduction	Yes	H	M	ILB
Gasoline Direct Injection, lean-burn	90%, (engine out emission compared with MPI engine out)*	x			Fuel volatility ?	17 - 20% reduction	Yes	H	M	LG-DI
Gasoline Direct Injection Stoichiometric	ca. 50% NOx improvement over lean-burn G-DI	x			Lubricity	ca. 10% benefit over conventional engine	No	H	L	SG-DI
NOx- Storage Catalyst	80%, conversion through the catalyst			x	None	~ 0	Yes	H	M	NSC
Controlled Auto-Ignition	CO & HC: 50%, NOx : 40%	x			Octane number may not be relevant	27% reduction claimed	No	M	L	CAI
Plasma	80% HC, 75% NOx, 50% CO	x			May enable G-DI without low sulphur	small decrease	No	M	L	PLA
Variable Valve Timing	CO_2 (Fuel consumption) reduction of 10-15% NOx reduction up to 80%	x			None	Reduction by 10-15%	Yes	H	M	VVT
Variable Compression Ratio	Fuel consumption reduction up to 34%	x			None	Up to 34%	?	L?	?	VCR

* NOx have to be further reduced by after treatment (de-NOx catalyst)

(1) An “enabling” sulphur level of max. 50 mg/km has been established for 2005 in the Fuel Directive 98/70/EC.

2.2. LIGHT DUTY DIESEL SUMMARY

2.2.1. The Current Situation

About 6.5% of the diesel vehicle models homologated in Germany during 1997 already have the potential to meet the year 2000 emission limits with the pre-2000 fuel quality. It is clear, however, that in most cases improvements in or full application of current emissions control technology will be needed to meet the 2000 limits and advanced technology will have to be applied to meet the year 2005 emission limits.

Modern light duty diesel vehicles are currently available with non-cooled EGR, for NOx reduction, and with oxidation catalysts which are able to reduce HC, CO and total particulates (TPM). Advanced oxidation catalysts and passive de-NOx catalysts are reported to be tolerant to 500 mg/kg sulphur. Concurrently with common rail injector systems, active de-NOx catalysts systems are now being introduced which provide 35% NOx conversion. In addition, despite the negative impact on engine out emissions, fuel economy and CO_2 emissions are currently driving a change from IDI to DI engines.

2.2.2. Strategies to meet Euro 4

The base case

As a result of the expected advances in diesel engine technologies, it is considered that only oxidation catalysts, and EGR, will be required to meet year 2000 emission limits. Some OEMs will use passive de-NOx for Euro 3. Introduction of advanced fuel injection systems, such as common rail, will allow pilot injection, rate shaping and post-injection and therefore will relax pressures on after-treatment systems. Most vehicles, with the exception of the larger SUVs, with such advanced injection equipment may not require any advanced after-treatment.

It is thought that Euro 4 LD diesel vehicles will consist of advanced combustion systems, with high speed DI engines, 4 valves/cylinder, new FIE, advanced EMS, rate shaped injection and cooled EGR. The requirement for after-treatment will be strongly dependent on vehicle weight. NOx emissions are generally higher for heavier vehicles due to the higher engine loads.

If the above technology is fully applied (i.e. new fuel injection equipment and cooled-EGR), it is believed that the small and mid-range diesel vehicles (<1500 kg) will require only oxidation catalysts to meet the Euro 4 emissions standards. Larger LD diesel cars (1500 -2000 kg) will probably require up to 40% NOx reduction. This will probably be achieved with advanced fuelling systems which allow post-injection and advanced active de-NOx catalysts. Larger LD diesel vehicles (>2000 kg) will require NOx conversion greater than 40%. This vehicle group consists of light commercial vehicles, which have to conform to different emissions standards, and SUVs, of which only six SUV models are currently marketed that exceed this weight. Currently the only proven option to deliver this level of conversion is SCR (urea injection). The logistics and packaging of such systems have always been considered a problem for LD diesel vehicles, however for LD vehicles of this size this should not be a problem.

Further advances in fuel injection equipment will take pressure off the after-treatment systems required to meet Euro 4 and may result in diesel passenger cars no longer needing de-NOx after-treatment systems. It may also result in the larger LD diesel vehicles only requiring the lower level of NOx conversion delivered by post-injection and advanced de-NOx catalysts.

Other after-treatment options are being investigated for LD diesel applications such as NOx storage catalysts, plasma, and particulate traps (incl. CRT). It is believed that NOx traps and plasma after-treatment systems will not be mature enough for use in 2005, whilst traps will lead to increased fuel consumption and CO_2 emissions. If traps (incl. CRT) are used, this will probably be as a solution to a local problem, and would most likely only be used by fleet operators such as taxis and delivery vehicles. However, year 2005 low sulphur fuel is considered adequate to meet the requirements of these after-treatment systems.

Fuel economy and CO_2 emissions

With vehicle weight being an important factor in determining the level of NOx after-treatment required, it is worth mentioning that pressure is increasing to reduce fuel consumption. This pressure can be currently observed with the increasing penetration of DI diesel vehicles compared to IDI diesels in the new vehicle fleet. In general, pressures to reduce fuel consumption will drive vehicle weights downwards, particularly for the larger vehicles, which will result in less stringent NOx after-treatment requirements. Conversely, passenger safety and comfort may result in weight increases but this will predominantly be in the small vehicle sector were impact protection and air conditioning are not yet standard. This should therefore have little impact on overall after-treatment requirements.

Introduction of advanced transmission systems and diesel/electric hybrids will also improve CO_2 emissions and fuel economy without having an impact on fuel quality.

Active de-NOx systems will lead to a 1-4% increase in fuel consumption, whilst PM traps may result in an increase of up to 10%.

2.2.3. The Sulphur Issue

It is anticipated that much of the emissions reduction for 2005 will be achieved by engine technology development options outlined in the previous section. It is believed that only active de-NOx and SCR (urea) catalyst systems will be required to meet 2005 emissions limits. Neither of these systems are sensitive to fuel sulphur and therefore do not require reduction in sulphur below year 2000 levels.

If CRTs are introduced into any light duty diesel vehicle fleet, either on new vehicles or as a retrofit, then the year 2005 low sulphur fuel would be available.

2.2.4. Other fuel implications

The technologies described here, will have the following fuel implications:

- Reduced sensitivity to fuel properties with regard to emissions
- Lubricity (pump and injectors/nozzles) and water sensitivity (cavitation) might be more critical with higher injection pressures.

Summary Table 2 LD Diesel Technologies

Technology	Emissions Reduction Potential	Sulphur			Other Fuel implications	Fuel Consumption	Availability			Index
		Insensitive	Sensitive, but no “enabling” level required	Sensitive, and “enabling” level required1)			1998 market	Technical by 2005	Market by 2005	
Oxidation Catalyst	PM 30% PM(SOF) 50% CO & HC 75% NOx 15%		x		Reduction of vehicle 'emissions sensitivity' to fuel changes	None	Yes	H	H	OxC
De-NOx Catalyst SCR (Urea)	NOx: 60-90% (ECE+EUDC)	Yes (only a reversible activity reduction at low temperature)			None	No penalty	No	H	L	SCR
De-NOx Catalyst Passive - FWC (Four Way Catalyst)	NOx 5-20% (ECE+EUDC)	x (2)		x	None	No penalty	Yes (very low efficiency)	M	M	FWC
De-NOx Catalyst Active - NCR (Non Selective Catalytic Reduction)	NOx 15-35% (ECE+EUDC)	x (2)	x		None	1-4% increase	Yes	H	M	NCR
NOx storage Catalyst	NOx conversion assumed to be >50%			no information	None	Some penalty, depending on regeneration efficiency	No	M	L	DNSC
Particulate trap (non-CRT)	PM 50% to 90+%	x			May require metal fuel additive	~5%	No	H	M	TRAP
JM continuously regenerative trap (CRT)	PM 50% to 90+% NOx 2% to 5%			x	None	~5%	No	H	L	CRT
EGR, Non-cooled	30% NOx, MVEG 70% NOx, st. state/cruising	x			No	Small increase	Yes	H	M	EGRD

Summary Table 2 LD Diesel Technologies

Technology	Emissions Reduction Potential	Sulphur			Other Fuel implications	Fuel Consumption	Availability			Index
		Insensitive	Sensitive, but no “enabling” level required	Sensitive, and “enabling” level required1)			1998 market	Technical by 2005	Market by 2005	
EGR, Cooled	30% NOx, MVEG 85% NOx, st. state/cruising Reduced soot/PM	x			No	Small increase	No	H	H	EGRD
Basic engine design improvements)	Unclear for Euro 2 to 4, but upgrading a HD Euro 1 to 2 gave 40-80% reduction in CO/HC/PM.	x			Significantly reduced fuel sensitivity	Reduced	Yes	H	H	BEDD
Engine management systems & strategies	Early days for diesel EMS, but 9% NOx and 35% PM reduction demonstrated.	x			Reduce density effect on PM and NOx	Significantly reduced	Yes	H	H	EMSD
New fuel injection types	75% PM, steady state/cruising 70% NOx, steady state/cruising in combination with EGR	x			Water sensitive (cavitation) ?Lubricity ?	Significantly reduced	Yes	H	H	FIED
New nozzles/Rate shaped injection	50% NOx at constant soot	x			No	None/Reduced	No	H	H	NRSD
Plasma	“Lean-burn”: 75% NOx, 75% HC, 50% CO, "removes soot"	x			Unknown	Unclear/none	No	M	M	PLA
Diesel/water injection and emulsions	All reg. emissions reduced by 20-30% with 20% water	x			Unknown	0-5% Increase	No	L	L	WAT
Diesel/water injection	-15 to –30% NOx –10 to –15% PM	x			None	0 – 4% reduction	?	H	M	WAT

(1) An “enabling” sulphur level of max. 50 mg/km has been established for 2005 in the Fuel Directive 98/70/EC.

(2) Newer developments

2.3. HEAVY DUTY DIESEL SUMMARY

2.3.1. The Current Situation

Meeting today's CO and HC emission limits is not a real issue for HD diesel vehicles currently marketed, mainly due to the combustion efficiency of diesel engines. NOx and PM (particulates) are the emissions of concern for HD vehicles. Although Euro 3 HD engines are not yet available in the market, it is understood that currently available technology will allow the production of Euro 3 HD diesel engines and will require no exhaust after-treatment. The current lack of Euro 3 engines is due to the fact that emissions standards have been re-defined for 2005 and beyond by the Council Common Position proposal (21 December 1998) and no final Directive being available for 2000, 2005 and beyond. A fuel consumption or engine cost penalty for Euro 3 engines compared with Euro 2 might play a role as well. The recently proposed limits for 2005 and beyond are more severe – especially the proposed year 2008 (Euro 5) standard. Significant advances in basic engine design and control, injection equipment, fuelling strategies and exhaust after-treatment will be required.

2.3.2. Strategies to meet Euro 4 (and beyond)

The proposed emission limits for year 2000 (Euro 3) and 2005 (Euro 4) for PM are about 30% and 80% lower than the Euro 2 limits respectively, and are lower for NOx by about 30%, 50% and 70% (2008/Euro 5) respectively. This tightening of emission standards is also implemented in the new test cycles - the semi-transient ESC/ELR cycle and the fully transient ETC cycle. It is difficult to judge how the use of these more "real life" transient cycles will affect the OEMs' technology preferences. The inclusion of transients and the accompanying change in the engine exhaust gas temperatures may influence the type of technology required for compliance. For instance for Euro 4 / Euro 5 where after-treatment is required the exhaust temperatures are critical to defining the after-treatment requirements, and will thus impact on sulphur sensitivities. Accordingly the preferred after-treatment solutions might be different for an engine tested over the R49 or the transient ETC cycle.

Euro 3 emissions standards can be achieved with a well optimised engine without advanced technology. The retarded fuel injection, for lower NOx, would result in an increase of fuel consumption and result in other technical problems such as increased soot in the lubricant, reduced engineering margins and thermal loading issues. Introduction of advanced fuelling equipment, which would allow pilot injection and rate shaping, would allow Euro 3 HD engines with good fuel economy but would increase the base engine cost. EGR may also be used in order to gain a fuel economy benefit. OEMs are likely to offer SCR (urea) as an option on the HD engines from 2000 onwards. This may be done to achieve tax incentives being proposed or may be in market trials of the SCR system.

HD engines for Euro 4 will use advanced fuel injection equipment, with rate shaping and pilot injection, and advanced engine management systems. In order to comply with the recently published European Council's Common Position proposal Euro 4, HD engines will also require a combined NOx / Particulate reduction strategy including after-treatment technology. Several options seem to be possible, such as SCR technology (urea) and combinations of cooled EGR and particulate traps. Of course SCR could also be combined with traps, but making use of the NOx/PM trade-off might be sufficient to meet the combination of low PM limits (0.02 g/kWh) and 3.5 g/kWh NOx by selecting either one of the two options.

If very high conversion efficiency from the SCR is required, an oxidation catalyst may be needed for protection against ammonia slippage, for which the mandatory 2005 low sulphur level (50 mg/kg) will be sufficient. Other potential options might include the use of a combination of cooled EGR and passive traps (e.g. additive) which would not even require a sulphur level below the 2000 specification. The likely use of a continuously regenerating trap (CRT) for PM reduction, which was previously reported to be very sensitive to sulphur, should operate satisfactorily with 50 mg/kg sulphur.[1]

The proposed Euro 5 (2008) NOx limits (2.0 g/kWh) will require further reduction of NOx using de-NOx catalyst technology. Depending how the PM/NOx trade-off will be applied, two options are available. SCR with very high conversion efficiency (e.g. >80%) will be required if particulate emission limits are achieved through engine measures (i.e. without a trap). Making use of the full SCR conversion rate will also contribute to low fuel consumption and no sulphur reduction below the 2005 level is required. Alternatively a combination of limited de-NOx control and a trap could be used with lower engine efficiency.

In view of the very low particulate limits proposed by the European Council's Common Position for 2005 and 2008 (0.02 g/km) it seems likely that further studies are necessary to investigate measurement capabilities of the current PM measurement methods.

Plasma treatment of exhaust gas could give substantial reductions in both NOx and PM emissions, however the technology is still in its infancy. Plasma treatment may offer potential for emission control post 2010.

NOx storage systems similar to those proposed for gasoline engines have been proposed, with suggested efficiencies >90%. However such systems are not yet developed for gasoline, and adaptation for diesel engines will be much more difficult. There is certainly no evidence that such systems will be available for 2005.

Local measures may also be taken to meet local air quality targets. Traps, including CRTs, will possibly be used in fleet operations, such as bus and local service fleets for 2000 and beyond. Low sulphur fuels (50 mg/kg) could be supplied to fleet operators to allow the use of such equipment. There will be an increasing use of alternative fuels, such as compressed natural gas (CNG) and dimethyl ether (DME), by 2005 for fleet operators.

2.3.3. The Sulphur Issue

Most diesel after-treatment systems currently in use or envisaged for year 2005 (Euro 4) vehicles and engines, e.g. passive de-NOx, active de-NOx, SCR, passive traps, can successfully operate with 500 mg/kg sulphur diesel fuels. For CRT the year 2005 sulphur level of 50 mg/kg will be satisfactory. This is also true for SCR when operated at very high conversion efficiency (> 70%). Further reductions in the sulphur content of diesel fuel are therefore not required. This situation might have to be reviewed if NOx storage catalysts for diesel application become available (currently believed to be highly sulphur sensitive).

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[1] See more recent publication (Warren et al. IMechE, 1998)

Some trap types, including CRT, are amongst the local options to meet local air quality targets. The CRT option, which is sulphur sensitive (sulphates, conversion efficiency, durability), would most likely be used by fleet operators as retrofit technology. Low sulphur fuels (50 mg/kg) could be supplied to fleet operators to allow the use of such equipment.

2.3.4. Other Fuel Implications

Most of the technologies described here will have the following fuel implications:

- Reduced sensitivity to fuel properties with regard to emissions
- Lubricity (pump and injectors/nozzles) and water sensitivity (cavitation) might be more critical with higher injection pressures.

