fuel quality, vehicle technology and their interactions

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ABSTRACT

CONCAWE has studied the many aspects important when considering fuel quality. The report reviews the complex interactions between fuels, vehicle technology, test cycles and reference fuels with regard to their relative influences on vehicle emissions, fuel consumption, CO_2, durability and customer acceptance. Implications for the refining industry and trends in vehicle technology are also discussed as these are fundamental for a cost effective approach to contribute to meeting air quality standards.

The study concludes that effects of fuel changes alone on emissions and performance are relatively small, but benefits arise when they are used to enable new technologies. Therefore, fuels and engines need to be developed together as a common system. Such developments have to be assessed in view of their global impact on a "cradle to grave" basis. To produce sufficient quantities of fuel, flexibility of the refineries has to be ensured by specifying fuel properties only where a clear link to vehicle performance or emissions is proven. Harmonising fuel specifications can only go in parallel with emissions limits, vehicle technology and test cycles.

CONCAWE believes that more joint industry technical programmes, such as EPEFE, AQIRP and JCAP, are required to expand the existing sound scientific database to the rapidly developing new technologies.

KEYWORDS

Fuel quality, fuel specifications, gasoline, diesel, global harmonisation, vehicle technology, engine technology, vehicle emissions, fuel consumption, CO_2 emissions, driveability, after-treatment systems, durability, engine deposits, low temperature performance

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SUMMARY

In the light of the automotive manufacturers' approach to develop common world-wide fuel recommendations as embraced in their World-Wide Fuel Charter, CONCAWE has prepared a report on the many aspects important when considering fuel quality, and principles which are key to development of fuel specifications. The report reviews the complex interactions between fuels, vehicle technology, test cycles and reference fuels with regard to their relative influences on vehicle emissions, fuel consumption, CO_2, durability and customer acceptance. According to CONCAWE's technical view, fuel quality has to be seen in context with vehicle technology, since both interact with each other and must work effectively together. Implications for the refining industry and trends in vehicle technology are also discussed as these are the fundamental basis for a cost effective approach to meeting air quality standards.

A number of general conclusions were drawn from the study of the interactions between vehicle technology and fuel quality. These clearly illustrate how important it is that the automotive and oil industry work jointly to develop vehicle technology together with fuel quality as a system.

While effects of fuel quality changes ALONE on emissions from fixed technology engines are relatively small compared to reductions achievable from changes to engine technology, real benefits from changes to fuel quality arise when they are used to ENABLE new technologies.

The introduction of Unleaded Gasoline for catalyst cars, low sulphur diesel fuels for Euro 2 diesel engines and development of detergent additives to prevent problems in fuel injected engines show where fuel properties are effective as an enabling tool. Some de-NOx catalyst technology currently under development is claimed to require lower sulphur fuel. IF such technology can be developed with adequate durability and demonstrated to require lower sulphur, further reduction of sulphur can be considered. This is in line with CONCAWE's view that fuels and engines need to be developed together as a common system to meet new challenging emission targets.

However, while satisfying society's demands with regard to improving local air quality, it is also important to consider the GLOBAL impact of resultant changes in vehicle technology and fuel quality. This must be done on an overall "cradle to grave" or "well to wheels" basis. With regard to fuel changes it is important also to consider carefully the effect of proposed fuel quality changes on refinery infrastructure and it's ability to produce sufficient quantities of fuels.

The oil industry has to manufacture fuels from different crude oils and to meet different demand patterns in different countries. To do this it needs some flexibility to vary composition of fuels. Consequently only those fuel properties which have a direct, substantial and proven effect on emissions, performance or customer acceptance should be specified.

It is clear that the environmental aspirations of different countries or regions vary according to their level of economic activity, their perceived air quality problems, their climatic and geographical conditions and their customer priorities (performance, fuel economy, environmental issues). Therefore, global harmonisation will be a long and complex task. This is reflected in the current variety of different emissions standards and test cycles existing around the world, which must be met by different combinations

of vehicle and fuel technologies. Fuel specifications should therefore only be harmonised in parallel with emissions limits, vehicle technology and test cycles.

Since both the automotive and the oil industry have common aims of reducing environmental impact whilst satisfying the same customers in the most cost effective way, there is a need to develop vehicle technology together with fuel quality as a system.

CONCAWE believes that more joint industry technical programmes, such as EPEFE, AQIRP and JCAP, are required to expand the existing sound scientific database to the rapidly developing new technologies.

1. INTRODUCTION

It has been suggested by the automotive manufacturers in their World-Wide Fuel Charter that there is a need to “develop common world-wide fuel recommendations for ‘quality fuels’ taking into consideration customer requirements and vehicle emissions technologies, which will benefit customers and other affected parties”.

It is CONCAWE's technical view that any consideration of fuel quality has to include in parallel vehicle technology and other related issues. Consequently this report reviews the complex interactions between fuels, vehicle technology, test cycles and reference fuels with regard to the major aspects of the factors influencing vehicle emissions, fuel consumption, CO_2, durability and customer acceptance. Other issues, such as implications for the refining industry and trends in vehicle technology are fundamental for a cost effective approach to key items outlined above. All measures have to be reviewed for their contribution to meeting air quality standards defined or to be defined in the various regions of the world. These have to be established based on the needs and conditions of those regions.

CONCAWE considers the principles outlined in **Section 2** of this report as key to development of fuel specifications. These principles should be the basis for a process to integrate the wide range of important subjects. The US AQIRP[1], the European EPEFE and the Japanese JCAP programmes have shown that the oil and auto industries can effectively work together to develop sound technical knowledge. CONCAWE believes that more technical programmes are required to expand this knowledge to the rapidly developing new technologies.

There is a need to develop vehicle technology together with fuel quality as a system to meet new emissions targets.

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[1] Abbreviations see Glossary

2. PRINCIPLES OF APPROACH TO DEVELOPING FUEL SPECIFICATIONS

2.1. BACKGROUND

The broad objectives of the current debate over future fuel and vehicle technology, which includes the recently published “World-Wide Fuel Charter” are clear:

- to reduce impact of transportation on the environment, both locally and globally.
- to satisfy customer expectations in terms of vehicle performance, driveability, economy, durability etc.
- to deliver both these objectives simultaneously in the most cost-effective way.

Fuel changes alone have small effects, real benefits only arise from fuels which “enable” the use of new technology

Fuels are only one aspect of the whole picture and should not be considered in isolation. Fuel quality effects on vehicle performance and emissions are statistically significant, but generally small. The key message is that changing fuel quality alone will not have a substantial impact on customers acceptance or the environment. Any real benefits would come from synergy between fuel and vehicle technology, i.e. “enabling fuels” which allow new technology to work effectively. Good examples are the introduction of unleaded gasoline to enable catalyst equipped cars and low-sulphur diesel fuel with lubricity additives where needed to allow Euro 2 diesel engines to meet emission limits.

Fuel quality should be linked to vehicle technology

Clearly, there must be a link between vehicle technology and fuel quality, as is accepted by the Charter with the concept of three categories of fuel qualities for different engine technologies, though these should be more clearly defined. However, some markets have a mix of vehicles at different technology levels, especially catalyst and non-catalyst vehicles, so more than one fuel category may be appropriate.

World-Wide harmonisation – a complex issue

Given the interactive nature of engine technology, engine calibration and fuels, a world-wide approach by definition needs to consider many aspects and is a complex task. In this context, it is important to have a comprehensive assessment of environmental and market needs in the various parts of the world.

Environmental needs depend on local circumstances. The achievement of good air quality is the goal, rather than reducing all emissions without regard to costs. The most critical pollutants and the degree of control needed will vary depending on the local situation. Solutions that meet the needs of Europe, for example, may not be appropriate elsewhere. Similarly, customer expectations vary: fuel consumption is a key driver in Europe, but is less important for US customers.

For advanced emission control requirements, there may be no common technological strategy, and in such a situation, optimal fuel specifications may be different for different technologies, requiring a compromise between the different fuel quality approaches. The US AQIRP, European EPEFE and the Japanese JCAP programmes demonstrate how the Oil and Auto Industries can work together towards a common goal. Such programmes develop good technical information, but more work is needed to expand the knowledge gained from these programmes to new technologies (as mentioned in the EPEFE report, EPEFE 1995).