Summary Table 3 HD Diesel Technologies

Technology	Emissions Reduction Potential	Sulphur			Other Fuel implications	Fuel Consumption	Availability			Index
		Insensitive	Sensitive, but no “enabling” level required	Sensitive, and “enabling” level required1)			1998 market	Technical by 2005	Market by 2005	
Oxidation Catalyst	PM 30% PM(SOF) 50% CO & HC 75% NOx 15%		x		Reduction of vehicle 'emissions sensitivity' to fuel changes	None	Yes	H	M	OxC
De-NOx Catalyst - SCR (Urea)	NOx 60-90%(ECE R49)	Yes (only a reversible activity reduction at low temperature)			None	No penalty	No	H	H	SCR
De-NOx Catalyst - Passive FWC (Four Way Catalyst)	NOx 5-20%(ECE R49)			x	None	No penalty	No	M	L	FWC
De-NOx Catalyst - Active NCR (Non Selective Catalytic Reduction)	NOx up to 40% (ECE R49)		x		None	1-6% increase depending on HC/NOx ratio	No	H	M	NCR
NOx storage catalyst	NOx conversion assumed to be >50% (based on LD)			no information	None	some penalty, depending on regeneration efficiency	No	M	L	DNSC
Particulate trap (non-CRT)	PM 50% to 90+%	x			May require Metal fuel additive	Typically 5%	Yes	H	M	TRAP
JM continuously regenerative trap (CRT)	PM 50% to 90+% NOx 2% to 5%			x	None	Typically 5%	Yes	H	M	CRT
EGR, Non-cooled	30% NOx, R49/13-mode	x			No	Small increase	No	H	M	EGRD
EGR, Cooled	45% NOx, OICA/13-mode 60% NOx, R49/13-mode Reduced soot/PM	x			No	Small increase	No	H	H	EGRD

Summary Table 3 HD Diesel Technologies

Technology	Emissions Reduction Potential	Sulphur			Other Fuel implications	Fuel Consumption	Availability			Index
		Insensitive	Sensitive, but no "enabling" level required	Sensitive, and "enabling" level required[1)]			1998 market	Technical by 2005	Market by 2005	
Basic engine design improvements	Unclear for Euro 2 > 4, but upgrading a HD Euro 1 > 2 gave 40-80% redn. in CO/HC/PM.	x			Significantly reduced fuel sensitivity	Reduced	Yes	H	H	BEDD
Engine management systems & strategies	Early days for advanced diesel EMS, but 9% NOx and 35% PM reduction demonstrated in LD.	x			Reduce density effect on PM and NOx	Significantly reduced	Yes	H	H	EMSD
New fuel injection types ; Common Rail, Unit injectors, HP rot. pump.	Significant, but % is unclear	x			Water sensitive (cavitation) ?Lubricity ?	Significantly reduced	Yes	H	H	FIED
New nozzles/Rate shaped injection	LD,50% NOx at const. soot HD,12% NOx at const. soot	x			No	None/ Reduced	No	H	*H*	NRSD
Plasma	"Lean-burn": 75% NOx, 75% HC, 50% CO, "removes soot"	x			Unknown	Unclear/ none ?	No	M	*L*	PLA
Diesel/water injection and emulsions	All reg. emissions reduced with 20-30% with 20% water	x			Unknown	0-5% increase	No	M	L	WAT
Diesel/Water injection	-15 to -30% NOx, -10 to -50% PM	x			None	0 to 4% reduction	?	H	M	WAC

(1) An "enabling" sulphur level of max. 50 mg/km has been established for 2005 in the Fuel Directive 98/70/EC.

2.4. HYBRID VEHICLES, NEW PROPULSION TECHNOLOGIES AND TRANSMISSIONS DEVELOPMENTS

Summary Table 4 Hybrid Vehicles, New Propulsion Technologies

Technology	Emissions Reduction Potential	Sulphur			Other Fuel implications	Fuel Consumption	Availability			Index
		Insensitive	Sensitive, but no “enabling” level required	Sensitive, and “enabling” level required[1)]			1998 market	Technical by 2005	Market by 2005	
Hybrid vehicle	> 90%, compared to equivalent gasoline car	x			None (those of the engine)	50% reduction	Yes	H	M	HYBV

(1) An “enabling” sulphur level of max. 50 mg/km has been established for 2005 in the Fuel Directive 98/70/EC.

Summary Table 5 Transmissions

Technology	Emissions Reduction Potential	Sulphur			Other Fuel implications	Fuel Consumption	Availability			Index
		Insensitive	Sensitive, but no “enabling” level required	Sensitive, and “enabling” level required[1)]			1998 market	Technical by 2005	Market by 2005	
Continuous Variable Transmissions	CO_2 (Fuel consumption) reduction of 10-15%	x			None	Reduction by 10-15%	Yes	H	M	CVT

(1) An “enabling” sulphur level of max. 50 mg/km has been established for 2005 in the Fuel Directive 98/70/EC.

3. EXHAUST EMISSIONS LIMITS - CURRENT AND FUTURE

3.1. GASOLINE

For gasoline vehicles, as for light duty diesel vehicles, the emissions limits are specified in terms of g/km. The limits are given on a combined basis for NOx and HC, and additionally for CO. As from the Euro 2 stage, this combined limit will be replaced for gasoline vehicles by separate NOx and HC limits.

The current test cycle (for Euro 2 emissions tests) is the ECE+EUDC (91/441/EEC and 94/12/EC) test. For the Euro 3 limits, a slightly modified test procedure will be applied:

- The MVEG cycle - the same driving schedule as the ECE+EUDC cycle, but with the removal of 40 seconds (s) of the idle period from the start of the test and the emissions sampling commencing from key-on.

Current Euro 2 and future emissions limits for gasoline passenger cars are given in **Table 1**. For comparison, the current limits have also been translated to the "equivalent" (typical) emissions of the MVEG cycle, based on factors established during the AO1 process. Only the applicable combinations of test cycle and emissions stages are highlighted in **Table 1**.

Table 1 Current and future emission limits for gasoline passenger cars (g/km)

	Euro 2		**Euro 3**	**Euro 4**
	91/441/EEC	**MVEG**	**MVEG**	**MVEG**
NOx	0.225	0.252	**0.15**	**0.08**
HC	0.275	0.341	**0.20**	**0.10**
HC+NOx	**0.5**	0.593	**-**	**-**
CO	**2.2**	3.28	**2.3**	**1.0**

Following from **Table 1**, NOx and HC have been reduced by 40% for Euro 3 and by about 70% for Euro 4. Reductions for CO are 30% and 70% respectively.

3.2. LIGHT DUTY DIESEL

For light duty diesel vehicles, as for gasoline vehicles, the emissions limits are specified in terms of g/km, and are given separately for Particulates (PM) and CO while NOx and HC are combined in to a single limit. This combined specification will remain in force up to the Euro 4 limits, although a separate NOx limit is also given which potentially removes some of the flexibility.

The current test cycle (for Euro 2 emissions tests) is the ECE+EUDC (91/441/EEC and 94/12/EC) test. For the Euro 3 limits, a slightly modified test procedure will be applied:

- The MVEG cycle - the same driving schedule as the ECE+EUDC cycle, but with the removal of 40 s of the idle period from the start of the test and the emissions sampling commencing from key-on.

Current Euro 2 and future emissions limits for diesel passenger cars are given in **Table 2**. For comparison, the current limits have also been translated to the “equivalent” (typical) emissions of the MVEG cycle, based on factors established during the AO1 process. Only the applicable combinations of test cycle and emissions stages are highlighted.

Table 2 Current and future emission limits for diesel passenger cars (g/km)

	Euro 2		**Euro 3**	**Euro 4**
	91/441/EEC	**MVEG**	**MVEG**	**MVEG**
PM	**0.08**	0.08	**0.05**	**0.025**
NOx	0.56	0.57	**0.50**	**0.25**
HC	**-**	-	**-**	**-**
HC + NOx	**0.7**	0.71	**0.56**	**0.30**
CO	**1.0**	1.06	**0.64**	**0.50**

For the period of time up to 10/99, DI vehicle are allowed higher PM and HC+NOx emissions than those given above for Euro 2. No such derogation is allowed past this date.

Following from **Table 2**, PM has been reduced by 40% (Euro 3) and by about 70% (Euro 4), NOx by 12% (Euro 3) and 56% (Euro 4), and CO by 40% (Euro 3) and about 50% (Euro 4) respectively.

3.3. HEAVY DUTY DIESEL

For heavy duty diesel engines, the emissions limits are specified in terms of g/kWh and are given separately for Particulates (PM), NOx, HC and CO.

Due to the simultaneous change in the test cycle, the situation is more complex from year 2000 onwards.

The current test cycle (for Euro 2 emissions tests) is the European 13-mode (ECE R49) test. For the new emission limits for year 2000 and beyond, two new test cycles are in place:

- The ESC cycle - a new 13-mode test cycle with different operating conditions and weighting factors and includes a dynamic load response test for smoke (ELR). This cycle will be used for all engines, with the exception of gas fuelled engines, where only the transient ETC cycle will be used.
- The ETC cycle - a new fully transient test cycle of 30 minutes duration. This cycle will be used in the Euro 3 stage for any engines considered to have *"advanced emissions control systems"* i.e. de-NOx catalysts and/or particulate traps. Thus an engine of this type will have to meet **both** test limits. Both test cycles will also have to be used during the Euro 4 stage and beyond. The ETC is the only test cycle to be used for gas fuelled engines.

Current Euro 2 and limits proposed by the Council Common Position (21.12.98) are given in **Table 3**. For comparison, the current limits have also been translated to the "equivalent" emissions of the R49 cycle, based on factors established during the development of the new cycles. Only the applicable combinations of test cycle and emissions stages are highlighted.

Table 3 Current and proposed future emission limits for Heavy Duty engines (g/kWh)

	Euro 2			Euro 3		Euro 4		Euro 5	
	R49	ESC/ELR	ETC	ESC/ELR	ETC	ESC/ELR	ETC	ESC/ELR	ETC
PM	**0.15** (1)	0.14	0.22	**0.10** (1)	**0.16** (1)	**0.02**	**0.03**	**0.02**	**0.03**
NOx	**7.0**	7.2	7.33	**5.0**	**5.0**	**3.5**	**3.5**	**2.0**	**2.0**
THC	**1.1**	0.94	1.19	**0.66**	-	**0.46**	-	**0.46**	-
NMHC	-	-		-	**0.78**	-	**0.55**	-	**0.55**
CH_4	-	-		-	**1.6**	-	**1.1**	-	**1.10**
CO	**4.0**	2.99	7.91	**2.1**	**5.45**	**1.5**	**4.0**	**1.5**	**4.0**
Smoke (m^{-1})	-	-	-	**0.8**	-	**0.5**	-	**0.5**	-

(1) For small engines, the PM limits are higher:
Euro 2: 0.23 g/kWh
Euro 3: ESC – 0.13 g/kWh; ETC – 0.23 g/kWh

Following from **Table 3**, it is proposed to reduce NOx limits by about 30% for Euro 3, 50% for Euro 4, and 70% for Euro 5. PM limits would be reduced by about 30% for Euro 3, and more than 80% (~86) for Euro 4 and beyond.

4. TECHNOLOGY REVIEWS

4.1. GASOLINE TECHNOLOGY REVIEW

4.1.1. Palladium Containing Three-Way Catalysts (PDC)

Application

- Conventional gasoline vehicles.

Advantages

- Improved emissions for same precious metal cost compared to platinum containing catalysts; up to 28% in THC, 30% in CO and 22% in NOx, (SAE961902)
- Higher thermal stability enabling use as close coupled catalysts
- Faster light off times.
- Same sulphur tolerance as platinum/rhodium catalysts over short-term operation (SAE 961901).
- Possibly more sulphur tolerant than platinum/rhodium catalysts over extended operation on high sulphur fuels.

Disadvantages

- Some groups claim that palladium containing catalyst are more sensitive to sulphur over extended operation, see above, but no data available.

Fuel Implication

- None.

Fuel Consumption

- None.

Likelihood

- Already in the market.

Description

In such catalysts palladium is combined with either rhodium only or rhodium and platinum. The latter formulation is often referred to as a trimetal or trimetallic catalyst. Their operation is identical to the more common platinum/rhodium catalysts which are designed to convert hydrocarbons, CO and NOx emissions from a gasoline vehicle designed to run stoichiometric.

Recent advances in catalyst manufacture have resulted in improved durability of palladium containing catalysts and better sulphur tolerance over their earlier palladium containing counterparts or the more common platinum/rhodium catalysts.

4.1.2. Changes in Catalyst Formulation and Loading of Three-Way Catalysts (CFL)

Application

- Conventional gasoline vehicles.

Advantages

- Increased loading will give improved emissions conversion. For example, doubling the platinum group metal or PGM loading can result in emissions reduction of 13% in both THC and CO and 8% in NOx. (SAE961902).
- Change in PGM loadings and formulation can result in large reductions in emissions. Catalyst formulations can be adapted to target particular emissions. For example, increases in the rhodium content of the catalyst can give large reductions, up to 70%, in NOx. (SAE961897).

Disadvantages

- Higher PGM loadings increase cost of catalysts. Doubling PGM loading will typically increase cost by $20 per application.

Fuel Implication

- None.

Fuel Consumption

- None.

Likelihood

- Already in market place.

Description

Works as conventional three-way catalysts.

4.1.3. Close Coupled Three-Way Catalysts (CCC)

Application

- Conventional gasoline vehicles.

Advantages

- Faster catalyst light off and hence low emissions, particularly HC.
- Positioning a catalyst close to the exhaust manifold, called close coupling, can give emissions reductions of 60% in THC, 9% in CO and 10% in NOx (EPEFE).

Disadvantages

- Lower catalyst durability.
- Lack of space in engine compartment for catalyst.
- Insulation of the exhaust system is an alternative where space is a problem.

Fuel Implication

- None.

Fuel Consumption

- None.

Likelihood

- Already in the market.

Description

Operates in a similar fashion to conventional three-way catalysts but is positioned closer to the exhaust manifold.

Catalysts are normally positioned under the body of the vehicle, often about a meter away from the exhaust manifold. During cold start a considerable amount of heat from the exhaust gases can be lost into and through the exhaust pipe. If the catalyst is moved closer then the exhaust gases enter the catalyst hotter. The catalyst therefore reaches light-off temperature quicker, and the exhaust gases are converted earlier.

Higher catalyst temperatures experienced during high vehicle speeds can accelerate the deactivation of the catalyst performance which results in a lower catalyst durability. Palladium containing catalysts have a higher thermal stability than the more common platinum/rhodium catalysts, and thus are a more appropriate formulation to use in a close coupled catalyst.

4.1.4. Catalyst Physical Design (CPD)

Application

- Conventional gasoline vehicles.

Advantages

- A simultaneous increase in cell density (400 to 900 cell/sq. in.) and decrease in wall thickness (0.16 to 0.11 mm) can reduce THC and CO exhaust emissions by 25%, and NOx emissions by 12% (ISATA 96EN044).
- Increased catalyst volume reduces emissions.

Disadvantages

- Probably less durable.

Fuel Implication

- Larger catalysts may be less sensitive to sulphur (ISATA 96EN043).

Fuel Consumption

- Small fuel consumption penalty due to higher back pressure of some systems.

Likelihood

- Thin walled catalysts have been introduced into the market.

Description

Decreases in catalyst wall thickness give a lower heating capacity. The catalyst will therefore reach light-off temperature faster, resulting in lower exhaust emissions. Increases in catalyst cell density increase the surface area of the catalysts. This results in a more reactive catalyst for the same quantity of precious metal, and thus lower emissions.

High vehicle speeds and loads can lead to a breakthrough of emissions from the catalysts. Under such conditions exhaust volume flow rates are high, and residence time of the exhaust over the catalysts is therefore short. Catalysts conversion efficiency is limited by catalyst volume, and thus larger catalysts would give higher conversions.

4.1.5. Advanced Engine Management Strategies: Cold Start Spark Retard and Enleanment - CSSRE (CSS)

Application

- Conventional gasoline vehicles.

Advantages

- Faster catalyst light off.
- Lower cold start emissions. No data available.
- No extra hardware.

Disadvantages

- Exhaust valves heat up more quickly, resulting in faster deposit formation.
- Valve stem expands more quickly than train and can sometime stick open.
- Increased engine noise.
- Poor idle stability.

Fuel Implication

- None.

Fuel Consumption

- None.

Likelihood

- Vehicle manufacturers currently investigating this strategy on prototype vehicles.

Description

During cold start, the engine is operated slightly lean (up to 1.05) and the spark timing retarded by around 20° which may lead to increased engine noise and poor idle stability. This management strategy results in later combustion with significant heat release in the exhaust port and pipe. Thus, the exhaust gas entering the catalyst will be hotter than for a conventional cold start strategy. CSSRE may be used in conjunction with close coupled catalysts to achieve rapid catalyst light off.

4.1.6. Advanced Engine Management Strategies: Rich Start and Secondary Air Injection (RSA)

Application

- Conventional gasoline vehicles.

Advantages

- Faster catalyst light off. Catalyst reached light-off after about 30 s for a vehicle operating with the above strategy compared to about 65 s for a conventional vehicle tested over FTP.
- Lower cold start emissions.

Disadvantages

- Requires additional hardware (air pump) and hence will be more expensive than a vehicle using a conventional cold start strategy.

Fuel Implication

- None

Fuel Consumption

- Possible small fuel consumption penalty due to early rich operation.

Likelihood

- Already in market

Description

The vehicle runs rich during the cold start. Exhaust gases, containing H_2 and CO, are mixed in the exhaust system with secondary air and react further producing heat. This increases the exhaust gas temperature at the catalyst inlet and accelerates catalyst light-off.

4.1.7. Transient Adaptive Learning (TAL)

Application

- Conventional gasoline engines

Advantages

- Lower vehicle emissions.
- Less sensitivity of emissions to fuel formulation changes

Disadvantages

- Development and extra hardware (wide range lambda sensor) costs.

Fuel Implication

- Lower sensitivity of emissions to fuel parameters describing distillation (E70, E100 and E150) and stoichiometric air to fuel ratio (aromatic and oxygenate content)

Fuel Consumption

- No information available.

Likelihood

- Already in market place (Toyota).

Description

A wide range lambda sensor can be used to monitor the duration and severity of a mixture strength excursion during a transient vehicle operation. A model based engine management system can use this information to adapt parameters with the model in order to minimise severity and duration of future excursions.

Parameters in the model which would be adapted would be those that describe the fuel behaviour in the inlet manifold (distillation) and those which determine the quantity of fuel required for stoichiometric operation (SAFR).

Reducing mixture strength excursions will reduce emissions.

4.1.8. Exhaust Gas Recirculation for Gasoline (EGR)

Application

- Conventional gasoline and lean-burn gasoline engines

Advantages

- Lower NOx emissions, up to 47% (EPEFE).

Disadvantages

- Extra hardware (EGR valve).
- EGR valve can become blocked with exhaust gas deposits, resulting in either lower exhaust gas flows or in active valve.
- Increased engine noise.
- Increased lubricant oil contamination.
- Increased engine wear.

Fuel Implication

- None.

Fuel Consumption

- Increased consumption.

Likelihood

- Already in market.

Description

Exhaust gases are added to the fresh charge for the next cycle in order to reduce the peak combustion temperature. NOx emissions are related to peak combustion temperatures. A certain amount of "internal" EGR occurs in all engines due to the overlap in inlet and exhaust valve timings. On vehicles equipped with variable valve timing (VVT) it will be possible to control the amount of internal EGR. Most vehicles which operate with an EGR system use external EGR, which involves recirculating a controlled amount of the exhaust gas via a valve into the intake.

4.1.9. Fast Light-off Lambda Sensors (FLS)

Application

- Conventional gasoline engines.

Advantages

- Lower emissions due to faster control of mixture strength. Fast light-off sensors can give 33% reduction in THC, 66% in CO and 46% in NOx over cold start (ECE 1 - 4) (SAE961901).
- Benefits can be achieved at no extra cost by moving lambda sensor closer to the exhaust manifold.

Disadvantages

- Electrically heated sensors are relatively expensive.

Fuel Implication

- Potentially sensitive to sulphur - no data available.

Fuel Consumption

- Small benefit (5%) over cold start (ECE 1 - 4) due to less rich operation(SAE 961901).

Likelihood

- Two options for fast light-off lambda sensors are currently available, vehicles with the sensor closer to the exhaust manifold and vehicles equipped with heated lambda sensors.

Description

In order for the engine management system to control mixture strength input from a sensor that measures mixture strength is required. Current sensors need to reach a certain temperature to operate. Thus, under cold start conditions the sensor will be below the lower temperature limit of operation. Under such conditions most engine management systems will default to rich operation. Sensors which light-off faster enable the engine management system to control the engine/vehicle mixture strength to stoichiometric earlier than for vehicles with conventional sensors. This leads to a reduction in emissions.

4.1.10. On-board Diagnostics (OBD)

Application

- Principally gasoline vehicles of all sizes, but legislators are considering extension to include LD/HD vehicles with CI engines (in line with the introduction of electronic powertrain management capabilities for these engines), and vehicles running on alternative fuels.

Advantages

- OBD helps to ensure that a vehicle's emission control devices are kept in good condition.
- OBD can provide automobile manufacturers with valuable feedback from their customers' vehicles that can be used to improve vehicle and emission control system designs
- OBD can facilitate the enforcement of good vehicle maintenance, e.g. OBD III being discussed in the US would enable authorities to enforce corrective action for the non-conforming vehicles.

Disadvantages

- Temporary deactivation of catalyst efficiency, e.g. by fuel sulphur, can cause the malfunction indicator light (MIL) to light up (customer complaint issue).
- Installation/maintenance cost implication upon wider market penetration.
- Cost.

Fuel Implications

- Fuel sulphur is a potential issue as suggested by US EPA (EPA White Paper, March 1997), i.e. while sulphur induced illumination was unlikely under normal operating conditions up to 100,000 miles, such events are possible for severely aged catalysts that might be at or approaching 1.5 times the emissions standard.
- EPA's proposal to combat the problem (EPA White Paper, March 1997) was to grant relief on a case-by-case basis using 2 options: (a) allow the manufacturer to use a higher value for the cut point, or (b) allow the manufacturer to revise the strategies for monitoring catalyst operation so that sulphur-induced MIL events are not detected.
- EPA felt (EPA White Paper, March 1997) that reducing sulphur was not a viable near term option while hardware solution existed to remedy the potential problems and that further study should occur towards developing a long-term resolution.
- CARB announced in 1998 that the OBD standards (or thresholds) are to be relaxed by raising the cut point from current 1.5 to 3. The recent CRC study on the effect of fuel sulphur on OBD indicates that there is no concern for the sulphur content in the current market fuels to trigger the lighting of the MIL with the new cut point of 3.

Fuel Consumption

- Impact on fuel consumption is considered to be small.

Likelihood

- Already in the European market (Swedish spec. Saab 900) and more widespread in the US market. Wider introduction into the European market over the next few years.

Description

On-board diagnostics systems are designed to detect vehicle malfunctions or deterioration within vehicle emissions control and fuel metering system to maintain acceptable emissions performance. OBD systems can reduce lifetime in-use emissions from motor vehicles by notifying the driver of a malfunction, thus shortening the time between when a malfunction of such a system occurs and when necessary repairs are performed. Oxygen storage is generally used as an indicator of catalyst effectiveness since as catalysts deteriorate, oxygen storage capacity of ceria-containing catalysts also tends to decrease. By examining changes in the oxygen storage capacity, it is possible to infer changes in catalyst effectiveness. Oxygen storage occurring in a catalyst can be measured by comparing the signals from the two oxygen sensors, one placed upstream of the catalyst (or catalysts) and one placed downstream. While the front oxygen sensor, normally used for air-fuel ratio control will see a fluctuating oxygen concentration due to the cycling of the air-fuel ratio around stoichiometric, the rear oxygen sensor signal will be relatively steady due to oxygen storage phenomenon occurring in the catalyst. Thus the rear oxygen sensor will produce a fairly damped signal in comparison with the front oxygen sensor when the catalyst is "healthy". This damping is reduced when a catalyst begins to deteriorate and is no longer capable of storing and releasing oxygen. Thus, by comparing the frequency and peak-to-peak voltage of the front oxygen sensor response to that of the rear oxygen sensor, one can infer the operating catalyst efficiency. (SAE952422)

4.1.11. "Early Light-off" Catalyst: Electrically Heated Catalyst (EHC)

Application

- Gasoline vehicles of all sizes.

Advantages

- Good reduction of cold start emissions. The following figures have been reported:
  - Exxon Study (SAE932760): 2 cars, 2 fuels
    CO: 30%, HC: 55.8%, NOx: 20.6% reduction over non-EHC equipped car
  - BMW Study (SAE970263): 1 car (BMW Alpina B12 in the market)
    CO: 75%, HC: 77%, NOx: 74% reduction over non-EHC equipped car
- Hyundai claim (Asia-Pacific Automotive Report, Vol. 248) to lower "harmful pollutions" to 10% of the current level of average passenger cars meeting ULEV standards.
- Good durability in the later generation EHCs (Corning, SAE960345).
- Most mature "early light-off" technology simply due to the fact that most manufacturers have much experience in working with EHCs.

Disadvantages

- Power limitation in heating the catalyst up to the light-off temperature as power requirement of an EHC can severely tax the existing electrical system of a vehicle.
- Durability in some older generation EHCs.
- NOx conversion can be an issue in some systems (SAE932760).
- Can be costly.

Fuel Implications

- EHCs can impact the way the fuel composition (e.g. T90, aromatics) affects the cold start emissions, principally HC. The effects of EHC on CO and NOx are inconsistent (SAE932760).

Fuel Consumption

- Additional fuel consumption is possible due to the power requirement of the extra battery for the EHC in some systems.

Likelihood

- Currently EHCs are available in the European market place (BMW Alpina B12). EHCs are considered to be the most mature "early light-off technology" and thus closest to application on a wide scale if "early light-off technology" becomes necessary to meet the indicated Year 2005 limits. Before this happens, however, perceived durability & power limitation issues need to be overcome.
- Recently, some OEMs & catalyst manufacturers, e.g. BMW (SAE970263), Hyundai (Asia-Pacific Automotive Report, Vol. 248) & Corning (SAE960345)

have all reported to have developed EHCs with good thermal/mechanical durability.

Description

The EHC with secondary injection is generally placed before the manufacturer's catalyst and resistively heated by the car's battery prior to start-up. This provides an active catalyst surface to convert start-up emissions. The secondary air injection is necessary since at cold start-up, engines run rich until they go into closed-loop control; and hence additional air is injected to the EHC to provide the extra oxygen necessary for the oxidation of HC and CO.

4.1.12. "Early Light-off" Catalyst: Gasoline Burner (GBC)

Application

- Gasoline vehicles of all sizes.

Advantages

- Good reduction of cold start emissions. The following figures have been reported from the 1994 Ford study (SAE942072) on a 1993 model Ford Grand Marquis:
  - Catalyst light-off time achieved in <15 seconds
  - Cold start HC emissions during the first 60 seconds of the FTP test were reduced by 60%
  - All three pollutants (CO, NOx and HC) were below the ULEV limits.
- Much greater amount of energy available for heating of the catalyst compared with EHC. The above Ford study reported the gasoline burner technology outperforming EHC.

Disadvantages

- Less mature technology than EHC.
- There may be slight fuel consumption debits (see "Fuel Consumption").
- Durability is an unknown factor.
- Customer safety issue needs to be clearly addressed before wider market introduction can take place.
- Cost.

Fuel Implications

- Considered to be small.

Fuel Consumption

- There is some fuel consumption debit. An AVL study reported 1% fuel consumption debit over a test cycle compared to a similar vehicle without a catalyst/burner system.

Likelihood

- Although the technology has not yet been marketed, it is believed that it can be made available relatively quickly, if "early light-off technologies" become perceived to be necessary to meet Year 2005 limits.

Description

In a catalyst/burner system, a gasoline fuelled combustion burner is incorporated into the exhaust system and used to heat the converter.

A simple burner system (Ford) consists of a burner head that is a piece of stainless steel exhaust pipe. Fuel to the burner is metered via an electronic fuel injector and a small compressor is used to force the fuel through a small orifice providing fine atomisation. The burner air is supplied by an electric air pump. The resulting fuel/air mixture is ignited by a spark plug which is operated continuously.

4.1.13. "Early Light-off" Catalyst: Exhaust Gas Ignition (EGI)

Application

- Gasoline vehicles of all sizes.

Advantages

- Good reduction of cold start emissions with standard formulation or with a trap as the front brick. The following figures have been reported:
  - Ford Study (SAE952417): comparative study of Ford 1.8 litre Zetec Euro I engine with EGI and EHC with secondary air system + 2 kW for 20 seconds. Claim to outperform EHC,
    EGI = HC: 0.06, CO: 0.234, NOx: 0.07 g/km (Euro 4 level) EHC = HC: 0.07, CO: 0.310, NOx: 0.10 g/km (Euro 4 level except NOx)
  - Ford/JM Study (ISATA 96EN041): EGI with catalysed carbon trap (CHT) as front brick gave HC emissions over first 200 seconds of MVEG cycle of 0.14 g (or 0.015 g/km over MVEG assuming HC is controlled after light-off), while standard EGI gave 0.34 g (or 0.03 g/km over MVEG).
- Conversion efficiency of EGI is more consistent than EHC where a temporary fall in the conversion efficiency (to 0 or negative values) occurs due to HC storage and release.
- Reasonable durability (up to 30k miles in the Ford study; SAE952417).

Disadvantages

- Less mature technology than EHC.
- Cost (1995 Ford study claims cost comparable to EHC).

Fuel Implications

- Currently unknown, but considered to be small.

Fuel Consumption

- Some fuel consumption penalty could be possible since for the first few seconds (Ford quotes 6 sec) after start, engine fuelling is calibrated to produce an exhaust AFR of around 9:1, plus an additional period of rich engine operation (11:1) is required to stabilise the catalyst light-off immediately following EGI.

Likelihood

- Although the technology has not yet been marketed, it is believed that it can be made available relatively quickly, if "early light-off technologies" become perceived to be necessary to meet Year 2005 limits.

Description

In an EGI system, rapid heating of an UB (Under Bonnet) catalyst after cold start occurs by combusting engine out pollutants in a small combustion chamber inserted between 2 catalyst monoliths.

4.1.14. HC Trapping System (HCT)

Application

- Gasoline vehicles of all sizes.

Advantages

- Good reduction in cold start HC emissions
    - JM Study (SAE970741): claims HC conversion efficiency of 80% in the first 20 seconds (TWC downstream of the HC trap).
    - Corning Study (SAE970267): 2 vehicles, 1 US Phase 2 RFG fuel used (in-line HC adsorber technology)
      4.0 litre V8 car = NMHC: 47, CO: 10, NOx: -73% reduction over TWC without the adsorber;
      3.8 litre V6 Buick = NMHC: 62, CO: 20, NOx: 3% reduction over TWC without the adsorber.
    - NGK Insulators Study (SAE970266): 2 vehicles, low S (<100 mg/kg) Japanese fuel (in-line HC adsorber technology)
      2.0 litre Toyota Camry (model year 1988) = NMHC: 0.049 (97.2% reduction), CO: 0.639, NOx: 0.200 g/mile
      3.8 litre Buick LeSabre (model year 1995) = NMHC: 0.052 (96.3% reduction), CO: 0.768, NOx: 0.162 g/mile
- Compared to other fast light-off technologies, relatively cheap: the zeolite-based Corning system is expected to add only 50 to 75 US$ to the cost of a converter.
- A passive system and has no moving parts.

Disadvantages

- Low molecular weight hydrocarbons are not trapped effectively, hence the overall (mass and/or reactivity) trapping efficiency is closely related to the distribution of HC species in the exhaust.
- No pre-lightoff control for other pollutants.
- Possible sulphur sensitivity (see Fuel Implications).
- Packaging (large volume of the unit).

Fuel Implications

- As the exhaust gas composition is significant in determining the overall trapping efficiency of the adsorbent, the fuel composition will play a part.
    - One study (Ford; SAE941999) indicated that a "conventional" US fuel was more prone to lower the reactivity trapping efficiency than the US reformulated fuel, as larger a proportion of the total reactivity was contributed by light HCs in the exhaust from the conventional fuel.
    - May be subject to fuel sulphur sensitivity. One HC trapping system used in the experimental Honda Accord EZEV is said to require low sulphur fuel (information from Honda).

Fuel Consumption

- Impact on fuel consumption is considered to be small.

Likelihood

- The hardware and the adsorbent technology are currently available (e.g. Ford, JM and Corning), but the wide introduction into the market place is considered to be unlikely.