In addition there seems little benefit from harmonising fuel specifications world-wide, while vehicle emission limits, test cycles, reference fuels and customer expectations for vehicle performance vary widely. Any move to harmonise fuel qualities should only be considered as part of an overall process to harmonise emission standards, cycles and certification procedures.

Evaluation of fuel and hardware effects on emissions is complex. Changes in fuel that may reduce one pollutant can have an adverse effect on another, equally important, emission. Equally, engine changes to reduce diesel PM, for example, may increase NOx. Therefore, judgements may be needed on the overall package of measures (engine, fuel, test cycle, etc.) selected, which should be based on the criteria of good scientific information used to meet air quality and performance targets in the most cost-effective way as, for example, set out in the European Auto/Oil programme.

All fuel quality effects on fuel economy and CO_2 emissions must be considered on a "well to wheels" basis

CO_2 is a world-wide rather than a local pollutant and therefore its effect does not depend on where it is emitted. Burning fuel in an engine produces CO_2 at the exhaust pipe, but manufacturing fuel in a refinery also produces CO_2. Changes to fuel specifications to reduce exhaust emissions (e.g. reducing sulphur) inevitably require more processing in the refinery and hence generate more CO_2. As a consequence, CO_2 emission must always be evaluated on a “well to wheels” basis. Overlooking this principle may lead to wrong conclusions.

Fuel properties should only be specified where there is a clear link to vehicle performance or emissions

Fuel properties should only be specified to control specific critical aspects of vehicle performance or emissions, where clear fuel effects are demonstrated, and the specification parameters should be directly linked to vehicle effects. Thus, for example, gasoline octane and diesel cetane specifications are based on engine tests measuring combustion performance. Another example is diesel fuel lubricity which is controlled by a specified test, e.g. the HFRR lubricity test. Similarly if control of gasoline engine Combustion Chamber Deposits (CCD) is deemed necessary, it should be controlled directly via an engine based CCD test rather than indirectly by limiting FBP or unwashed gum as discussed below.

2.2. PRIORITIES

Currently the main thrust behind changes to vehicle technology and fuel quality is to improve the local environment, i.e. reduce pollutant emissions. However, it is necessary to achieve a balance between this and the often conflicting priorities of reducing fuel consumption, CO_2 emissions and ensuring customer satisfaction, as discussed below.

Fuel specifications cannot be considered independently of each other, as they combine to reduce refinery operating flexibility. Long term, unnecessary limits on fuel composition will restrict the ability of refineries to produce sufficient quantities of future fuels. This restriction in flexibility will translate in processing requirements and energy use.

2.2.1. Local Air Quality

The priority for any programme of air quality improvement must be to identify specific pollutant problems in any region, and initiate an appropriate set of measures to address the situation.

In certain areas (e.g. California), reformulated fuels (in synergy with improved vehicle technology) have been perceived as significantly reducing HC and CO emissions and urban smog. However, the same reformulated fuels will not necessarily give benefits in other regions (it should be noted that California has different fuels from the rest of the USA). The air quality problems in the Los Angeles basin result from the large number of vehicles operating in a land depression with long hours of exposure to sunlight. This highlights the vital need to consider the underlying causes of the air quality problem:

- Climatic or geographical conditions
- Customer driving patterns and expectations
- The profile of the vehicle parc (size, diesel/gasoline, LD/HD, age)
- Social demographics and alternative transport infrastructure
- The scale of the problem (e.g. inner city versus regional)

In individual situations, different approaches will give the most cost-effective and practical solutions.

As modern technology vehicles produce far less emissions than older vehicles, regardless of fuel quality, the key factor in improving air quality is fleet replacement and renewal. Additional effective measures include reduction of emissions by improvement of vehicle condition (stricter Inspection and Maintenance programmes) and traffic management policies.

2.2.2. CO_2 Emissions

Public and political interest in green house gases is growing and many governments are committed to introducing CO_2 reduction measures. In terms of transportation, this will translate into more demanding fuel economy requirements and measures to reduce vehicle usage. In response to legislative requirements and growing public interest in CO_2 reduction, automotive manufacturers will have to generally improve car parc fuel economy. Possible options include vehicle size and/or weight reduction, gasoline direct injection, lean-burn technology, increasing the proportion of the diesel share, optimised (linked) engine-transmissions systems and hybrid vehicles.

To extend diesel and gasoline lean-burn applications to their full potential, breakthroughs are still required in development of exhaust gas de-NOx technology. For such technology very low sulphur fuels are seen as enablers, but this is not yet demonstrated:

- Tests on selected vehicles have raised some uncertainty about the sulphur sensitivity of commercial de-NOx catalysts and traps.

- The need for “zero” sulphur fuel to provide adequate durability has not yet been demonstrated.

- In considering any further reductions in fuel sulphur, it is vital to consider the effect of increased CO_2 incurred in the production of those fuels in a “well to wheels” approach. Though yet not fully evaluated, these emissions could outweigh the benefits (if any) of supplying the new fuels to the vehicle fleet.

The extent to which these moves to improve fuel economy align with customer expectations will vary across the regions. For example, fuel economy has long been a major customer consideration in Japan and Europe because of high fuel costs. In the USA, there is not such customer interest in improving fuel economy.

2.2.3. Customer Expectations

In the drive to achieve low emissions, the needs of the vehicle owner/driver should not be forgotten. Fuels and engines are carefully developed to ensure smooth and reliable operation under all operating conditions; changes to reduce emissions may conflict with this objective. For example, increased use of Exhaust Gas Recirculation (EGR) to control NOx, or changes in gasoline volatility to control HC emissions can both adversely affect driveability if not carefully considered. Other performance features of the vehicle can also be impacted by fuel changes: low temperature operation of diesel fuels will be adversely affected if the T95 point is set at too low a temperature, since cold flow additives will not work effectively in such fuels. Of the emissions that are controlled to achieve air quality targets, most are not directly detectable by the driver, however the levels of smoke emitted from the exhaust can be perceived, and can be a cause of customer complaints. Odour and noise are primarily problems associated with diesel vehicles, and can be important for customer acceptance of the technology.

3. VEHICLE TECHNOLOGY AND TRENDS

3.1. TEST CYCLES AND REFERENCE FUELS

Vehicle technology and fuel quality impact the pollutants resulting from road traffic. The amount of pollutants generated by vehicles is controlled by a range of legislated emissions limits which vehicle models have to meet. Since the behaviour of road driving varies significantly with the respective location, such as the type of road, traffic load, traffic structure and vehicle parc, typical driving patterns have to be identified to simulate road traffic behaviour for the various vehicle categories. Test cycles for vehicle and engine certification are defined to reflect these driving patterns.

Developments of new engine / vehicle technology must meet the respective emission limits over the defined test cycle on a defined test (reference) fuel. These reference fuels should reflect the average fuel quality marketed in the region in which the vehicle / engine will operate. Since the currently applied test cycles and the reference fuels are specific to the respective region (e.g. Europe, USA, Japan), engines and vehicles certified in one region will not necessarily meet emissions requirements of another region. If a test cycle does not satisfactorily represent real driving patterns, emissions generated by the vehicle would be quite different. It is of major importance that emissions control is not lost when the vehicle is operated under conditions away from the prescribed cycles. A deviation of the reference fuel from the average market fuel quality will have some effect as well. The overall message from this review is that vehicle technology has to meet the needs for the respective driving patterns of a region and that the reference fuel used for certification has to be a market average. Any move to global harmonisation must take all these issues into account and identify if there are real differences in driving patterns in the various regions. There is no justification to harmonise fuel specifications without harmonising test cycles and procedures.

3.2. VEHICLE TECHNOLOGY

For all types of vehicle, OEM’s are actively researching methods to enable future emissions (**Table 1**) and fuel economy targets to be met. For gasoline vehicles improvements in engine design and control, fuelling strategy and exhaust after-treatment are all viable options to achieve year 2000 (Euro 3) and year 2005 (Euro 4) standards. Most light duty diesel vehicles will need improvements to fuelling control (advanced injection equipment) and oxidation catalysts to meet Euro 3 and Euro 4, but some may need particulate traps and active de-NOx systems. For heavy duty applications, 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 (including water injection) and exhaust after-treatment (including active de-NOx catalysts and particulate traps) will be required.