Description

HC adsorption is an approach to reduce cold start HC emissions by means of a HC trap to collect and store hydrocarbons from the exhaust in the first several seconds of operation using an adsorbent, e.g. activated carbon or a zeolite material. An adsorbent would be placed in the exhaust system collecting and holding hydrocarbons until the catalyst lights up. The hydrocarbons could then be released from the trap to be converted by a traditional three-way catalyst located either downstream (JM system, SAE970741) or on the same monolith as the hydrocarbon trap (Corning system, SAE970267).

4.1.15. Saab "Cold Start" Exhaust Emission Bags (SCB)

Application

- Gasoline vehicles of all sizes for the moment.

Advantages

- Potential for reduction in cold start emissions: Saab claim that this technology will meet ULEV standards, HC = 0.029 g/mile vs. 0.125 for the cleanest currently available US engines, NOx = 0.09 Vs 0.40, CO = 0.50 Vs 3.40.
- Simple yet effective technology.
- Relatively cheap add-on costs (ca. $150 per vehicle).

Disadvantages

- Spatial logistics for the bags in the vehicle.
- Durability of the bag material (polyvinyl) and potential leakage of gases into the passenger space.

Fuel Implications

- Considered to be small.

Fuel Consumption

- Impact on fuel consumption is considered to be small.

Likelihood

- The hardware is currently available and Saab are planning to introduce this system in the next 1-2 years, but the possibility of a wider introduction into the market place is uncertain.

Description

Saab developed a boot-mounted polyvinyl sack (two will be mounted in the rear wheel-arches) that collects the cold start exhaust in the first 25 seconds. The gases are then gradually released from the bags (volume = 100 litre) and recycled through the engine.

4.1.16. MPI Lean-burn (ILB)

Applications

- Gasoline Engines

Advantages

- Fuel economy typical 10% (over Japanese 10.15 cycle), range reported from 5 to 20% (if combined with CVT), benefits in Europe may be lower

Disadvantages

- Cost penalty up to 5% compared to conventional design.
- Control difficulty of complex operation.
- For Euro 4 a lean De-NOx catalyst or NOx trap will be needed with moderate conversion efficiency.
- To address HC cold start emissions problem.

Fuel Implication

- Potential problem with oxygenates. Oxygenates can misinform the EMS system causing poor driveability and increased HC emissions.
- For moderate NOx conversion with more sulphur tolerant de-NOx catalyst fuel sulphur level of 200 mg/kg will be adequate.

Fuel Consumption

- Typical 10 percent (over Japanese 10.15 cycle) improvement compared to conventional design though higher figures are quoted (16% Mazda, 20% Honda when plus CVT). In Europe, benefits may be lower.

Likelihood

- Several makes and models currently marketed in Japan. To meet Euro 3 an evolutionary change is expected. For Euro 4 a lean de-NOx catalyst or NOx trap will be required.
- An alternate route may be use of a sulphur trap upstream of the NOx storage catalyst.

Description

The aim of MPI Lean-burn is complete or almost complete combustion of the air- fuel mixture so that fuel consumption is reduced and levels of pollutants controlled. Engines can now operate with high air-fuel ratios (e.g. 21-23) under part throttle conditions.

Common features of various designs (Toyota, Honda, Mazda, Nissan, Mitsubishi) are :

- Improved in-cylinder gas motion (e.g. through creation of swirl, vortex, tumble) by means of swirl control valve, design of intake port, Variable Valve Timing (VVT). The combustible mixture may be homogeneous, slightly stratified or stratified depending on the design.

- Advanced air / fuel mixture control by means of sensors (A/F, O_2, combustion pressure) and powerful EMS.
- Advanced TWCs (CC (close coupled), wide range or plus de-NOx cat).

References

Indirect (MPI) Lean-burn:

1. Killman, G. (1995) The lean burn engine: recent developments by Toyota. Presentation at the course 'Spark ignition engine emissions', 27 November - 1 December 1995

2. Boosman, D.J. (1993) Verbeterde Toyota lean burn motor: zuinig, maar óók schoon? (Improved Toyota lean burn motor) *Auto + Motortechniek 53, 11, 30-33*

3. Honda (1998) Honda develops new 3-stage VTEC engine. *Asia-Pacific Automotive Report 218, 25-27*

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7. Takami, A. et al (1995) Development of lean-burn catalyst. SAE Paper No. 950746. Warrendale PA: Society of Automotive Engineers

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9. DeNOx cat. Zeolite based plus TWC (Nissan). *Asia-Pacific Automotive Report 216*

4.1.17. Stoichiometric Gasoline Direct Injection (SG-DI)

Application

- Gasoline vehicles of all sizes.

Advantages

- Ca. 10% fuel consumption (or CO_2) benefits achievable (Fiat paper, AVL Engine & Environment Conference '97) over conventional engines through higher compression ratio and EGR tolerance,
- Enhanced performance (6 - 10% BEMP gain) through optimised charge homogenisation and increased compression ratio (Fiat paper, AVL Engine & Environment Conference '97).
- No lean-running engines' problems with NOx seen in lean-burn DI engines. Fiat claim a 50% reduction in NOx compared with lean-burn G-DI such that Euro 4 can be reached with conventional exhaust after treatment (FT Auto. Env. Anal., No. 33, Oct. 1997).
- The $\lambda = 1$ engine is less demanding on injector and combustion system characteristics than lean G-DI engines leading to cost advantage.

Disadvantages

- Fuel consumption benefits slightly smaller than lean-burn direct injection engines, i.e. 10% over conventional engines in stoichiometric G-DI compared to 15 - 20% in lean-burn G-DI (FT Auto. Env. Anal., No. 33, Oct. 1997).
- Deposits (both IVD (Intake Valve Deposits) and CCD (Combustion Chamber Deposits)) could be a problem, especially the inlet valve is no longer subject to detergency provided by the fuel.
- Possible lube thinning through direct fuel spray impingement on cylinder wall leading to cylinder bore wear
- Fuel pump failure (high pressure fuel injection system)
- Cost may be higher than MPI, but no numbers available yet.

Fuel Implications

- In general, considered to be similar to conventional gasoline engine. Fuel lubricity could be a factor with respect to potential fuel pump failure problem.

Fuel Consumption

- Fiat claim ca. 10% fuel consumption benefits can be achieved over the conventional MPI engine (FT Auto. Env. Anal., No. 33, Oct. 1997).

Likelihood

- Many OEMs are believed to be working on the stoichiometric GDI concept. Fiat are reported to consider this technology to be the most promising alternative to DI diesel; though no announcements on launch yet.

Description

The G-DI technology is based on the injection of fuel into the combustion chamber, instead of the intake port or the throttle body. However, unlike lean GDI, $\lambda = 1$ operation is maintained.

The benefit of direct injection of fuel in cooling the intake charge within the combustion chamber (seen in lean G-DI engines) is utilised to improve volumetric efficiency. The latter is further improved by the fact that the much finer fuel droplets vaporise more easily and penetrate less, i.e. not hitting the walls, and all the heat would be subtracted from the air instead of the walls as is normally the case in PFI engines. One of the consequences of the lower charge temperature is the possibility of increasing the knock-limited compression ratio as seen in lean G-DI (Fiat data show knock was detected at 7 CAD more advanced ignition setting in stoichiometric G-DI engines). The combined effect of improved volumetric efficiency and increased compression ratio is the performance benefit manifested by a BMEP gain (up to 10%) and BSFC improvement (ca. 3%).

Although the $\lambda = 1$ G-DI EMS can be based on existing PFI hardware/software, the injection timing remains flexible which is an important advantage for the general G-DI concept. The flexible injection timing was utilised by Fiat to show that retarding the injection timing can achieve emission reduction potentially down to the Euro 4 level but with increased fuel consumption.

Two combustion chamber layouts were considered by Fiat (Fiat paper, AVL Engine & Environment Conference '97): (1) central injector position with both the injector and the spark plug situated in the centre of the combustion chamber, and (2) side injector position where the injector is placed between the intake ports while the spark plug is in the centre of the combustion chamber. The central injector system was shown to give slight advantage in terms of charge homogenisation and HC emissions but the differences were small and the configuration is considered to be governed mainly by manufacturing issues.

4.1.18. Lean-burn Gasoline Direct Injection Engine (LG-DI)

Application

- Gasoline vehicles, all sizes.

Advantages

- Running lean offers the lowest fuel consumption for gasoline engines. The Mitsubishi's Carisma, now sold in Europe with a G-DI engine, has a fuel consumption which is 19% lower than the equivalent MPI engine (see end of this section) equipped vehicle. CO_2 emissions are very similar to those from a Direct Injection Diesel Engine [1].
- Engine out NOx emissions are up to 90% lower than engine out NOx emission from a conventional MPI engine [2]. Nevertheless, after-treatment is still required for Euro 3. Mitsubishi has already launched a "D3" version capable of meeting the D3 German emissions standards, which are similar to Euro 3.
- Better torque and driveability than the MPI engine.

Disadvantages

- More costly than current gasoline engines ($200? per engine)
- After-treatment required to provide high NOx reduction (70 - 80% ?) under lean conditions to meet Euro 4. Today, such an efficiency is only achievable by NOx storage catalyst.
- Produces particulate. The available data indicate some emissions, about 0.013 g/km on a cold start MVEG test.
- Some concerns have been raised about possible increased wear due to the fuel spraying onto the lubricating layer on the cylinder liner.

Fuel implication

- Without major advance in the technology of NOx reduction after-treatment, low sulphur gasoline (<50 mg/kg) will be required to meet Euro 4 because of the use of NOx storage catalysts. Communication with a manufacturer has revealed that Euro 3 G-DIs with NOx reduction catalysts could achieve the emissions standards with Euro 3 sulphur levels.
- Fuel distillation probably affects combustion process, through volatilisation in the combustion chamber. The more volatile the fuel, the better the combustion, but such an effect has not been quantified yet.
- This technology is likely to induce specific deposit formation on piston, injector tip, probably with fuel compositional effects. However, no combustion chamber deposit problem has been reported yet in Japan, where this technology is marketed since autumn 96.
- Potential inlet valve deposit problems. Deposit build up can still occur due to lubricating oil on the valve, EGR and fuel being drawn back into the inlet manifold. In a G-DI there is no fuel spray onto the back of the valve, and therefore no associated detergency, required to help clean up the valve.

- The octane rating of the engine is probably different from that of a conventional stoichiometric engine, but no data are available yet. Octane requirement may be decreased by 6 ON. However, most OEMs will take advantage of this reduced octane requirement by increasing the compression ratio. This would increase the volumetric efficiency and hence give additional improvements in fuel economy.

Fuel consumption

- The lowest fuel consumption for gasoline engines. Mitsubishi claims 6.3 l/100 km on the MVEG test cycle for the 1.8 litre G-DI Carisma (European Specification).
- Recent investigations showed that fuel consumption strongly depends on driving pattern. In an aggressive driving pattern, the engine frequently runs at high load, where it is set stoichiometric by the Engine Management System. The fuel economy advantage of lean-burn is lost in that case.

Likelihood

- Toyota, Nissan and Mitsubishi market vehicles equipped with G-DI engines in Japan, and Mitsubishi also market a vehicle in Europe. Mitsubishi's monthly production in Japan is about 20 000, but no number is available yet for sales in Europe. Mazda also seems very active in G-DI R/D.
- Attractive technology for EU because of the low fuel consumption and low CO_2 emissions. Several European engine makers are seriously considering it [3].
- To achieve Euro 4 emissions limits and maintain a reasonable fuel economy benefit it currently seems likely that G-DI will have to be equipped with NOx storage catalysts. These are currently extremely sensitive to sulphur. See NOx Storage catalyst for more explanation.

Description

The G-DI technology is based on the injection of the fuel into the combustion chamber, instead of the intake manifold as for conventional port injected engines. Specific high pressure injectors (up to 120 bar) have been developed for G-DI.

Direct Injection Gasoline offers several modes of operation, which are under the control of the Engine Management System :

- If the fuel is injected during the compression stroke, the air-fuel mixture remains stratified (a rich zone and a very lean zone). In combination with the required aerodynamics (swirl or tumble motion), the fuel charge is transported to the spark plug, allowing good ignition even when the overall air-fuel mixture is very lean.
- If injection occurs early in the intake stroke, the air-fuel mixture is homogeneous. Depending on the amount of fuel which is injected, the mixture can be stoichiometric or lean.
- Fuel can be injected at more than one point in the cycle. For example, a small injection during intake stroke, and a large one during compression stroke (so-called « two stage mixing ») or also a small injection during expansion stroke (« two stage combustion »). The first strategy improves engine performance, the second one speeds up the light-off of the catalyst.

Running stratified is only possible at low speed (idle, or constant and low vehicle speed), homogeneous lean at intermediate conditions, and stoichiometric is the only possible mode at high load.

Expanding the field where the engine runs stratified improves fuel economy, but deteriorates NOx emission. This trade-off situation will result in different control strategies in Japan and in Europe because of different driving condition and test cycles. This will result in a different fuel economy benefit and different regulated emissions.

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4.1.19. NOx Storage Catalyst (NSC)

Application

- Lean-burn gasoline vehicles, all sizes. In use by Toyota in Japan.
- Application to diesel cars or trucks being considered, but no operational system is currently available.

Advantages

- The most efficient existing lean NOx catalyst, about 80% NOx removal. Only advanced SCR systems (urea injection with advanced ammonia slip control) could do better, but are not available yet.

Disadvantages

- Works in combination with an advanced Engine Management System (EMS), which periodically produces rich excursions to regenerate the catalyst.
- As it is very sensitive to sulphur, the activity of currently marketed catalysts is deteriorated if the sulphur content of the gasoline is greater than 50 mg/kg, even for a short period.

Fuel implication

- Current catalyst require a very low sulphur gasoline content (<50 mg/kg). This is due to the blockage of NOx storage sites by sulphates. Communication with Japanese manufacturers has revealed that NOx storage catalysts may be able to operate on Euro 3 sulphur levels by 2001.
- OEMs are currently investigating improved thermal management of these systems to reduce their sensitivity to sulphur [1]. Catalyst manufacturers are currently investigating the possibility of sulphur tolerant systems ([2], [3]).
- Another concept for improving the sulphur tolerance could be the use of a SOx trap upstream the NOx storage catalyst.

Fuel consumption

- If high sulphur gasoline is used, rich excursions have to be longer or more frequent, with a negative impact on fuel consumption. No number available yet.
- Minor penalty, similar to the one of TWC, because of the very small backpressure created by pressure drop.

Likelihood

- This technology is being used on Toyota's lean-burn engines (MPI & G-DI) in Japan, but not in Toyota's lean-burn vehicles in Europe. All catalyst makers are active on R/D levels.
- It is likely to come onto the European market if an acceptable trade-off can be founded between catalyst sulphur tolerance and effective sulphur levels that could be achieved in the European gasoline.

Description

NOx storage catalyst typically incorporates barium oxide into a conventional Three Way Catalyst (TWC) formulation. When the engine runs lean, the NO (nitric oxide) reacts over the catalyst to form barium nitrate. When the EMS evaluates that the catalyst is close to saturation in NOx, it triggers a very short (0.3 s in Toyota's system) gasoline rich excursion which generates carbon monoxide and unburnt hydrocarbon. The nitrates are decomposed to NO_2, which then react with the available reductant over the catalyst to form nitrogen.

The sulphur oxide also reacts with the barium oxide to form barium sulphate and thus competes with the nitric oxides to form barium nitrate. The barium sulphate blocks the NOx storage, resulting in a loss of efficiency of the catalyst. Through desulphation, the NOx storage catalyst could be regenerated at higher temperatures (about 650°C) at the expense of some fuel consumption (fuel enrichment during desulphation).

Effect of sulphur at levels up to 150 mg/kg has been recently found to be irreversible for the Toyota NOx storage catalyst. Also, road ageing of these catalysts has revealed that the catalysts activity is severely degraded by 5,000 km ageing on 30 mg/kg sulphur fuel. This suggests that these catalysts are either extremely sulphur sensitive or are not thermally durable under typical European driving conditions.

References

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4.1.20. Controlled Auto-Ignition Engines (CAI)

Applications

- Two- and four-stroke gasoline engines.

Advantages

- Fuel economy improvement of 27 - 29%.
- Significant lower CO, HC (50% - 99%), NOx (40%) emissions.
- Improvement in driveability.

Disadvantages

- Production prototype stage of two-stroke engines, development stage of four-stroke engines.

Fuel implications

- Not clear. Conventional octane number may not be anymore relevant characteristic.

Fuel consumption

- Significant improvement (comparable to DI engine). 27 to 29% claimed for Honda Arc.

Likelihood

- To be introduced as a 2-stroke engine for motorcycle production.
- Development of a 4-stroke engine announced.

Description

Third combustion process applied to the piston-compression, internal combustion engine. (The first and second types are the spark-ignited gasoline and the compression-ignition diesel process). In given field of engine conditions (Medium and high speed, low to medium speed) combustion occurs by a smooth auto-ignition, controlled by the temperature of the residual exhaust gas and the pressure remaining in the cylinder when the exhaust port is closed.

Pressure at exhaust closing is regulated by a movable valve to throttle flow at the exhaust port and thus higher pressures are retained in the cylinder.

Spark ignition is still employed at very low load (Not sufficient temperature with little incoming charge) and at high loads (Too little residual charge and heat from the charge). A high rate of EGR seems to be the key feature.

References

Controlled Auto-Ignition Engines:

1. Honda (1997) Honda readies activated radical combustion two-stroke engine for production motorcycle. *Automotive Engineering* *January 1997*, *90*

4.1.21. Iridium containing catalysts for lean-burn gasoline engines (IRC)

Application

- Lean-burn gasoline engines.

Advantages

- Provide sufficient conversion to enable G-DI engines to meet Euro 2 and Euro 3 emissions limits.
- These catalysts are sulphur tolerant (H Ando, Mitsubishi, at AVL “Engine and Environment Conference”, & SAE972850). Mitsubishi claim no adverse effect of long-term operation on 440 mg/kg m/m sulphur. (Mitsubishi Web site).
- Show adequate thermal durability for lean-burn engines (SAE972850)

Disadvantages

- Current formulations do not provide enough conversion for Euro 4.
- Some concern about the volatility of iridium. Volatile at temperatures above 800°C. Possible toxicity issue.
- Because of thermal limitations (see above) catalysts will be in underfloor location with TWC downstream. Thus, the TWC will be at lower temperature than normal and therefore will not reach light off temperature as quickly.
- There is some concern over the thermal durability of these catalysts due to the potential loss of iridium during high temperature operation.
- Currently the cost of iridium is not prohibitive, however the availability and cost of iridium may prevent the widespread use of such formulations.

Fuel Implication

- Does not require low sulphur for Euro 2 and Euro 3.

Fuel Consumption

- Does not require rich mixture strength spikes for catalyst regeneration, and thus will provide a small fuel consumption benefits over NOx traps. Conversely, does not provide same degree of NOx conversion under lean operation as NOx storage catalysts and therefore may result in less lean-burn operation of the vehicle.

Likelihood

- Currently in European market on Mitsubishi G-DI Carisma.

Description

These systems contain about 2 g/litre of iridium as catalyst and give a maximum NOx conversion under lean-burn conditions of about 70% at a catalyst temperature of about 380°C. The catalysts are used immediately upstream of a conventional three-way catalyst. It is unclear how these iridium based catalysts work.

4.1.22. Variable Valve Timing (VVT)

Application

- Gasoline vehicles

Advantages

- Improved fuel economy (10 - 15%) (6th. Aachener Kolloquium, 1997, p. 985)
- Reduced exhaust gas emissions (especially NOx up to 80%) (Paramins Post, Spring 1998), in complete engine map and during cold start and warm up
- Increased volumetric efficiency and high ‘ low end torque ‘
- Potential for idle speed reduction due to minimal residual gas fraction
- Valve- and cylinder deactivation
- Improved engine transient behaviour

Disadvantages

- Practical implementation of a flexible VVT system remains engineering challenge

Fuel Implications

- None

Fuel Consumption & CO_2 Emissions

- Significantly improved (10 -15%)

Likelihood

- Simple VVT systems (hydraulic/Alfa Romeo, mechanical/Honda VTEC) already in market
- Prototypes of fully independent VVT (electromagnetic/FEV, electrohydraulic/ Fiat) exist
- Higher market penetration of simple and more complex VVT systems expected

Description (general principles of technology)

To meet conflicting requirements engines can have a variable valve timing or valve lift versus the cam angle, described as a variable valve actuation system (VVA) or as a variable valve timing system (VVT).

Different possibilities in valve lift variation exist. Less sophisticated systems are able to vary only the phasing shift of the camshaft. More sophisticated systems vary more parameters such as phasing, lift, opening duration or even combine these variation possibilities. They can be classified as follows (6. Aachener Kolloquium Okt. 20-22 1997, p.985):

1. First generation system (shifting of the valve lift): the valve lift contour remains unchanged, only the phasing of the valve lift is varied. Such systems known as Variable Cam Phasing (VCP) systems have become standard in high

performance cars. Due to an optimized intake valve closing time, engine torque can be increased (from 3 to 8%). Additionally the reduction of the valve overlapping time during idle operation results in better idle quality.

2. Second generation system (restricted variation of the valve lift contour (or deactivation of an intake valve): such systems enable a variation of the valve lift contour within restricted ranges (VTEC/ Honda, MIVEC/Mitsubishi). As the whole lift lapse can be varied for maximal performance in the entire speed range their potential for torque optimization is significantly higher than VCP systems (from 6 to 12%).

3. Third generation system (fully flexible variation of the valve lift contour for load control (VVA)): advanced systems envisaged to fully exploit the variable valve control concept potential through a complete and highly flexible Electronic Control of the valves opening laws (EVC system). Two main technologies are the electro-magnetic and the electro-hydraulic system.

The electro-magnetic system is based on the electromagnetic oscillation principle (Tec Info FEV) with electromagnetic holding of the valve in both final positions. The switching time amounts to 3 ms to open (or close) the valve. The valve opening duration can be adjusted freely. The switching time and the seating velocity are no function of engine speed and load.

The electro-hydraulic EVC system operates in a continuous mode. Tappet and brake piston are connected through an oil chamber, which is closed by a solenoid valve.

Variable valve timing allows for an optimum gas exchange throughout the engine speed and load range. Control of the cylinder charge by early intake valve closing minimizes gas exchange pumping losses with corresponding improvement in fuel consumption. The combustion process is improved because the composition of the cylinder charge is adjusted by varying the time of the intake valve opening as a function of load and speed (e.g. improvement of IMEP (Indicated Mean Effective Pressure) of 30 percent at low engine speed with electro-magnetic controlled engine).

The EVC system based on the electro-hydraulic valve actuation, gives rise to an improvement of engine torque and power density close to 25% and to a reduction of consumption of 15%, while maintaining low emission levels.

A minimized residual gas fraction at idle, an increased residual gas fraction for stoichiometric mixtures and a lower residual gas fraction for lean mixtures improve the fuel consumption and the exhaust gas emissions effectively, especially the NOx emissions. Under full load conditions the maximum volumetric efficiency is increased by an optimized time of intake valve closing.

4.1.23. Variable Compression Ratio Gasoline Engines (VCR)

Application

- Light duty gasoline vehicles.

Advantages

- Up to 34% reduction in fuel consumption, without lean-burn operation (Saab/Swedish EPA).

Disadvantages

- Cost and durability?
- Need to have rapid change in compression ratio. Otherwise may experience knocking problems.

Fuel Implication

- Provides fuel economy benefit without running under lean-burn conditions and therefore does not require an enabling fuel (low sulphur).

Fuel Consumption

- Up to 34% reduction in fuel consumption

Likelihood

- Patented in 1981 by Saab. Ongoing R+D. Saab will be manufacturing 80 engines for product development and verification of functionality, emissions and durability.

Description

The compression ratio of conventional gasoline engines is limited to between 9 and 11:1 by their octane requirement at high load. However, maximum thermal efficiency and therefore fuel economy is obtained in the range of 13 to 14:1. An engine with variable compression has the potential to be optimised with a high ratio for best fuel economy at the part load conditions typical of normal driving, while allowing detonation free full load operation at a lower ratio.

Direct injection gasoline engines allow compression ratios of up to 12.5:1 to be used. Increasing compression ratio from this towards 14:1 with a variable compression ratio engine does not provide a large benefit.

It is believed that Saab control the compression ratio by mounting the cylinder head on a hinge. Saab have a patent on the sealing mechanism used on the “open” side of the chamber.

4.1.24. Emerging Gasoline Engine Technologies (EGET)

Application

- All gasoline engines.

Advantages (general)

- Improvement in fuel economy/CO_2 emissions.
- Reductions in emissions.

Disadvantages (general)

- Increased complexity.
- Cost.

Fuel Implications (general)

- In general, reduced sensitivity to gasoline properties expected.

Fuel Consumption

- In general, significant reduction expected.

Likelihood

- The systems described here are all available now as workable prototypes.

Description

Skip firing (e.g. Rover): generate "residuals" which are burnt gases from the previous cycle that remain in the cylinder. The residuals give benefits by diluting the charge with inert gases (N_2, CO_2, H_2), lowering in-cylinder temperature and thus NOx. The reduced temperature also lowers wall heat transfer temperature improving fuel consumption. Less throttling is required for the same intake air flow rate which reduces the pumping loss and again improves the fuel consumption. Rover claim that high residual levels can achieve up to 90% NOx reduction and 7% fuel consumption reduction.

Air assisted injection (e.g. Orbital, GM Corsa): is based on the principle of pre-mixing the charge and then inject either directly or indirectly into the combustion chamber. The Orbital system, for example, has the fuel injector which injects a precisely controlled quantity of fuel into an air chamber. The air injector is then used to deliver the air and fuel mixture as a finely atomised cloud that is immediately ready for combustion. The key features include better atomisation and fast evaporation of fuel, and lower pressure for fuel injection (esp. in a DI engine). The ability of good charge preparation even for the late injection strategy, the air assist system is less engine speed dependent, enabling good control of both stratification and NOx control across the operating speed range.

The 3-valve engine concept (Mercedes-Benz): will be used in the new Mercedes-Benz 2.8 and 3.2 litre V6 engines with 150/165 kW power output at 5,700/5,600 rpm respectively. The engines consist of 2 inlet valves and a single, large, sodium-cooled exhaust valve with a 41mm-diameter head. The surface of the exhaust port is smaller (typically 30% smaller) than that of a 4-valve engine of similar dimensions, resulting in significantly lower heat loss (a temperature gain of ca. 70°C) in the exhaust gas flow resulting in quicker catalyst light-off, resulting in 40% reduction in pollutants (Automotive Engineer, Dec. 1997).

However, at start-up, ignition is retarded by 5 -10° crank angle leading to reduced engine efficiencies. The 3-valve technology allows enough room to fit a second plug, shortening flame travel. The two plugs are located close to the cylinder wall to achieve almost complete mixture ignition. Dual ignition allows more EGR leading to fuel consumption benefits.

Cylinder deactivation (e.g. Lotus): cylinder deactivation (CDA) can be achieved in a number of different ways:

(a) the simplest way is to turn off the fuel injector & spark stopping the combustion process in the chosen cylinders. This has several drawbacks, e.g. unburned HC can be passed from the intake manifold through the engine into the exhaust manifold, and the pumping losses of the engine will not be significantly reduced as the deactivated cylinders will still be pumping air through.

(b) disable either the intake or exhaust valve(s). If either valve(s) is disabled air will not be pumped through the engine preventing the HC problem, however some pumping losses will still be incurred.

(c) disable both intake and exhaust valves. There will be no HC passing through the affected cylinders and also the pumping losses will be all but eliminated from these cylinders (Lotus claim fuel consumption savings of ca. 15% is possible).Diesel Technology Reviews.

4.2. DIESEL TECHNOLOGY REVIEW

4.2.1. Oxidation Catalyst (OXC)

Applications

- Light and heavy duty diesel engines.
- (2-Stroke gasoline engines.)

Advantages

- LD: Reduction of TPM (30%), PM (SOF) from 20 up to 50 percent.
- HD Bus: Reduction of TPM: up to 30% for 500 mg/kg sulphur.
- HD Truck: Reduction of TPM: 20% to 30%
- General tendency to decreased mutagenicity due to elimination of PAHs.
- Reduction of HC up to 75 percent.
- Reduction of CO up to 70 percent.
- Version with NOx reduction (up to 15%) capability.
- Improvement of diesel exhaust odour.

Disadvantages

- No universal catalyst. A limited temperature window exists due to trade-off between HC (and SOF) conversion and sulphate production.
- Particularly for light duty cars catalyst light-off difficult at cold start or urban conditions. N_2O formation possible.
- Possible sulphate, thus extra PM formation at high temperature due to SO_2 oxidation and sulphate storage. Thus merits less in heavy duty as the SOF of PMs is lower and SO_2 oxidation becomes more critical (European cycle (R49), not US transient cycle), depending on the exhaust temperature (e.g. Bus vs. Truck). Catalyst specifications for heavy duty geared to ECE-R49 cycle, therefore a problem for high conversion at low exhaust gas temperature conditions.
- Reported formation of aldehydes.

Fuel Implication

- Much progress has been made to make the oxidation catalyst more sulphur tolerant (less sulphate formation).
- Sensitivity of vehicle emissions to fuel changes (density, cetane number) are reduced by the catalyst.

Fuel Consumption

- Considered to be small.

Likelihood

- Currently used in light duty and heavy duty (mainly US) diesel vehicles.

- Expected more generalised use in heavy duty diesel, possibly in combination with particulate trap.

Description

Underfloor ceramic monolith catalyst with Pt as active noble metal on wash coat to oxidise CO, HC and PM (SOF) under lean conditions.

The carbon fraction of the PM remains unaffected.

New version with improvement of interaction between support, stabilisers and promoters with the precious metal package led to high CO and HC activity, better thermal durability and better sulphur tolerance with15% NOx reduction.

References

Oxidation Catalyst:

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5. Wyatt, M. et al (1993) The design of flow-through diesel oxidation catalysts. SAE Paper No. 930130. Warrendale PA: Society of Automotive Engineers

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4.2.2. De-NOx - Selective Catalytic Reduction - Reducing Agent: UREA (SCR)

Applications

- HD Diesel - Likely
- Not likely for LD Diesel

Advantages

- High NOx conversion: 60-90% (SAE952493) and is the highest at present for diesel
- HD will comply with indicated Euro 4 NOx emissions (SAE970185)
- No NOx/PM trade-off penalty; the NOx abatement doesn't result in a PM emission increase
- No impact on engine
- Low NOx to N_2O conversion rates
- Sulphur tolerant - can be used with 500 mg/kg sulphur (SAE952391)

Disadvantages

- Urea injection equipment required (tank, nozzle, air blower)
- Possible ammonia slip
- NOx or NH_3 sensor required in order to optimise the urea injection
- Oxidation catalyst might be required to avoid ammonia slip (see Oxidation Catalyst section - sulphur tolerance)
- Packaging problems (estimated minimum tank capacity: about 40 l)
- Refilling problems (infrastructures needed; probably, methods to compel the replenishment of the urea tank have to be employed)
- High freezing point of the aqueous solution (-11°C)
- Reversible ammonia-sulphates formation (200-300°C) (SAE952493)
- Cost: $4000 to $5000

Fuel Implications

- Fuel with low sulphur levels might be required, if an oxidation catalyst was used, to avoid reversible ammonia-sulphate formation.

Fuel Consumption

- No penalty on fuel consumption.

Likelihood

- The introduction of this technology is considered probable for heavy duty applications. Urea lean NOx catalyst systems are currently under fleet testing.
- Packaging problems and high costs are likely to prevent the use of SCR for passenger cars (possible exception: very large sized cars).

Description

This technology is based on the injection of urea as an aqueous solution into the exhaust gas before the catalyst with an air assisted injection nozzle (SAE952493). The use of powdered urea is also being considered, in order to avoid the freezing issue.

The injection rate must be carefully controlled to avoid ammonia slip or low NOx conversion.

Urea reacts with NOx to form N_2, H_2O, CO_2.

The catalyst is based on metal oxides, namely V_2O_5,TiO_2 and WO_3.

The optimum operating temperature range is 250-500°C.