Table 1 European Exhaust Emission Standards, 1996-2008 (including proposal)

LIGHT DUTY GASOLINE EMISSIONS LIMITS (g/km)

	Pm	NOx	HC	CO	HC+NOx	TEST CYCLE
Euro 2 - 1996	-	-	-	2.20	0.50	ECE+EUDC
Euro 3 - 2000	-	0.15	0.20	2.30	-	ECE+EUDC (I)
Euro 4 - 2005	-	0.08	0.10	1.00	-	ECE+EUDC (I)

LIGHT DUTY DIESEL EMISSIONS LIMITS (g/km)

	Pm	NOx	HC	CO	HC+NOx	TEST CYCLE
Euro 2 - 1996	0.080	-	-	1.06	0.71	ECE+EUDC
Euro 3 - 2000	0.050	0.50	-	0.64	0.56	ECE+EUDC (I)
Euro 4 - 2005	0.025	0.25	-	0.50	0.30	ECE+EUDC (I)

HEAVY DUTY DIESEL EMISSIONS LIMITS (g/kWh) [see note (ii)]

	Pm	NOx	HC (iii)	CH4	CO	smoke	TEST CYCLE
Euro 2 - 1996	0.15	7.0	1.1	-	4.0	-	ECE R49
Euro 3 - 2000 "conventional"+"advanced" diesel (iv), (v)	0.10	5.0	0.66	-	2.1	0.8	ESC and ELR (viii)
Euro 3 - 2000 "advanced" diesel + gas (v)	0.16	5.0	0.78	1.60	5.45	-	ETC (ix)
Euro 4 - 2005 all engines except gas (vi)	0.02	3.5	0.46	-	1.50	0.50	ESC and ELR (viii)
Euro 4 - 2005 all engines (vi)	0.03	3.5	0.55	1.10	4.00	-	ETC (ix)
Euro 5 - 2008 all engines except gas (vi), (x)	0.02	2.0	0.46	-	1.50	0.50	ESC and ELR (viii)
Euro 5 - 2008 all engines (vi), (x)	0.03	2.0	0.55	1.10	4.00	-	ETC (ix)
EEV (vii) all engines except gas (vi)	0.02	2.0	0.25	-	1.50	0.15	ESC and ELR (viii)
EEV (vii) all engines	0.02	2.0	0.40	0.65	3.00	-	ETC (ix)

Notes

(i) "key on" cycle, without 40 sec idle
(ii) All HD limits beyond Euro 2 are Council "Common Position" proposals, 21/12/98
(iii) For ETC cycle limits are for NMHC
(iv) "conventional" diesel includes EGR and / or oxydation catalysts, for small engines Pm max 0.13
(v) "advanced" diesel includes de-NOx and / or Pm traps plus alternative fuels, for small engines Pm max 0.21
(vi) From Euro 4 all engines except gaseous fuelled engines will be tested on both ESC / ELR and ETC tests
(vii) "EEV" = Enhanced Environmentally Friendly Vehicle.
(viii) ESC is modified 13 mode steady-state test. Includes ELR load response smoke test
(ix) ETC is fully transient test
(x) Euro 5 proposal will be reviewed in 2002

Based on currently available information (up to September 1998), lists of technology options have been developed by CONCAWE, together with their indicated availability for commercial application and the potential effect on emissions and fuel economy. These are presented separately for gasoline, light duty diesel and heavy duty diesel vehicles as tables in the Appendix.

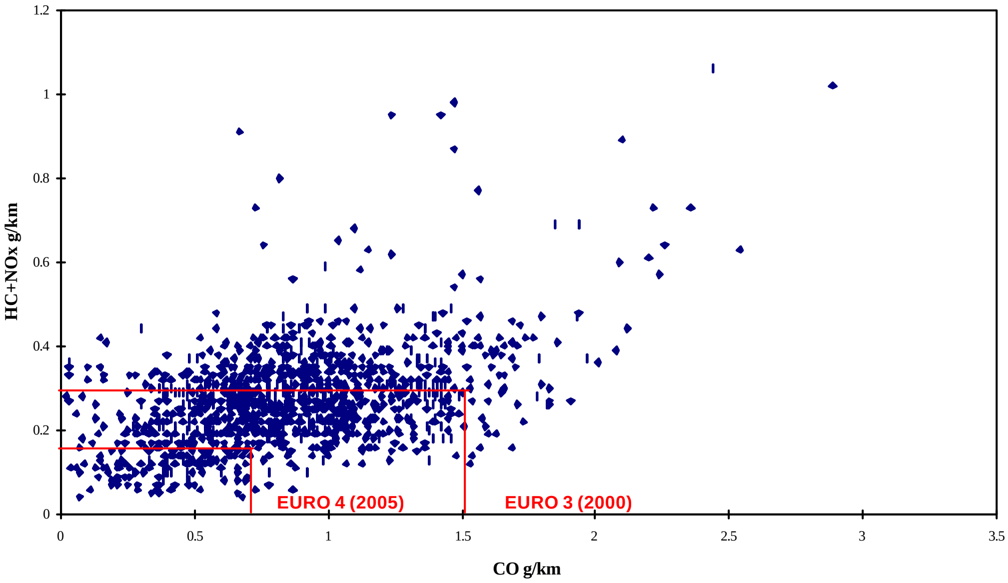
3.2.1. Conventional Gasoline Engines

Over many years, exhaust emission levels have decreased dramatically through progressive improvements in engine design and fuelling and ignition control strategies. In recent years, manufacturers have made significant advances in electronic fuel injection control, the use of EGR and control of air-fuel ratio in transient operation. However, exhaust after-treatment has been essential to allow vehicles to meet more severe emission limits and the vast majority of modern vehicles are now equipped with three-way catalysts for control of regulated exhaust emissions.

Generally, the performance of these catalysts improves as the fuel sulphur level is reduced. However as fuel sulphur content is reduced to very low levels, there are substantial increases in refinery energy consumption and the incremental cost of production. Therefore deciding the optimum level of sulphur in the fuel is one of the key questions in planning strategies to reduce emissions.

The extent of fuel changes necessary to enable future emission limits to be met is unclear. German homologation data (KBA, 1997, **Figure 1**) shows that vehicle hardware already exists that is capable of meeting the Euro 4 limits using conventional three-way catalyst technology. Approximately 65% of the 1997 models shown met year 2000 (Euro 3) limits and about 15% met year 2005 (Euro 4) requirements, whilst operating on current (pre 2000) fuel quality. These low emissions vehicles represent wide ranges of vehicle technologies and engine capacities with many vehicle manufacturers being represented.

Figure 1 1997 German homologation data for gasoline vehicles (data: KBA, 1997)



The most advanced vehicles in 1997 could already meet the severe Euro 4 limits. In general base engine design will need to become at least equivalent to what was “state of the art” for Euro 2 (1996). In addition improved fuelling control and mixture preparation will enable air-fuel ratio transients to be reduced to minimal levels (<+/- 0.5 AFR), allowing optimum catalyst conversion efficiency and preventing periodic breakthrough.

Conventional three-way catalysts are limited by their light-off characteristics, as high levels of CO and HC emissions may be measured before the catalyst temperature increases sufficiently. Systems to achieve rapid light-off include electrically heated catalysts, burner-heated catalysts, HC traps and close-coupled catalysts.

3.2.2. Fuel Economy, G-DI and De-NOx Technology

In the development of strategies to meet CO_2 reduction targets, vehicle manufacturers have a clear objective to reduce fuel consumption. There are a large number of technology options that can be considered to achieve this goal. For example, improved transmission design, variable valve timing (VVT), cylinder deactivation, hybrid and gasoline direct injection (G-DI) technology are all viable means to improve fuel economy.

The G-DI engine is currently receiving a great deal of attention, but two options of combustion are available, stoichiometric and lean-burn, both of which reduce CO_2. It should be emphasised that a lean burn approach is not the only technology available. Nevertheless, the commercialisation of the first lean burn G-DI engines must be regarded as a significant technological achievement.

G-DI technology improves engine efficiency. Vaporisation of the fuel cools the intake air and allows the use of a higher compression ratio without limitation by knock. EGR rates can be increased to give less intake throttling. Both of these effects are beneficial to fuel consumption, although the engines still do not approach the efficiency of the diesel engine. Further improvements in efficiency are dependent on the ability to operate the engine with a very lean air-fuel ratio (e.g. stratified charge lean burn). This requires very careful control of the air motion and fuel spray characteristics to minimise soot formation and wall-wetting (a major source of HC emissions). Critically, the potential of G-DI technology depends on the ability to control NOx emissions, for example through high EGR rates and exhaust after-treatment. The lean operating range is currently limited by the power and torque characteristics demanded by customers, and so real world fuel economy benefits are restricted. EGR rates need to be carefully optimised to reduce NOx formation without significantly increasing CCDs.

The development of de-NOx and NOx-storage catalysts shows some promise for reduction of NOx. However, their current performance still has major limitations regarding operating range and durability, even on low sulphur fuels. Cu/ZSM-5 based catalysts become active above 300°C with conversion efficiency maximum of around 60%, but at about 500°C, conversion efficiency has reduced to only 40%. This means that there is only a very narrow operating window for de-NOx of the exhaust gas. In their commercial G-DI vehicles, Mitsubishi use an iridium based catalyst which appears to be slightly more robust (but still limited by effective temperature range), but is also insensitive to fuel sulphur. For current de-NOx technologies, durability (ageing above 700°C, especially in presence of water) is understood to be still a major issue and this restricts the option of a close-coupled de-NOx system (Ricardo, 1998; CONCAWE, 1999 STF-13 report). Further development of advanced catalyst technologies will be necessary to give satisfactory conversion efficiencies over a wider temperature range. This is critical to enable G-DI lean burn technology to meet more stringent NOx standards.

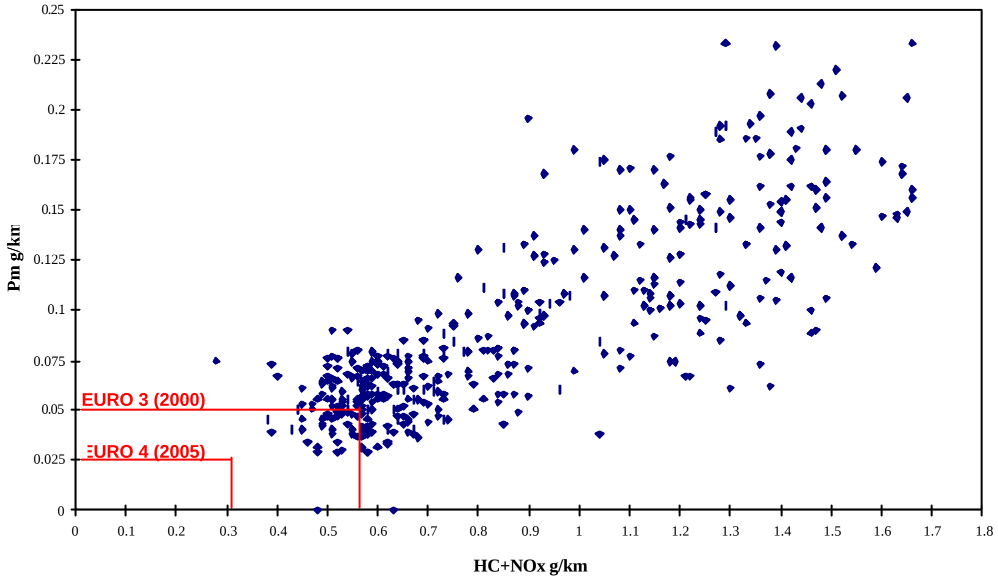
Vehicle and catalyst manufacturers have claimed that a sulphur content of less than 50 mg/kg is required for G-DI engines with NOx storage catalysts to achieve the 2000 emissions limits. Since sulphur sensitivity is an issue, OEM’s are active in investigating in the desulfation process (Günther et al, 1999) and in solutions to improve the sulphur tolerance of these catalyst systems (Dahle et al, 1998; Phlips et al, 1997; Brogan et al, 1996; Strehlau et al, 1996). Through these improvements (including improved thermal management and the use of SOx traps), Euro 3 and Euro 4 direct injection gasoline vehicles may be capable of operating on higher sulphur levels than currently claimed.

The rapid development in this technology has to be closely monitored and resulting performance then further investigated to determine if lower sulphur level could enable further improvements in fuel economy. Such studies should be conducted in co-operation between both the automotive and oil industry.

3.2.3. Light Duty Diesel Vehicles

Diesel vehicles continue to play an important role, both in commercial vehicles and in the substantial European diesel car parc. The benefits of diesel engines in terms of good fuel economy are clearly important to the drivers and owners, leading also to lower emissions of exhaust CO_2. However, overall emissions of NOx and PM from diesel engines are much higher than from spark ignition engines.

Figure 2 1997 German homologation data for light duty diesel vehicles (data: KBA, 1997)



1997 German homologation data for light duty diesel vehicles (**Figure 2**) presents a stark contrast to the data for gasoline vehicles shown earlier, in terms of the ability of current technology to meet future emission limits. Only a small proportion (6.5%) of current light duty diesel vehicle models is capable of achieving the Euro 3 emissions limits with current (pre 2000) quality diesel. None of the 1997 light duty diesel vehicles achieve limits for Euro 4.

Expected advances in diesel engine technologies, such as advanced fuel injection equipment and cooled EGR, will further improve combustion characteristics. Therefore, it is considered that most light duty vehicles will require only oxidation catalysts to meet year 2000 emission limits. However, heavier sports utility vehicles (SUV's) and light commercial vehicles (>2000kg) may need active de-NOx catalysts with conversion efficiencies of up to 40%.

For year 2005 (Euro 4), the situation is very similar to that for year 2000 for vehicles below 1500kg. However, the lower NOx limits mean that for vehicles above this weight, active de-NOx catalysts with up to 40% conversion efficiency will be required. Above 2000kg (a small percentage of the car parc) vehicles will need active de-NOx with greater than 40% conversion efficiency. This can be achieved with selective catalytic reduction (SCR - urea), which is insensitive to sulphur and does not require sulphur levels below those specified for year 2000.

3.2.4. Heavy Duty Diesel Vehicles

Although Euro 3 HD engines are not yet in the market, it is understood that currently available technology will allow the production of Euro 3 HD diesel and will require no exhaust after-treatment. The use of EGR may be an option which achieves the same NOx and PM emissions levels, but with slightly improved fuel economy.

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 (Warren et al, 1998).

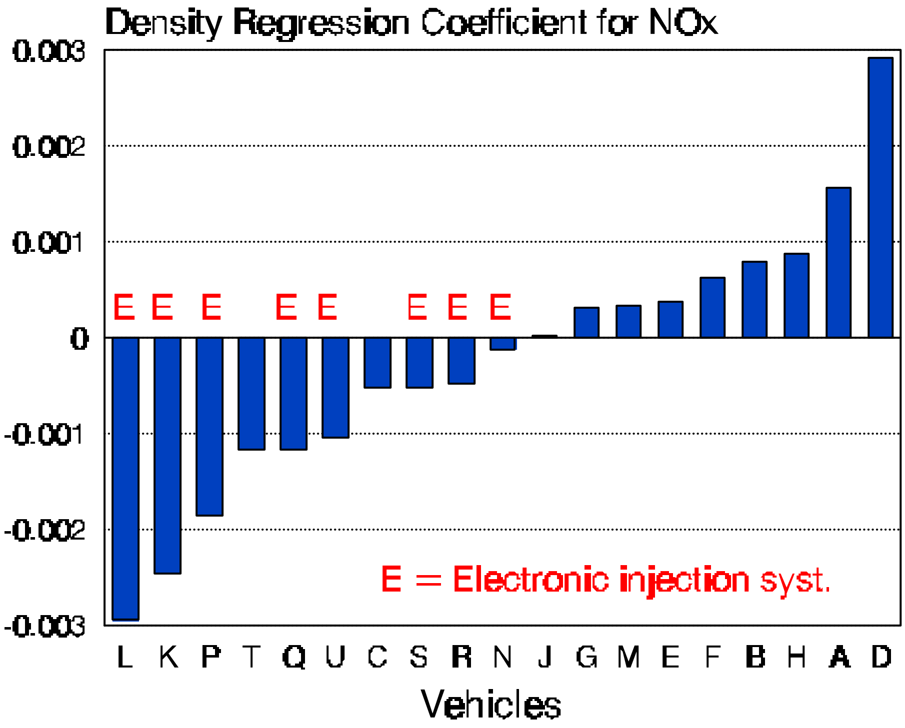
The proposed Euro 5 (2008) NOx limits (2.0 g/kWh) will require further reduction of NOx using de-NOX catalyst technology. Depending how the PM/NOx trade-off will be applied, two options are available. SCR with very high conversion efficiency (e.g. >80%) will be required if particulate emission limits 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 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.