4.2.3. De-NOx Catalyst - Passive (FWC)

Applications

- HD Diesel
- LD Diesel

Advantages

- NOx abatement: 5-20% (LD: SAE952491, SAE950751), SAE 980191 (HD/LD: SAE962041) (HD: SAE961129)
- Low complexity of implementation (as the 3-way catalyst technology)
- No or low impact on engine

Disadvantages

- Low NOx conversion efficiency due to the low hydrocarbon selectivity. Only 10-15% of exhaust hydrocarbons are used to reduce NOx; the remaining 85-90% are oxidised (SAE950747) (SAE952491).
- Hydrocarbon exhaust enrichment is currently needed to improve NOx abatement
- LT catalyst:
  - narrow temperature range of activity (200-300°C)
  - high sulphate formation rates at high temperatures(SAE950747)
  - high NOx conversion to N_2O at low temperatures (ca. 50-90% of the NOx reduced goes to N_2O; N_2O is a greenhouse gas) (SAE950747)
- HT catalyst:
  - active above 350°C
  - poor stability in a moist environment at high temperature due to de-alumination of the zeolite (SAE952491)
  - high sensitivity to SO_2, high sulphate formation (SAE952491)
- Possible need of combinations of different catalysts to cover the whole exhaust temperature range
- No catalytic technology available for NOx reduction below 150-100°C. Possible need for NOx traps (SAE952491)

Fuel Implications

- At present, some De-NOx catalyst technologies currently available might require fuels with low sulphur levels in order to avoid SO_2 impact and high sulphate formation (LD: SAE950750) (LD/HD: SAE950149) (HD: SAE942066). New catalyst formulations are more sulphur tolerant and show reduced SO_2 to SO_3 conversion (LD: SAE952491) (HD: SAE961129).
- LD Diesel
  - Sulphate formation is not a problem for light duty vehicles because of the low exhaust temperatures occurring during the MVEG test cycle. Since

Pt-based catalysts show good ageing stability, with a 500 mg/kg fuel sulphur level (SAE 980191), even 500 mg/kg may be adequate for a passenger car equipped with such a catalyst.

  - If in addition a NOx trap and/or a high temperature catalyst (zeolite based) are used, low sulphur levels might be needed to avoid excessive catalyst deactivation.

- HD Diesel
  - Using a Pt-based catalyst the sulphate formation is high because of the high exhaust temperatures occurring during HD engines test cycle.
  - High temperature catalysts require low fuel sulphur level due to their high sensitivity to SO_2.

Fuel Consumption

- No FC penalty

Likelihood

- Methods of catalytic conversion of nitrogen oxide in lean exhaust gas are on the threshold of operability. However, their efficiency is very far from that of the 3-way catalyst and a breakthrough in the technology is still required in order to improve NOx conversion rates. (SAE962041)
- Nevertheless, in order to make diesel passengers cars meet 2005 emission standards, the development of an efficient De-NOx catalyst is considered necessary. The alternative approach, consisting of lowering the NOx emissions by EGR and combustion improvements and reducing PM with PM traps, is considered more difficult to achieve.
- N_2O formation might become a serious issue in the future and it might be a new criterion to evaluate De-NOx catalysts performances in general.

Description

NOx abatement is achieved using the exhaust hydrocarbons as reducing agent.

Diesel exhaust conditions depend on engine type and on the certification cycle. The certification cycle for diesel passengers cars results in exhaust gas temperatures lower than those occurring during the ECE R 49 test for heavy duty engines. Consequently, the optimum catalyst operating range is different for LD and HD applications which makes it very difficult to realise a universal catalyst.

- LD optimum catalyst operating range : 150-350°C
- HD optimum catalyst operating range: 250-450°C

The catalytic materials currently available are active in a temperature range that doesn’t match the typical exhaust gas temperature range of LD and HD vehicles.

Current catalysts formulations together with their temperature range of activity are listed below:

- Noble metal catalyst (i.e. Pt/Al2O3): 200-300°C
- Zeolite based catalysts (i.e. Cu/ZSM-5): >350°C

- Special oxides (i.e. Ti, Zr, Ga) >300-350°C

No catalytic technology is available to reduce NOx below 150°C; a possible solution is to use a NOx trap that stores NOx until the catalyst temperature is above 200°C (SAE950747). An alternative approach, mostly suitable for HD applications, aiming to provide sufficient hydrocarbons for NOx reduction, is to use catalysts with HC storage ability; hydrocarbons are adsorbed at low temperature when the production of NOx is low and they are desorbed at higher temperature when NOx emissions are high (SAE961129).

Several different solutions have been proposed for LD and HD applications

- LD Diesel :
  - LT + HT with or without a NOx trap (SAE962041) (SAE950747)
  - LT + NOx trap (SAE950747)
  - Manifold LT catalyst with HC storage ability and with both internal bypass and underfloor LT catalyst with HC storage ability (SAE 980191, Mercedes C220 CDI)
- HD Diesel :
  - LT+ HT (SAE962041) (SAE950747)
  - HT+ NOx trap (SAE950747)
  - HT with HC storage ability (SAE961129) (SAE952491)

(LT: Low Temperature catalyst; HT: High Temperature catalyst)

4.2.4. De-NOx Catalyst - Active NCR (Non Selective Catalytic Reduction) - Reducing agent: hydrocarbons (NCR)

Applications

- HD Diesel
- LD Diesel

Advantages

- NOx reduction: 15-35% for LD; up to 40% for HD. (LD: SAE952491, SAE980751, SAE980191); (LD/HD: SAE962041); (HD: SAE961129)
- Higher NOx conversion rates are achieved with respect to the catalyst without hydrocarbon exhaust enrichment
- An extra fluid on board is not required; just the fuel in the tank is used

Disadvantages

- The same as passive De-NOx: narrow temperature ranges of activity, high sulphate and N_2O production (Pt-based cat), poor hydrothermal stability and sensitivity to SO_2 (zeolite based).
- Fuel consumption increase
- Too high HC/NOx ratios may result in a HC emissions increase partly due to increased untreated HC emissions and secondly due to overloading and consequent reduction in efficiency of the catalyst (SAE962041).
- An oxidation catalyst may be needed after the De-NOx catalyst to clean up HC and CO from the fuel post injection (SAE950747)
- Possible need for a PM trap due to the increased PM emissions
- A NOx sensor may be needed in order to optimise the quantity of the fuel injected
- In cylinder post injection:
  - common rail or similar devices required
  - possible increased rates of cylinder-bore wear due to oil dilution resulting from possible wall wetting fuel spray at post-injection (SAE980191)
- In exhaust post injection: - a second FIE is required

Fuel Implications

- The same as passive De-NOx catalyst; depending on catalyst type, fuel with low sulphur levels may be required to avoid catalyst activity reduction or high sulphate formation rates. For LD application, Pt-based catalysts even with HC storage ability show good ageing stability at current sulphur level (SAE980191)

Fuel Consumption

- The fuel consumption increase is proportional to the HC/NOx ratio which the catalyst requires to achieve a sufficient NOx conversion rate and is dependent on the fuel injection strategy. Fuel consumption increase is typically 1% per unit HC/NOx ratio (Ricardo).

- Typical current values are 1-4% for LD (HC/NOx ratio <5); 4-6% for HD (HC/NOx ratio of 4-6) (LD/HD: SAE962041) and 1-3% for HD (HD: SAE961129).

Likelihood

- The fuel post injection is a currently available technology (VW Passat designed to tolerate up to 0.14% sulphur fuel in the USA[1]). However, the NOx conversion is still too low and further improvements of the catalyst efficiency are required. Moreover, the fuel economy penalty may make this technology less attractive than others to enable diesel vehicles to meet the 2005 standards.

Description

Due to low hydrocarbon selectivity of current De-NOx catalysts, the addition of hydrocarbon to the exhaust gas is needed in order to improve NOx abatement. The NOx reduction rate increases as HC/NOx ratio is increased by the hydrocarbon exhaust enrichment.

There are two main methods to obtain the hydrocarbon exhaust enrichment:

- In cylinder post injection

  After the main injection and after the combustion has occurred, a small amount of fuel is injected into the cylinder in order to increase the HC/NOx ratio.

- In exhaust post injection

  The fuel is directly injected into the exhaust gas just before the catalyst.

References

1. Ricardo (1996) Current technology and future trends in automotive catalyst after-treatment development. Shoreham-by-Sea: Ricardo Consulting Engineers Ltd.

4.2.5. Diesel NOx Storage Catalyst (DNSC)

Applications

- HD Diesel
- LD Diesel

Advantages

- Potential unknown, but based on gasoline experience should exceed active diesel de-NOx systems (i.e. >50% conversion averaged over test cycle), if it can be developed. Bailey shows calculated conversion of 52% for LD vehicle in typical case, with main loss in efficiency due to low exhaust temperatures (<200°C) which are below operating range of system. (http://www.dieselnet.com/papers/9712bailey.htm)
- No additional reagent required - only normal fuel

Disadvantages

- Not yet developed, (R. Searles, AECC, at UBA Heavy duty Vehicles Workshop, 1-2 July 1996; SAE 972845) therefore many unknowns:
    - NOx conversion efficiency, at full range of operating conditions, not proven. Bailey shows conversion efficiencies >90% from 200°C to 350°C, but zero conversion below 175°C.
    - durability / reliability, particularly the effect of fuel sulphur on storage capacity, and unknown thermal ageing stability.
    - ability of developing a regeneration procedure, without excessive CO, HC or PM emissions, which may require additional or specific hardware (e.g. common rail).
    - impact of regeneration strategy on other emissions and driveability?
    - Additional hardware and control system (including sensors) to achieve NOx regeneration (desorption), and sulphate regeneration if possible.
    - cost?

Fuel Implications

- Sulphur (Sulphate) storage is a similar problem as in the gasoline case, causing gradual reduction of the NOx storage capacity. Sulphate regeneration is likely to be more difficult than in gasoline case, due to lower exhaust gas temperatures and leaner operation in a diesel engine.

Fuel Consumption

- Relatively small penalty: only due to regeneration process, but will be directly related to the efficiency of the regeneration process, and, in particular, the ability to minimise the excess oxygen flowing through the catalyst which will consume the majority of the extra HC that has been injected.

Likelihood

- Appears to be gaining significant consideration for Euro 4, as it is one of the few options that may have the potential conversion efficiency required, but due to the current immaturity of this technology for diesel engines it is very difficult to predict the outcome. If it proves capable of achieving similar NOx conversion to SCR systems, then the NOx storage route will be more favourable (particularly for LD) due to the lack of any second reagent, and thus no refilling or tampering problems.

Description

This is generally similar to the description of the gasoline system, and relatively little information is available on the diesel application. Under normal (lean) operation, the catalyst system performs an oxidation and storage function. Thus the NO is oxidised to NO_2 and, at the typical exhaust temperatures, this reacts with the Barium (the normal storage medium) to form solid nitrate which can be stored over a reasonable period of time (i.e. 60 seconds). This reaction is reversed either through an increase in the exhaust temperature or through a change in the mixture strength. In the gasoline case, the engine can be run rich for the necessary short period of time, during which the nitrate is released as NO_2 and is reduced by the CO and HC to be emitted as N_2. In the diesel engine case it is not clear if this strategy can be employed, as great care would have to be taken not to generate high levels of smoke or HC. However a high temperatures regeneration strategy is also difficult, and would require some significant engine control changes (i.e. timing retard, inlet throttling) which may not be practical under all operating conditions.

Fuel sulphur can follow a very similar reaction path to the nitrogen, and becomes stored on the trap as barium sulphate. This is however more difficult to remove than the nitrate (requiring higher temperatures), and tends to stay in place during the normal regeneration process. Thus over a period of time the sulphate fills the majority of the capacity of the trap, and the NOx storage becomes significantly reduced, reducing the efficiency of the catalyst. The removal of the sulphate may be an even greater problem for the diesel engine due to the lower and less controllable exhaust gas temperatures.

4.2.6. Diesel Particulate Trap Systems - non CRT (TRAP)

Applications

- HD Diesel Buses & Utility Vehicles - Likely
- HD Diesel Trucks - Possible
- LD Diesel - Unlikely

Advantages

- Significant Particulate Removal (Soot more so than VOF):
  - 50% to 90+% Particulate Mass Reduction - depending on Trap Type / Size (SAE960127, 960130, 960136, 960135, 950367, 950472, 960473, 950370, 950736, 950737, 952355, 952391, 950152, 950153, 950369, 942069, 942264, 970184)
- Can allow Euro 4 to be achieved on a low NOx (high PM) engine
- Can be removed for Regeneration in certain limited applications
- Can replace Muffler with no packaging change when Single Trap used
- Can allow the supply of "clean" EGR
- (Can be retrofitted - although not an issue for new production vehicles)

Disadvantages

- Cost:
  - Production costs not available, but likely to be significant:
  - Sintered metal are 5x cost of cordierite traps
  - Cost of regeneration system - burner /heater /backflow
- Reliability of regeneration:
  - Simple (passive) system - unreliable = high backpressure + large exotherms (probably leading to failure)
  - Active (fuel burner or elec. heater) system - needs reliable control system / sensors and ability to regenerate under all engine conditions
  - Active (backflow into collector) system - needs reliable control system / sensors and additional combustion / removal system
- Ash build-up (backpressure) from lubricant, fuel metal additive (if used), other debris
- Possible toxicity of fuel metal additives (if used)
- Tank for additive + system (if additive required, but not in fuel)
- Durability under Regeneration for Ceramic Monoliths
- Complexity of Regeneration System for Burner type, Backflow type
- Packaging of Twin Trap system, if used with Backflow Regeneration
- CO emissions during regeneration

- (Fuel Consumption Increase)

Fuel Implications

- No evidence of any concern over Sulphate fraction of Particulate
- May require Metal Additive to be present in fuel at pump

Fuel Consumption

- Increases in proportion to backpressure, therefore depends on trap size but there will be an additional penalty to pay in achieving a low NOx engine, which is required for this strategy - typical system may show 5%-10% increase

Likelihood

- A relatively practical way of removing the Black Smoke problem of city buses, without having to de-rate, particularly as retrofit in many fleets. For heavy duty trucks, this provides one of the two scenarios of achieving Euro 4 emissions - low NOx from cooled-EGR and injection retard / low PM from Trap - but has fuel consumption penalty from several sources - retard / backpressure - (estimate 10%). In this application it needs to be ultra reliable and durable. For light duty vehicles, the trap regeneration is more difficult due to the lower exhaust temperatures, and packaging would probably preclude any hardware additional to the trap (i.e. active regeneration systems). Since oxidation catalysts are likely to be used on LD vehicles, the CRT approach may be favourable, if NOx can be controlled.

Description

The simplest systems consist solely of some form of trap located typically where the exhaust muffler would be, and takes the full flow of the exhaust gas. There are several types of traps (cordierite monolith, SiC monolith, sintered metal woven ceramic fibre) which trap in different manners due to differences in pore size and structure, but all give rise to some exhaust backpressure which increases with the particulate loading. This backpressure can be reduced by increasing the trap volume, but will then cause packaging problems. After a given period of time it becomes necessary to remove the particulate from the trap - regenerate - in order to regain the low backpressure. In certain applications (mining, fork-lift trucks, buses) it may be possible for the trap to be removed from the vehicle at sufficiently regular intervals for external regeneration - using either a back-flushing technique or hot air flow. On-vehicle regeneration can take place naturally (SAE950151) due to the high oxygen content of the exhaust gas, if sufficiently high gas temperature is reached (>500°C). Achieving this temperature is possible in HD applications, but becomes less likely as the load factor is reduced. However, except in very predictable engine operating conditions, it is too unreliable to rely solely on this type of natural regeneration, such that much too much particulate could be trapped before the necessary conditions were met. Therefore, some more controlled form of regeneration is necessary.

Three possible routes of regeneration have been considered:

1. The <u>controlled supply of additional heat to the exhaust gas</u> in order to reach the necessary temperature, with the possible control of additional air flow. The heat can be supplied from a fuel burner (SAE 961978, 960130, 950152, 942264), from electrical heating (SAE 960469, 960470, 950737, 950152, 950153) or from control of the engine operation (SAE950737) to increase the exhaust temperature (i.e.

throttling or injection retard). The system must be capable of operating under varying engine speed / load and exhaust flow rate conditions, unless a bypass system is employed.