4. FACTORS INFLUENCING VEHICLE EMISSIONS

There have been many investigations of the effects of vehicle and fuel technologies on emissions performance. However, the most relevant and robust data in a European context is that produced in EPEFE (European Programme on Emissions, Fuels and Engine Technologies) (EPEFE 1995). One of the key findings of this study was that different vehicle models responded differently to changes in fuel properties (example see **Figure 3**). This means that caution is needed in interpreting data produced from a single vehicle. Where possible data from the EPEFE programme were used to illustrate the points made in the following sections.

Figure 3 NOx sensitivity to density in different light duty diesel engines (EPEFE, 1995)



4.1. OXIDES OF NITROGEN (NOx) EMISSIONS

4.1.1. Year 2000 Emissions Regulations

GASOLINE

The EPEFE gasoline fleet was made up of sixteen prototype vehicles which met the 1996 European emissions standards (Euro 2). A wide range of vehicle technologies (catalysts formulation and position, fuelling equipment, number of valves, EGR) was present in the fleet which resulted in vehicle-to-vehicle NOx emissions ranging from 0.05 g/km to 0.30 g/km, i.e. Euro 2 to Euro 4 levels.

For conventional gasoline engines the tailpipe NOx emissions are predominantly controlled with the use of three-way catalysts, although the increasing use of Exhaust Gas Recirculation (EGR) will also provide some NOx benefit. Improvements in catalyst precious metal and washcoat formulations and support design have provided faster catalyst light-off and better emissions control during fully warmed up engine transients. For example, optimising catalyst formulation for improved NOx conversion resulted in a 0.1 g/km (or 40%) reduction in NOx emissions for a typical European vehicle. (Bates et al, 1996).

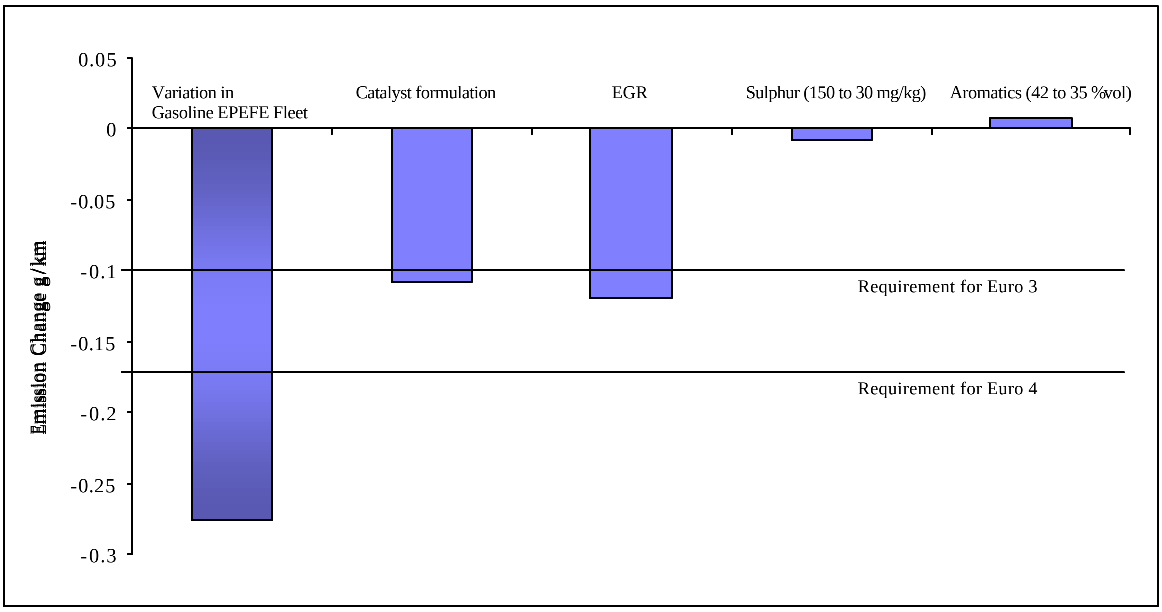
Changes in fuel quality can influence the emissions performance but generally the magnitude is small. The main fuel parameters which can influence NOx emissions from gasoline cars are sulphur and aromatics, with a very small effect of olefins. High sulphur levels cause reduced catalyst efficiency, particularly when the catalyst is fully warmed up and the tailpipe emissions are low. Reductions in gasoline sulphur content from the year 2000 maximum of 150 mg/kg to 30 mg/kg would give NOx emissions from the EPEFE fleet over the ECE + EUDC cycle that were only 0.006 g/km (3.7%) lower, or 1 gram in 135 km.

The effect of aromatics on NOx emissions is more complex. Engine out NOx emissions increase with increasing aromatic content due to higher peak flame temperatures with aromatic fuels. Many catalyst cars however, when operating with fully warmed up catalysts show the opposite effect, i.e. reduced catalyst-out NOx with higher aromatic content fuels. This effect can be large enough in the hot part of the test cycle to overcome the flame temperature effect seen in the cold part, leading to an overall reduction in NOx with higher aromatic fuels. Many test programmes including EPEFE have shown this effect which is clearly due to improved catalyst efficiency with higher aromatic fuels. Thus reductions in gasoline aromatic content from the year 2000 maximum of 42 %vol. to the year 2005 maximum of 35 %vol. would actually **increase** NOx emissions by 0.003 g/km (1.6%).

Two complementary mechanisms to explain this effect have been identified (McArragher et al, 1997). The first is a leaning of metered air/fuel ratio on low aromatic fuels due to increased hydrogen and reduced heavy hydrocarbons in the exhaust causing the lambda sensor to give a false rich reading. This can be sufficient to move the closed loop AFR slightly lean of stoichiometry into an area of low NOx conversion efficiency. The second mechanism is an increase in exhaust methane content from low-aromatic fuels. Methane has very low reactivity for NOx reduction and contributes little to it's conversion.

The effects of the above vehicle hardware and fuel formulation changes are compared in **Figure 4** to changes required for future vehicle homologation and with the measured vehicle to vehicle spread in EPEFE. Where percentage effects have been reported for the emission changes attributed to vehicle technology changes, the absolute change in emission has been calculated. A base emission of 0.25g/km NOx (Euro 2 emission levels) has been used for this conversion. The Euro 2 emissions level over the future test cycle is based on the Euro 2 emissions standard and factors used by the European Commission to take into account differences in the test cycle and the splitting of the emissions standard for HC+NOx into individual standards for HC and NOx.

Figure 4 Change in NOx emissions due to changes in gasoline vehicle technologies and fuel qualities.