2. The reduction of the regeneration temperature through the use of catalysts. Either through the addition of the catalyst to the fuel (Cu, Fe, Ce) (SAE960136, 940455, 960128, 960135, 952355, 952391, 950152, 950369, 942069) or through a catalyst coating to the trap. The former shows the more promise, and there is evidence that the Ce additive also reduces the engine-out particulate mass by typically 15%. This produces a more continuous (stochastic) type of regeneration over a wider range of temperatures.

3. Back-flushing of the trap into a collector (SAE960127, 960473, 950370, 950371, 950736, 950735, 940463), where the particulate is either stored for later removal or incinerated (normally through electrical heating). The back-flush can not take place reliably while there is flow through the trap, and thus the exhaust flow must be diverted, either to a second trap or via a bypass (unfiltered) to atmosphere. The former arrangement doubles the bulk of the system. Additionally, an air reservoir, pump and multiple valve system is necessary for the back-flush procedure.

A control system is required for both systems (1) and (3), in order to decide when to regenerate, and to perform the operation. The thermal regeneration may start in only a small part of the trap, and then spread due to the heat generated. High localised temperatures can be a major problem in the low conductivity ceramic monolith, particularly if the exhaust gas flow suddenly drops during the regeneration period, as the forced convection is its only significant heat sink. Complete regenerations may take several minutes, otherwise partial regeneration will require much more frequent regeneration. A typical HD engine trap may accept 50 g of particulate before regeneration, which should be several hours of operation.

Systems involving electrical precipitators ("low voltage soot removal equipment - LVSRE") have also been investigated, but are not discussed further.

4.2.7. JM[1] Continuously Regenerative Trap (CRT)

Applications

- HD Diesel Buses - Likely
- HD Diesel Trucks - Possible
- LD Diesel - Possible

Advantages

- Significant Particulate Removal (Soot more so than VOF) - as for standard trap:
  - 80% to 90% Particulate Mass Reduction - using cordierite traps (Platinum Metals Review, Jan '95, Vol. 39, No 1; SAE 970182)
- Can allow Euro 4 to be achieved on a low NOx (high PM) engine
- Gives 2% to 7% NOx reduction (JM/Emissionstechnik, SAE 970182)
- May be retrofitted, depending on packaging of catalyst and trap
- Can allow the supply of "clean" EGR
- Should provide almost totally reliable regeneration - proven in HD, but not LD
- Gives low CO and HC emissions from high oxidation catalyst activity

Disadvantages

- Applications may be limited due to required (high) NOx / PM ratio in exhaust gas - otherwise may require de-NOx after the trap?
- Cost:
  - production costs not available, but likely to be significant:
  - suggested in excess of $1500 per vehicle
  - Currently uses cheaper cordierite traps
  - Cost of oxidation catalyst(s) with high Pt loading
- Ash build-up (backpressure) from lubricant and other debris
- Packaging of system (catalysts + trap)
- (Fuel Consumption Increase)

Fuel Implications

- Sulphur reduces effectiveness of oxidation catalyst, and thus NO_2 generation, which may reduce regeneration to below a sustainable level, and could result in trap damage/failure, but not proven.
- Currently, there is conflicting evidence for the required fuel sulphur level, and no definitive study, so pressure will remain on sulphur until proven otherwise.
- 50 mg/kg is generally accepted as OK, and JM were agreeable to 100 mg/kg (Platinum Metals Review, Jan '95, Vol. 39, No 1) and looking at extending this to 500 mg/kg, ADL quote 75 mg/kg maximum based on Swedish fleet test (no

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[1] Johnson Matthey

reference). JM quote 10 mg/kg in an article (New Scientist, April 1997), but revert to 50 mg/kg in SAE 970182, although this also shows that tests with 75 mg/kg were apparently satisfactory. This issue is the subject of current JM work.

- High level of Sulphate likely from oxidation catalyst, which may inhibit the oxidation process on the trap and still collect on the PM sample paper and show as particulate mass (insignificant?).

Fuel Consumption

- Increases in proportion to backpressure, therefore depends on trap size as for standard trap - typical system may show 5%-10%% increase, when including low NOx strategy.

Likelihood

- Currently marketed in Europe as retrofit devices. Not currently endorsed by H-D manufacturers, but Volvo may offer as an option for new buses and trucks in near future.
- Many of the comments are repeated from the standard trap section. A relatively practical way of removing the Black Smoke problem of city busses, without having to de-rate, particularly as retrofit in many fleets. Currently 1000 units are in operation in Scandinavia, in a range of H-D applications. For heavy duty trucks, this could provide one of the two scenarios of achieving Euro 4 emissions, but the high exhaust temperatures are less favourable for this system. For light duty vehicles, the lower exhaust temperatures may provide a possible application - if required in order to achieve the emissions limits - but HSDI is more NOx than PM limited, so any NOx problem would remain. Packaging could be a major problem in the LD vehicle.

Description

The trap filter works in the same way as described for the standard particulate trap, although all applications found so far have used the cordierite monolith. The regeneration differs in that the temperature of the carbon combustion is lowered by the use of NO_2 as the oxidising agent rather than oxygen. It is stated that NO_2 gives significant rates of regeneration above 275°C, enough to equal or exceed the rate of trapping. Since the proportion on NO_2 in the exhaust gas is relatively low (more NO), an active oxidation catalyst is used upstream of the trap to convert a significant proportion of the NO to NO_2. This reaction is also temperature sensitive, and has a maximum rate somewhere in the region of 300°C. Therefore, at temperatures above 400°C, relatively little NO_2 may be generated in the catalyst, and there could be a drop in the trap regeneration rate. At even higher temperatures (>500°C) the trap will regenerate with oxygen. The system should be designed to operate in the NO_2 regeneration regime, otherwise relatively uncontrolled regeneration could take place. Care must therefore be taken in the location of the system on different applications. Overall, there is apparently a small reduction in the total NOx along the exhaust system, which must result from reduction in the trap. The optimum ratio of NO_2 to particulate is not known, but the system is stated to be not suitable for use on low NOx / high PM engines. The high activity of the oxidation catalyst gives very low CO and HC emissions once the light-off temperature has been reached, but will consequently give high sulphate formation. The effect of high levels of sulphate on the trap regeneration is not clear. Nor is it clear what happens to the sulphate when the low-particulate exhaust gas is sampled on a filter paper.

4.2.8. Diesel EGR (EGRD)

Application

- NOx reduction in *LD and HD diesel vehicles*.

Advantages

- Most commonly used method for NOx-reduction until now.
- Superb trade-off flexibility for NOx/PM in combination with HP Common Rail and/or with a CRT system.
- Non-cooled:
  - Proven technology.
  - LD: Up to 30% NOx-reduction in European cycle, up to 70% reduction at 2000 rpm/cruising and constant soot level.
  - HD: Up to 30% reduction in European cycle.
- Cooled:
  - Emerging, promising technology, especially if also filtered or via ventury bypass control.
  - Provides also reduced soot/PM (MTZ/EHT 1/97).
  - LD: Up to 30% NOx-reduction in European cycle, up to 85% reduction at 2000 rpm/cruising and constant soot level.
  - HD: Up to 45% reduction in OICA cycle, or 50% in combination with non-after treatment technologies such as increased injection pressure, rate shaping, turbo-compounding.
    Up to 60% reduction in standard 13 mode cycle (TNO).

Disadvantages

- PM emissions can increase
- Increased lube oil contamination and potential engine wear
- Deposit formation into the intake.

Fuel Implications

- None

Fuel consumption and CO_2

- Small increase

Likelihood

- Non-cooled EGR;
  already in the market for LD.
- Cooled/filtered EGR;
  - soon "mature" technology (before 2000 ?)

- regarded by AVL as the only technology necessary to meet HD Euro 3 emission standards
- together with a CRT (requiring low sulphur diesel) considered to be sufficient for HD Euro 4 emission standards
- Ricardo believes EGR is one option (not necessarily needed) for Euro 3, but EGR (or SCR) will be needed for Euro 4.

Description

Max 30-40% of the exhaust is recirculated to the fresh air inlet.

Dilution - biggest effect for diesel: CO_2 in exhaust → reduced O_2 for combustion → less NOx-formation

Thermal - biggest effect for gasoline: CO_2 has high heat capacity; "heat sink"

Chemical - less effect: CO_2 dissociation

Total effect: NOx reduced due to charge air dilution and lower combustion temperatures.

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4.2.9. “Basic Engine” Design Improvements – Diesel (BEDD)

Application

- All diesel vehicles, LD to HD.

Advantages

- Better combustion quality (low soot), also at low speed
- Lower pumping losses
- Lower fuel consumption
- Reduced lube oil consumption
- Higher torque/power
- Enables new FIE like Common Rail, Unit Injector and HP Rotary pump.
- Lower charge air temperature for lower NOx and PM (more O_2)
- A simple upgrading of a HD engine from Euro 1 to 2 by improved combustion chamber design, lube oil control (piston + rings) and higher injection pressure gave 40 to 80% reductions in PM, CO, HC. A slight increase in NOx emissions was found because injection timing was optimized from OEM against Euro 2 limit. (96/60).
- Emission reductions due only to Basic engine design improvements when going from typical Euro 2 to 4 are unclear, but in view of CONCAWE report (see above) one can suggest that combined technology effects (as listed under "description" below) reduce regulated emissions significantly.

Disadvantages

- Increased cost & complexity

Fuel Implications

- Significantly reduced sensitivity to diesel properties.
- No other unwanted fuel implications.

Fuel consumption and CO_2

- LD: ~30% lower than Euro 2 (IDI) technology.
- HD: ~15% lower than Euro 2

Likelihood

- All described basic engine design technologies are introduced in the market - partly or wholly in the respective engines/vehicles, especially for HD applications.
- Most technologies will be introduced for LD applications by major OEMs before 2000.
- Market penetration in 2005 (new vehicles): 80% (Ricardo: 70% LD/DI in 2000).
- Several new diesel vehicles (e.g. Mercedes, Fiat/Alfa/Lancia, VM Motori, Renault) with parts or all of the typical technology package of HSDI engines as

listed below (+ Common Rail) have been launched, and others are announced to be on sale during 1998/99.

Description

- For LD: 4 valve high speed DI (HSDI) (all HD diesels are already DI)
- Central & vertical injector allow for new nozzle concepts
- Combustion chamber design; re-entrant combustion chamber bowl in piston.
- Central bowl allows gallery cooled piston and therefore higher thermal load.
- Inlet swirl control by port de-activation (Opel)
- Improved piston ring/groove design
- Variable geometry turbocharger (Audi)
- Charge air cooling (intercooler)

References

1. Paramins post, Spring 1998
2. Piccone, A. and Rinolfi, R. (1997) Fiat third generation DI diesel engines. Paper No. S490/004/97. Presented at IMechE - Ricardo seminar “The Euro 4 challenge - future technologies and systems” London, 03-04.12.1997
3. Peters, A. et al (1998) Catalytic NOx reduction on a passenger car diesel common rail engine. SAE Paper No. 980191. Warrendale PA: Society of Automotive Engineers
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5. VM Motori - Detroit Diesel Press release on new C.R. engine series meeting Euro 3
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8. Christmann, U. et al (1997) Opel’s new Ecotec diesel engines with Direct Injection. MTZ 9/97

4.2.10. Technology: New Fuel Injection Types (FIED)

Application

- All diesel vehicles, LD to HD.

Advantages

- High pressure provide better atomisation.
- Better control of start/stop of injection.
- Common Rail (CR) enables higher EGR rate (lower NOx) as follows: increased PM/soot due to higher (non-cooled) EGR rate can be counteracted with higher CR pressure and in total can provide increased PM/NOx trade-off flexibility.
- PM reductions ~75% with C.R. for LD at 2000 rpm/2 bar BMEP.
- NOx reductions ~70% with C.R. for LD at 2000 rpm/2 bar BMEP and EGR-possibility mentioned above (35% EGR).

Disadvantages

- Increased cost & complexity

Fuel Implications

- Potential lubricity problems with increased injection pressures.
- Higher sensitivity to water content (cavitation) for the same reason.
- Fuel stability issues in CR high pressure side, such as temperature and deposit control.

Fuel consumption and CO_2

- Significantly reduced.

Likelihood

- Unit injectors already in the market for HD engines, intro for LD (VW Golf) planned.
- High Pressure (HP) rotary pumps already in the market for LD diesels.
- Common Rail: Several new diesel vehicles (e.g. Mercedes, Fiat/Alfa/Lancia, VM Motori) with Common Rail have been launched and others are announced to be on sale during 98/99 (e.g. PSA, Toyota).
- High market penetration expected for Common Rail solutions by 2005.

Description

- Unit Injectors - solenoid controlled (via ECU) injection start/stop in injector centrally placed in 4 valve cylinder head (HD and soon in LD). High pressure (1500-2000 bar) provided mechanically by cam actuation directly on top of injector.
- Other systems more or less similar to the Unit Injector exist (Caterpillar HEUI etc.)

- High Pressure (HP) rotary pump - with/without solenoid controlled injection start/stop via ECU. Developed from traditional rotary pump for LD diesels.
- Common Rail - solenoid controlled (via ECU) injection start/stop in injector centrally placed in 4 valve cylinder head. Pilot and post injection also possible. Hydraulic pump generates high pressure - also at low engine speed - in a common rail (accumulator) mounted to the engine block side. Pressure regulation/control possible; 200-1500 bar. Gives full flexibility; "all" fuelling strategy possibilities enabled by advanced EMS.

References

1. Paramins post, Spring 1998
2. Piccone, A. and Rinolfi, R. (1997) Fiat third generation DI diesel engines. Paper No. S490/004/97. Presented at IMechE - Ricardo seminar “The Euro 4 challenge - future technologies and systems” London, 03-04.12.1997
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4.2.11. Engine Management/Strategies (EMSD)

Application

- All diesel vehicles, LD to HD.

Advantages

- Improvement in fuel economy possible in combination with new FIE.
- Reductions in emissions possible when fully exploited.
- Between 48 and 93% of the density effect on PM emissions can be eliminated by EMS re-calibration on a LD engine, and ~40% of the density effect on NOx. The effect of EMS on the absolute levels of PM+NOx has not been investigated (CONCAWE report 96/60)
- HD: Used to improve emissions, fuel consumption and performance in Volvo D12 series engine with unit injectors
- LD: Ricardo has demonstrated in initial tests on a CERES demo car that an alternative EMS strategy - not yet refined or optimised for low emissions or fuel economy - can give emissions reductions of 9% NOx and 35% PM with no other changes to hardware etc. (IMechE 517/035/96)

Disadvantages

- Increased cost & complexity

Fuel Implications

- Significantly reduced sensitivity to diesel properties, such as density, expected.
- No other unwanted fuel implications will occur.

Fuel consumption and CO_2

- Improvement possible when fully exploited in combination with FIE.

Likelihood

- Simple EMS systems on the market for Unit injectors and new HP rotary pumps.
- Breakthrough in 1997 when Common Rail was launched for LD.
- High market penetration expected for advanced EMS by 2005.

Description

- LD and HD diesel engines have traditionally been "regulated" by very simple mechanical regulators for idle control and overspeed (run-out control). Some engines have also had a mechanical smoke limiter device (Volvo).
- The typical rotary injection pump (LD) and inline pump (HD) have - by nature - not had the capabilities of taking the advantage of modern engine management systems (EMS or ECU) as implemented for gasoline vehicles a decade ago.

- Upgraded versions of rotary and inline pumps allows for some more freedom in EMS/ECU fuelling strategies, like in the new generation of High Pressure (HP) rotary pumps (Bosch VP44, Lucas ESR).
- New generation of fast, reliable and durable solenoids combined with powerful ECU (software/EPROM) enables the latest generation of fuel injection pumps - Unit injectors, HP rotary pumps, Common Rail - to work fully integrated in the fuelling system.
- This new "package" gives full flexibility;
    - Individual cylinder temperature corrections, ignition delay feedback, boost pressure and temperature corrections.
    - All fuelling strategies are possible including:
        - Max. response (power/torque) strategy
        - Smoke limiting strategy (limited fuelling response to pedal movement/position)
        - Boost limit strategy
        - Model based strategy (low total emissions)
        - low NOx strategy (EGR rate) etc.
- Pilot/post and rate shaped injection is also possible with Common Rail.
- Future options can be:
    - Density corrected strategy (sensor required)
    - Emission controlling strategy based on exhaust sensor/feedback (sensor required).