DIESEL

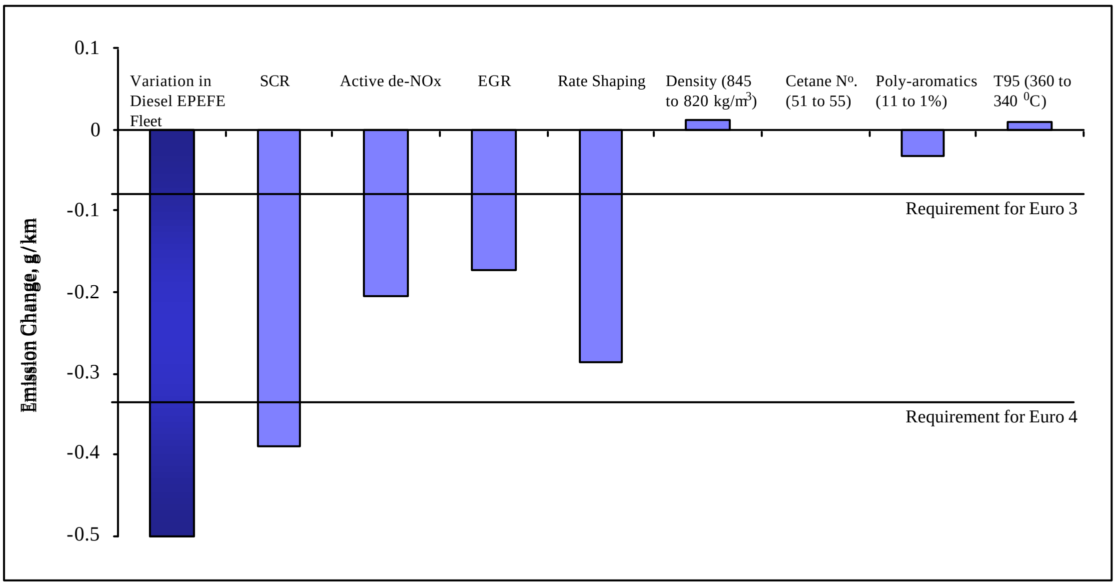
EPEFE also showed a large range in NOx emissions (0.38 to 0.88 g/km) across the nineteen light duty diesel vehicles (EPEFE 1995). Again the fleet covered a range of vehicle size and technologies; IDI vs. DI, engine capacities, turbocharged vs. naturally aspirated, EGR, etc.

It is likely that both light and heavy duty diesel engines will be able to meet the Euro 3 (2000) NOx emission limits with only engine modifications such as advanced fuel injection equipment, Exhaust Gas Recirculation (EGR) and turbocharging. Oxidation catalysts will be further used for LD vehicles, but it is unlikely that de-NOx catalysts will be required.

The EPEFE study investigated the effects of key fuel parameters. Reductions in T95 (360 to 320 °C) and in density (845 to 820 kg/m^3) actually result in **increases** in NOx emissions of 0.011 and 0.008 g/km respectively. A reduction in polycyclic aromatic content (from 11 to 1%) would lead to a decrease in NOx emissions of only 0.027 g/km. NOx emissions are not influenced by cetane number.

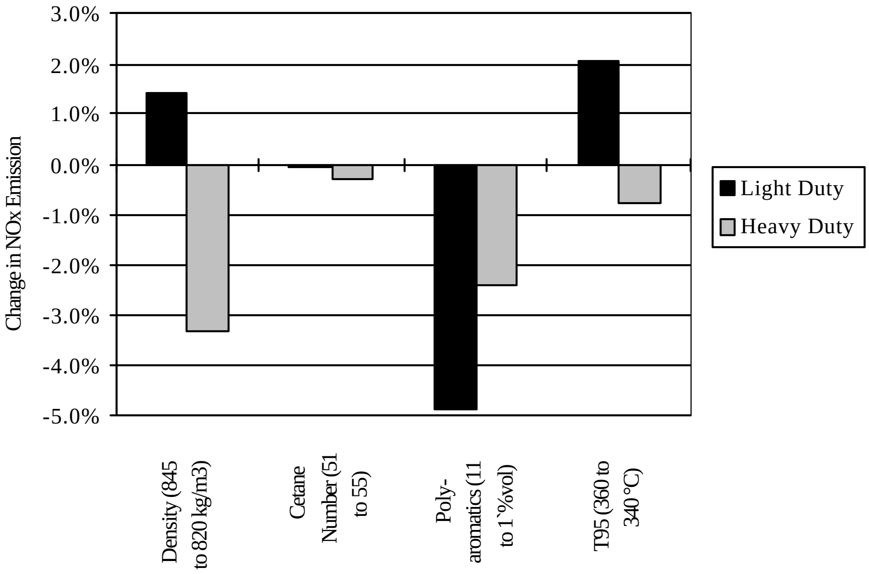
These fuel effects are small compared to the range in NOx emission of 0.50 g/km that can be attributed to differences in vehicles technologies over the EPEFE fleet. The effect of changes in fuel quality on NOx emissions of light duty diesel vehicles is compared in **Figure 5** to the range in emissions over the nineteen vehicle EPEFE fleet and to the reported benefits for different vehicle hardware options (CONCAWE 1999, STF-13 report). A base emission of 0.57 g/km for NOx has been used to convert the reported percentage reductions attributed to vehicle technology changes into absolute emissions reduction.

Figure 5 Change in NOx emissions due to changes in light duty diesel vehicle technologies and fuel qualities.



The EPEFE heavy duty engine tests again showed that the spread in NOx emissions from engine to engine was larger than the changes in NOx emissions caused by changes in fuel quality. In fact, some fuel quality changes resulted in an opposite effect on NOx emissions to the effect seen on the light duty fleet, as shown in **Figure 6**. For example, reductions in T95 and density both gave increases in NOx emissions from the light duty fleet and decreases in NOx emissions from the heavy duty engines.

Figure 6 Comparison of fuel effects on NOx emissions from light duty and heavy duty diesel EPEFE fleets for a range of property changes.

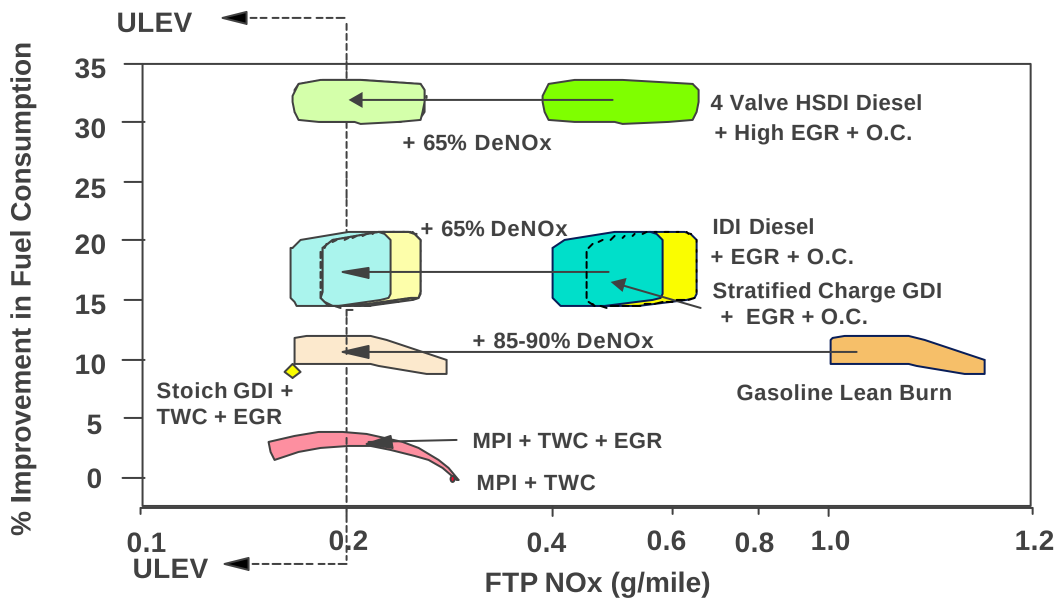


These data show that engine and vehicle hardware changes will be needed to achieve future emission levels and that fuel changes alone have relatively small effects. The fuels that are needed for the future are those that will enable future engine technology; the necessary properties need to be decided on the basis of factual evidence.

4.1.2. Advanced Emissions Control

Future tightening of legislative emissions standards with the simultaneous goal of reducing CO_2 emissions still presents a significant technology hurdle for automotive and catalyst manufacturers. To illustrate this for US emission standards, **Figure 7** shows potential strategies for both gasoline and diesel light duty vehicles to achieve US medium-term advanced emissions standards (e.g. ULEV level) as well as to reduce fuel consumption during FTP test cycle conditions. Though the values shown in **Figure 7** would be different, the trends would be the same for the European situation.