References

1. CONCAWE (1996) Diesel fuel/engine interaction and effects on exhaust emissions - Part 1: diesel fuel density, Part 2: heavy duty diesel engine technology. Report No. 96/60. Brussels: CONCAWE
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4.2.12. New Nozzles/Rate Shaped Injection (NRSD)

Application

- All diesel vehicles, LD to HD.

Advantages

- Injection rate control
- Better nozzle flow control
- Injection pressure control
- For LD ~50% NOx reduction can be achieved with variable or two stage orifice nozzle (at constant soot level).
- For HD ~12% NOx reduction can be achieved as per today's R&D status.
- Influence on PM unclear
- Reduced noise.

Disadvantages

- Increased cost & complexity

Fuel Implications

- None

Fuel consumption and CO_2

- None/reduced.

Likelihood

- High market penetration by 2003-2004

Description

- Two or three stage variable nozzle
- Allows modulated or "rate shaped" injection of diesel to take place
- "Pilot injection" can also be modulated.
- Allows more controllable, gentle combustion stories, promoting lower peak temperatures and reduced for NOx formation.

References

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4.2.13. Plasma (PLA)

Application

- Plasma is equally applicable to lean gasoline, LD diesel and HD diesel exhaust.

Advantages

- Potential conversion of NOx, HC and CO independent of stoichiometry.
- Instantaneous conversion independent of exhaust temperature.
- Simple, non precious metal dispersion materials.
- Controlled conversion rate which may be adaptive.
- No need for closed-coupling, therefore tuned exhaust systems can be maintained with benefits for engine performance and durability.
- Conversion rates of 75% NOx, 80% HC and 50% CO have been demonstrated in laboratory tests (SAE 970543).
- Conversion rates for NOx and PM is consistently reported to around 70% for diesel vehicles, in particular from test work on trucks (HD).
- AEA prototype "Electrocat Clean Emissions System" installed on a vehicle provided 70% PM reductions and 30% NOx reductions.

Disadvantages

- Research for gasoline applications still at a very early phase with the major parameters not yet optimised such as:
- Voltage, frequency, dispersal material, geometry, packaging features.
- It is expected that the power requirement will be of a similar magnitude to a vehicle ignition system.
- Possible concerns with regard to N_2O and ozone generation.

Fuel Implications

- Not yet known. However, possible sulphur sensitivity or activity reduction by other properties. No durability work has been carried out.

Fuel consumption and CO_2

- Largely dependent on the power requirement. A prototype "Electrocat Clean Emissions System" requires 2.5% of engine power, but aimed to be reduced to 1%. However, the system should be a low backpressure device.

Likelihood

- Some work on investigating plasma systems for NOx reduction of lean-burn gasoline engines seems still to be in the very early stages.
- In 2000: "Unlikely to be in mass production for LD diesels oxidation by the turn of the century" (Ricardo).
- Guideline: Year 2010 for HD diesel applications?

Description

- Pulsed Corona Plasma systems have been used for several years for Municipal solid waste incinerator after-treatment (NOx, SOx, Dioxin, VOC (HC)). Microwave systems are used for solvent abatement and filtration.
- Plasma is an ionised gas which is reactively "hot" but thermally "cool" which converts electrical energy → electron energy → free radicals. With the controlled generation of free radicals (N, O, OH, etc.) the radicals promote decomposition of key pollutant molecules.
- Possible free radical mechanisms include:

  $N + NO \rightarrow N_2 + O$

  $5O + 2HC \rightarrow 2CO_2 + H_2O$

  $OH + CO \rightarrow CO_2 + H$
- Electro catalytic process.

References

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12. Plasma/catalyst combo tolerates diesel sulfur. Hart's Diesel Fuels News 19 February 1998

4.2.14. Diesel/Water Injection (WAT)

Application

- HD diesel vehicles
- Application for LD not clear yet

Advantages

- Substantial reduction of both NOx and particulate. Typical values obtained with emulsion : -15 to -30% NOx, -10 to -50% PM. Reduction depends on water to fuel ratio; roughly, 1% water induces 1.1 to 1.3% NOx.
- Substantial reduction of the smoke (30 to 80% less opacity)

Disadvantages

- Not yet demonstrated on a commercial scale.
- Frost and winter conditions problems
- Small loss of power (in the case of emulsion)
- Induces an increase of HC emission, but no problem to meet HC standards
- Potential corrosion and wear issues
- Requires an extra tank if the water and the diesel fuel are injected separately

Fuel implication

- No known implication on the diesel fuel quality

Fuel consumption

- Emulsion : up to 4% less fuel consumption for the same power duty
- Water injection : very small increase of the specific fuel consumption

Likelihood

- Demonstration with emulsion is currently running on buses in several cities. Emulsion seems more appropriate for captive fleets.
- One independent engineering company sees the injection of water in the combustion chamber as one of the technologies, besides others, contributing to meet the Euro 4 limits for HD.

Description

Two ways :

1. A stable water - fuel emulsion is prepared and filled into the tank of the vehicle. In that case, no modification is needed on the engine. But the emulsion must be time and temperature stable and resistant to bacterial contamination, must not freeze at low temperature. Packages of additives are used for that. The water to fuel ratio is fixed. That application is the most appropriate for current vehicle fleets, even Euro 2 trucks.

2. Water and fuel are available in separated tanks on board, and injected into the combustion chamber. Injection can be done with two separate injectors (twin injector or sequential injection in the same injector). It can also be done by an on-line prepared emulsion. In both cases, the engine must be adapted. The water-fuel ratio is controlled and mapped with the engine conditions. That is perceived by one independent engineering company as the most appropriate for Euro 4.

4.3. HYBRID VEHICLES, NEW PROPULSION TECHNOLOGIES

4.3.1. Hybrid Electric Vehicles (HEV)

Application

- Gasoline and diesel vehicles, truck, bus.

Advantages

- 50% reduction in fuel consumption.
- Exhaust emissions reduced to 1/10th of the current Japanese regulated level (Toyota sources).
- Regeneration of electric energy through braking and deceleration periods.

Disadvantages

- Higher production cost. Toyota are currently selling the vehicle in Japan for an equivalent of $17,000. This is a premium over their conventional vehicles of $4,000. However, it is estimated that the actual production cost is close to $42,000. Production costs will obviously reduce with increased production.
- Greater vehicle mass.
- Mechanical and electrical complexity.

Fuel implication

- Basically, the fuel implications are identical to those of the heated engine used in the hybrid propulsion system. In the event that the hybrid system is powered by a lean-burn engine (gasoline or diesel), there could be some fuel requirements related to exhaust after-treatment system.

Fuel consumption

- The lowest fuel consumption of any fuel engine. Toyota announced a 28km/l (3.6 l/100 km) economy with its hybrid vehicle on Japan's 10/15 mode urban test cycle which is twice that of a typical small car powered by an equivalent gasoline engine.

Likelihood

- Toyota was the first automaker in the world to mass-produce hybrid cars. The gasoline-electric powered vehicle (named "Prius ") was launched in Japan in December 1997 and the sale expectations were about 1000 vehicles a month. Due to a very high demand, Toyota has decided to double its production to 2000 units a month.
- Audi has announced its intention to market a hybrid vehicle (named "Duo ") based on a diesel engine coupled with electric motor. The production will be limited to 500 units per year targeted to corporate fleets.
- Honda has recently presented a hybrid vehicle which combines a 1-litre , three cylinder direct injection engine with a revolutionary electric motor and continuously variable transmission. This vehicle is said to achieve a fuel consumption of 30 km/l and could be on sale before the end of 1999 in Japan.

- Nissan is currently to commercialising its first hybrid vehicle. The company has announced and unveiled its HEV concepts based on series and parallel hybrid technologies. Nissan wants to offer a flexible selection of driving systems by developing both the parallel and series types.

Description

A Hybrid Electric Vehicle (HEV) is a vehicle that has two sources of motive energy. A vast range of hybrid electric vehicle configurations have been developed but the basic elements in each case are similar. There is a heat engine - usually a conventional engine or possibly gas turbine - coupled to an electric energy storage system, which generally consist of a battery pack. The vehicle can either be driven by the engine, the electric motor drawing energy from the battery or by the combination of the two. Whatever the exact configuration is, the basic philosophy is that the heat engine operates only over a limited range of speed and load which corresponds to the optimum efficiency and best emissions performances. When the power output from the heat engine exceeds vehicle traction requirements, the excess capacity feeds into the energy storage system. Conversely, when a large power requirement is demanded both the output from the engine and any stored energy may be used simultaneously. A significant advantage of a hybrid vehicle over conventional technologies is its capability of converting vehicle motion (kinetic energy) back into electric energy through braking and deceleration periods.

There are two basic configurations for a hybrid powertrain: series and parallel. These terms refer to the way the engine supplies power to the propulsion system:

- In the series hybrid system, a heat engine powers a generator which either charges the battery or supplies power directly to the propulsion system and thereby reduces demand on the battery. All of the output developed by the heat engine is used to generate electricity.
- In the parallel hybrid system, the heat engine and the electric motor can deliver mechanical power directly to the propulsion system. With this type, either the battery electric system or the heat engine may be used to propel the vehicle or they may be used simultaneously for maximum power.

The best power system architecture and control strategy for a hybrid-electric vehicle is still the subject of ongoing investigation. Each car manufacturer has his own approach regarding the choice of powertrain configuration (series or parallel), heat engine (gasoline, diesel, gas turbine) and electricity storage system (battery, capacitors). Even for the same configuration, the way the electric motor and the heat engine are operated can be very different. For example, the Toyota Prius and Audi’s Duo are both parallel systems but Audi’s vehicle never runs simultaneously on the heat engine and the electric motor. The vehicle is always alternatively driven by one of the two propulsion systems. On the other hand, Toyota’s vehicle is equipped with a system that can choose to power the vehicle with either the engine, the electric motor or a combination of both depending on speed and driving conditions. The control management system also maintains the battery at a constant charge, eliminating the need to provide external charging connections.

4.4. TRANSMISSIONS

4.4.1. Continuously Variable Transmissions (CVT)

Application

- Gasoline and Diesel vehicles

Advantages

- Improved fuel economy, particularly at part load (10-15%)
  (ATZ, 96(1994) 10, p. 578; SAE 970685, "Ecotronic -The CVT ZF Transmission")
- Optimum combination of performance (torque) and fuel economy
- Improved driveability (smooth, dynamic acceleration, low noise)
- Lower cost, less weight, less complex (more reliable) than conventional automatic transmission

Disadvantages

- Application range restricted to small and medium sized vehicles

Fuel Implications

- None

Fuel Consumption & CO_2 Emissions

- Significantly improved (10 - 15%)

Likelihood

- Already in the market, particularly in Japan and Europe (Honda/ CVT+VTEC, Subaru, Nissan/ECV, VW, BMW, Volvo/ZF-Ecotronic), Ford)
- Wider adoption expected also in larger engines

Description

Automatic transmissions have large efficiency variations throughout the wide dynamic range of torque and speed conditions that constitute a typical automotive operating envelope. Continuously or infinite variable transmission (CVT) offer better efficiency particularly at part load.

CVT type transmissions can be grouped into three major types (SAE 970688) :

- Belts (steel, rubber) : 90-97% efficiency
- Traction (toroidal, nutating) : 70 - 96% efficiency (prototype)
- Epicyclic : 85-93% efficiency (prototype)

As an example, the operation of the push belt system is described (Driveline Symposium 1996 Yokohama, W.C. Ward et all, Lubrizol , p 209): the system consists of two split-sheave pulleys and a belt that is made of a number of elements. The elements transmit the drive force between the pulleys by compressive load and are, in turn, restrained on either side by a number of steel bands acting under tension. The exact number of elements and bands in a belt varies but is typically 300 elements and 10 steel bands on each side. Each of the split sheave pulleys consists of a fixed sheave, a moveable sheave and a hydraulic cylinder to control the movement. As the system operates the primary pulley and the secondary pulley act in unison to provide an appropriate ratio for the particular speed, load and demand, according to throttle angle, in addition to maintaining belt tension. Belt alignment is maintained by virtue of the fixed halves of the sheaves being on opposite sides of the belt. Hydraulic pressure to the cylinders places an ‘inward’ force on the belt ensuring that traction is maintained and placing the whole assembly under pre-load.

Transmission ratio is varied by the pulley sheaves opening and closing relative to each other so that the belt rides either lower or higher on the pulley faces. Thus, the transmission can run at any ratio available, within the design limits of the system .

A CVT’s advantage is that the engine can produce a broad range of torque at any given speed demanded, or a broad range of engine speeds for any given torque demand. For any given power demand, however, there is only a very narrow operating speed and torque window at which the engine is most efficient. Because the CVT allows an engine to run at this most efficient point virtually independent of vehicle speed, a CVT equipped vehicle yields fuel economy benefits when compared to a conventional transmission offering only a limited number of input/output ratios.

Thus a CVT provides the precise, independent coupling of engine speed and torque output with drive wheel requirements that allow an optimized combination of performance and fuel economy to be realised.

5. GLOSSARY

AFR	Air fuel ratio
BMEP	Break Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
CAD	Crank Angle Degree
CARB	Californian Air Resources Board
CC	Close Coupled
CDA	Cylinder Deactivation
C/H ratio	Carbon / Hydrogen ratio in the fuel
CCDs	Combustion Chamber Deposits
CI	Cetane Index
CN	Cetane Number
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CR	Common Rail
CRC	US “Co-ordinating Research Council”
CRT	Continuously Regenerative Trap
CVT	Continuous Variable Transmission
de-NOx	NOx reduction
DI	Direct Injection
DME	Di-Methyl Ether
E70, E100, E150 etc	% gasoline evaporated at 70, 100, 150°C in ASTM distillation test
ECU	Electronic Control Unit
EGI	Exhaust Gas Ignition
EHC	Electrically Heated Catalyst
EMS	Engine Management System
EPA	US Environmental Protection Agency
EPEFE	“European Programme on Emissions, Fuels and Engine Technologies” Report
EPROM	Erasable Programmable Read-Only Memory
ERGA	“Emissions Regulations Global Approach” study
ESC/ELR	New 13 mode steady state test cycle (ESC) and load response test cycle (ELR) for HD engines from year 2000 on
ETC	New transient test cycle for HD engines from year 2000 on
EUDC	Extra Urban Driving Cycle
EVC	Electronic Valve Control
EZEV	Equivalent Zero Emission Vehicle
FBP	Final Boiling Point
FIE	Fuel Injection Equipment
FTP	US Federal Test Cycle
G-DI	Gasoline Direct Injection
HC	Hydrocarbons
HD	Heavy Duty
HEUI	Hydraulic Electronic Unit Injector
HEV	Hybrid Electrical Vehicle
HFRR	High Frequency Reciprocating Rig (determines wear scar diameter)
HP	High Pressure
HSDI	High Speed Direct Injection
ICVWG	Inter-Company Volatility Working Group
IDI	Indirect Injection

IMEP	Indicated Mean Effective Pressure
IVD	Inlet Valve Deposits
JCAP	Japan Clean Air Programme
JM	Johnson Matthey
LD	Light Duty
LRG	Lead Replacement Gasoline (contains additive to prevent valve seat recession)
MMT	Methyl cyclo-pentadienyl Manganese Tricarbonyl (anti-knock additive)
MON	Motor Octane Number
MPI	Multi Point Injection
NMHC	Non-Methane Hydrocarbons
NOx	Nitrogen Oxides
OBD	On-Board Diagnostic systems
ORI	Octane Requirement Increase
PAH	Polycyclic Aromatic Hydrocarbon
PGM	Platinum Group Metals
PFI	Port Fuel Injection
PM	Particulate Matter
Pt	Platinum
Rd	Rhodium
RON	Research Octane Number
RVP	Reid Vapour Pressure
SAFR	Stoichiometric Air Fuel Ratio
SCR	Selective Catalytic Reduction
SO_2	Sulphur dioxide
SOF	Soluble Organic Fraction
SPI	Single Point Injection
SUV	Sport Utility Vehicle
T95	Temperature at which 95% v/v fuel has evaporated
TGA	Thermo-Gravimetric Analysis
THC	Total Hydro Carbons
TWC	Three Way Catalyst
UB	Under Bonnet
ULEV	Ultra Low Emissions Vehicle
VCP	Variable Cam Phasing
VCR	Variable Compression Ratio
VVA	Variable Valve Actuation System
VVT	Variable Valve Timing

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