Figure 7 Strategies to achieve US ULEV NOx emissions levels and to reduce fuel consumption with LD vehicles at FTP75 test cycle conditions (diesel and gasoline design concepts). (Source: Ricardo, 1994)



GASOLINE

Gasoline engines can achieve very low NOx emissions using latest 3-way catalyst systems, combined with reduced light-off time and improved control of air/fuel ratio. However there are other pressures on the gasoline engine to reduce fuel consumption. It is claimed that lean burn direct injection engines provide 15% to 20% or even greater reduction in fuel consumption and CO_2 emissions. Unfortunately lean-burn G-DI vehicles have higher NOx emissions than conventional gasoline vehicles because of the difficulty of NOx conversion under lean conditions. This requires a new generation of “lean de-NOx” catalysts, which are claimed to require gasolines of low sulphur content to enable these vehicles to meet future emissions standards.

The only G-DI technology currently available in Europe has been shown by the manufacturer to be tolerant, over both the short and long terms, to gasoline sulphur contents of up to 440 mg/kg (Mitsubishi – Website; Ando et al, 1997). However, it is recognised that after-treatment systems for future lean burn direct injection gasoline vehicles may have to give higher NOx conversion than that offered by current technology.

NOx storage catalysts are currently the preferred candidate to provide the required NOx conversion for 2005 (Euro 4) lean burn G-DI vehicles. At the moment these systems are said to require very low sulphur levels (below 30 mg/kg). However, even at lower sulphur levels this technology has not yet demonstrated adequate durability. In addition there is concern over the thermal stability of these catalyst systems (see also after-treatment durability section).

DIESEL

Changes in engine technology which can reduce NOx emissions will generally increase PM emissions and fuel consumption. This leads to a NOx/PM trade-off situation, which is resolved by a compromise in engine tuning. If however emission limits are set at very low levels (as now proposed for Heavy Duty Euro 4 and 5 standards), this may not be sufficient and after-treatment technology must be used. This will generally take the form of either particulate traps or lean de-NOx catalysts, such as SCR and storage de-NOx (similar to those required for lean burn G-DI engines).

Combinations of turbocharging, cooled EGR, advanced Fuel Injection Equipment (pilot injection and rate shaping) should allow small LD diesel vehicles (<1500 kg) to meet Euro 4 emission limits without the need for de-NOx catalysts or traps. Medium LD vehicles (1500 - 2000 kg) may require de-NOx catalysts. Systems using extra fuel injection late in the expansion stroke so that partially burned HC can reduce NOx over the Pt/zeolite catalyst have been shown (Peters et al, 1998) to provide up to 35% conversion with current quality fuels.

For heavier light duty vehicles (>2,000 kg) greater than 40% de-NOx may be required to meet future NOx limits. This is achievable with Selective Catalytic Reduction (SCR) using urea as the reductant. Such a system has already been shown to give nearly 70% NOx conversion over the European test cycle. With SCR systems, computer control is used to inject the correct amount of urea in the exhaust manifold to completely consume the NOx over a dedicated catalyst. The urea system has the disadvantage that a separate tank of reductant must be carried on the vehicle and replenished periodically. In spite of this, urea remains a serious contender, not least because high levels of NOx conversion have not been achieved by rival systems.

For Heavy Duty engines advanced combustion technologies, such as high pressure common rail injection, cooled EGR, or even water injection can be applied to meet future emission standards. For year 2005 proposed standards and beyond such advanced technologies will be used in combination with de-NOx after-treatment systems, such as SCR, and / or particulate traps including CRT. While cooled EGR together with a particulate trap should be satisfactory to meet the 2005 standards, the application of SCR technology would facilitate improved fuel economy as well, while the engine would be tuned towards higher engine-out NOx (trade-off between both NOx/PM and NOx/fuel economy). For 2008 (Euro 5) a high conversion efficiency SCR or a combination of SCR and CRT seems likely. It should be noted, however, that differences in the heavy duty test cycle, R49 pre-2000, and ESC/ELR and ETC in 2000 and beyond, make it difficult to predict how fuels will affect emissions from future vehicle technology.

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.

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 (Hammerle et al, 1995). For CRT the year 2005 sulphur level of 50 mg/kg will be satisfactory (Warren et al, 1998). 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).

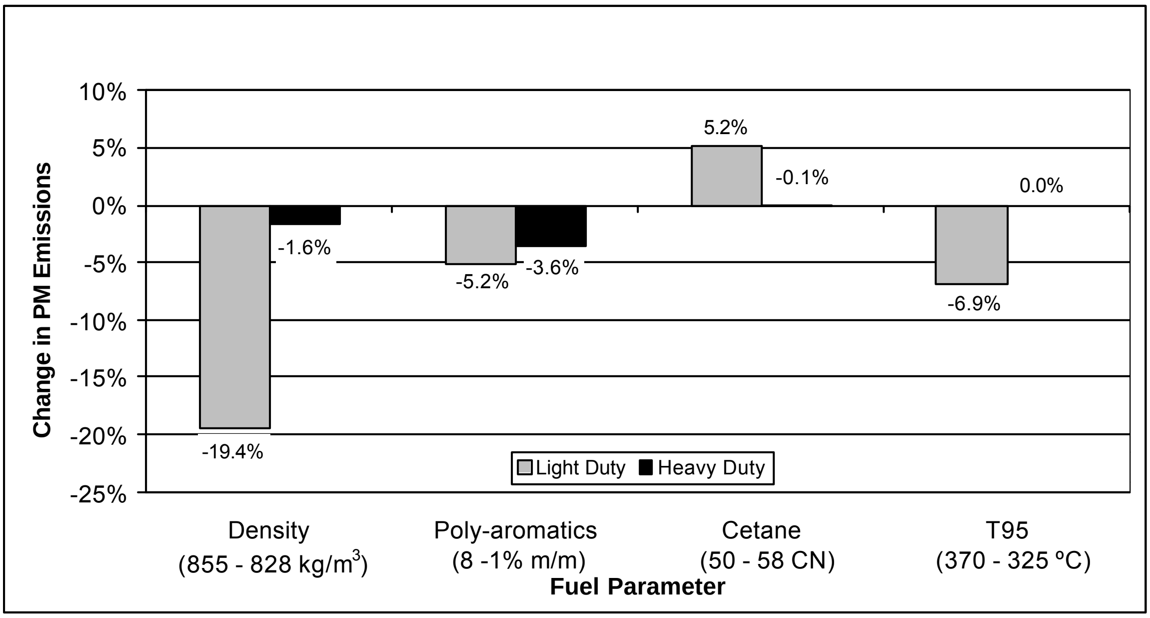
4.2. PARTICULATES (PM) EMISSIONS

Emissions of particulate matter (PM) are generally associated with diesel vehicles. Black smoke continues to be a problem with some diesel engines, and is the most visible aspect of PM. It is the larger particles in the exhaust gas which contribute to smoke, but the exhaust can also contain much smaller particles, which although invisible have been linked to health problems. The regulated emissions test for diesel vehicles and engines includes a measurement of the mass of PM emitted. Because spark ignition vehicles generally produce much lower levels of PM mass, there is no regulated test for gasoline PM emissions in Europe, although recent studies suggest that older gasoline cars can produce high levels of particulate emissions (Rickeard et al, 1996).

4.2.1. Diesel

Fuel effects on diesel PM emissions were studied as part of the European EPEFE programme in 1993-95. The importance of categories of vehicle engine technology is highlighted by the strong differences in fuel response between the light duty vehicles and heavy duty engines tested in the programme (different test cycles). Substantial differences in response were also seen between individual vehicles and engines. The average results for the LD vehicles and the HD engines are shown in **Figure 8**.

Figure 8 Comparison of fuel effects on PM emissions from light duty and heavy duty diesel EPEFE fleets for a range of property changes



The effects of fuel changes are much smaller for HD engines than for LD vehicles. In the EPEFE study, the only significant HD effect was a 3.6% reduction when poly-aromatics were reduced. Density, cetane number and T95 changes had no significant effect. For light duty vehicles, fuel changes had more effect, with density having the greatest impact. The reduction of the maximum density specification to 845 kg/m^3 in 2000 will help to lower emissions with currently homologated engines and vehicles, but will also somewhat reduce power. More detailed studies in EPEFE indicate that density affects emissions largely through physical interactions in the fuel injection and electronic control systems. CONCAWE investigations (CONCAWE 1996, Heinze et al, 1996) have further documented this physical interaction and more recent work (Mann et al, 1998) showed that changes to the engine calibration could considerably reduce the impact of changes in density (and viscosity) on emissions. The effect of density therefore could be compensated by changes in engine calibration or a density sensor.

Modest but significant reductions in PM were also seen as poly-aromatics and T95 were reduced. These emissions benefits need to be considered in the light of the substantial fuel changes needed to achieve them. For light duty vehicles, an increase in PM was seen as cetane number was increased above 50. This is in line with other recent studies that also show no benefit for cetane numbers above 50. The reason is that PM is formed primarily in the diffusion burning stage. Higher cetane, by reducing the ignition delay, increases the amount of fuel burned under diffusion conditions and hence increases soot emissions. Engine design will also have an influence.

Fuel sulphur is a component of diesel PM: a small portion (around 2%) of the sulphur in the fuel is oxidised to sulphates which become incorporated into the particles. As a percentage of the total PM, sulphate is not a large contributor, carbon and adsorbed HC constitute most of the particulate matter. The presence of sulphate can however become significant with exhaust catalysts. Oxidation catalysts have been fitted to LD diesel vehicles for some years, primarily to reduce hydrocarbon emissions. Early catalysts oxidised sulphur to such an extent that PM emissions could be increased with the addition of the catalyst. The use of more advanced catalyst designs with today's maximum 500 mg/kg sulphur indicates that this should not be a problem.

Advanced Emission Control

Diesel exhaust particles consist of a carbonaceous core, created as a product of incomplete combustion, to which a range of organic and inorganic species are adsorbed. The major fraction is hydrocarbon originating from incomplete combustion of the fuel and lubricant. The percentage of carbon depends on the temperature in the combustion chamber. At high engine speed/load conditions the PM can contain more than 80% carbon, whereas at lower loads when the engine is cooler, carbon may form less than half of the PM.

This implies that the conditions under which combustion takes place are critical for soot formation. As emission limits have tightened, engine manufacturers have improved the performance of fuel injection equipment by improved injector and combustion chamber design, and by significantly increasing the pressure at which fuel is injected. This has the effect of producing smaller fuel droplets that are more widely dispersed throughout the combustion chamber. However, reduction of soot may not eliminate the number of ultrafine particles emitted. Without the presence of a carbon core, species that would naturally adsorb onto the carbon may self-nucleate, producing very small particles of variable composition.

To meet Euro 4 limits after-treatment technology will have to be used. There is a long history of development of exhaust particulate traps, and some manufacturers have declared their intention to introduce them for light duty diesels by 2000. Although traps are effective in collecting particulates, eventually the trap will become plugged unless the accumulated soot can be burned off and the trap regenerated. Thermal regeneration techniques are available, but these require high temperatures and the associated vehicle equipment can be complex. The use of metals as catalysts can dramatically reduce the temperature at which the particles will oxidise, and some traps using this approach have seen limited use. The catalyst can be supplied either as a component of the trap, or as an additive to the fuel. Traps containing platinum are in limited use in aftermarket conversions, but because of the sensitivity of platinum to sulphur are currently only suitable for use where the fuel sulphur level is no more than 50 mg/kg. Some fuel additive approaches can eliminate sulphur sensitivity. Additives containing copper, iron or cerium have been proposed. Metal emissions to the atmosphere are avoided if the trap can retain the metal components, but there are potential health concerns if the additives are used in vehicles not equipped with traps and metals are emitted to the atmosphere.

One other area that needs to be considered with trap technology is the potential for exhaust gases passing through the trap to self-nucleate as they emerge, thus producing a high number of very small particles.

PM traps are one option for heavy duty engines to enable control of particulate emissions, to meet Euro 4 and later PM limits proposed by the EU Council. A moderate improvement of fuel consumption might be achieved as well by reoptimisation of the engine using the NOx/PM trade-off to give low PM emissions and fuel consumption, but higher NOx which could be reduced by using an SCR system.

Oxidation catalysts offer excellent control of HC and CO emissions and are likely to be used on smaller engines where HC control may be an issue, but wide scale use in the premium truck market is unlikely.

4.2.2. Particle Size and Number

More recently, attention has focussed on the number and size of particles emitted rather than the mass. The debate is continuing to address the relative potential impact on health from PM_{10} and $PM_{2.5}$ emissions. The smallest particles are considered to have most impact on health, since they can penetrate more deeply into the respiratory tract, and may be retained for longer periods than larger particles. Several studies (e.g. Hammerle et al, 1995; Rickeard et al, 1996; CONCAWE 1998) have now provided data in this area and show a number of consistent features.

Light Duty Vehicles

The conclusions below reflect those from a CONCAWE study of number, size and mass of exhaust particles emitted from European diesel and gasoline vehicles (CONCAWE, 1998) (see also **Figures 9,10,11**).

- The particles emitted are very small, with a peak size generally in the range 50-100 nanometres
- The size distribution is remarkably insensitive to changes in fuel or vehicle technology
- Diesel vehicles emit far more PM under steady-state (50 km/h) driving conditions than gasoline cars.
  - 40-85 times more particle mass
  - up to 2000 times higher numbers of particles
- Diesel vehicles also emit significantly greater numbers of PM than gasoline cars over the European legislated test cycle
- At high speeds, gasoline vehicles emit large numbers of particles (within an order of magnitude of Diesel)
- Fuel effects on the number of particles emitted are small.

Other work (Rickeard et al, 1996) shows that the fitting of a catalyst reduces gasoline vehicle emissions to very low levels (see vehicles V4 versus V5 in **Figure 12**).

Figure 9 Total Number of Particles Emitted per KM for Diesel Versus Gasoline Vehicles (Averaged Over Test Fuels)

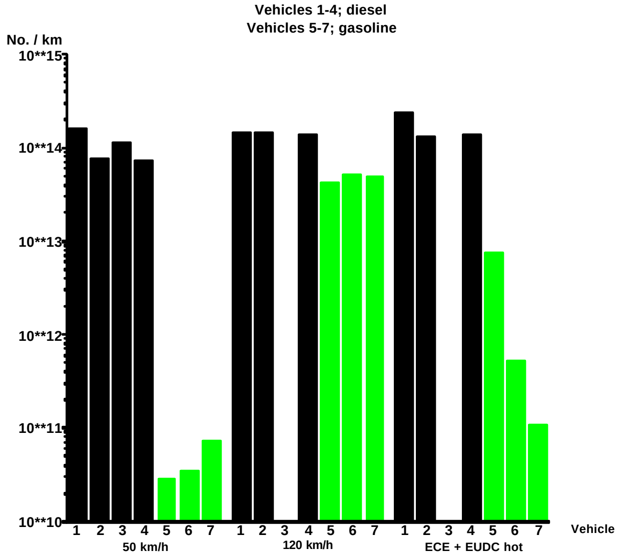
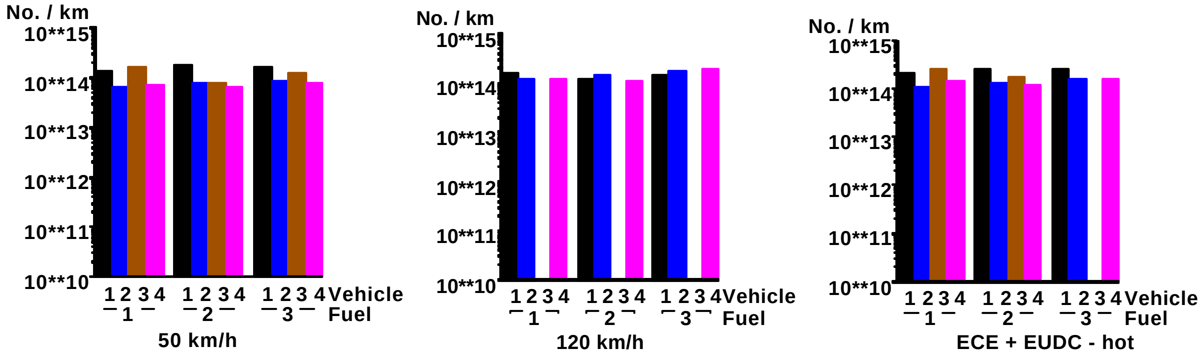
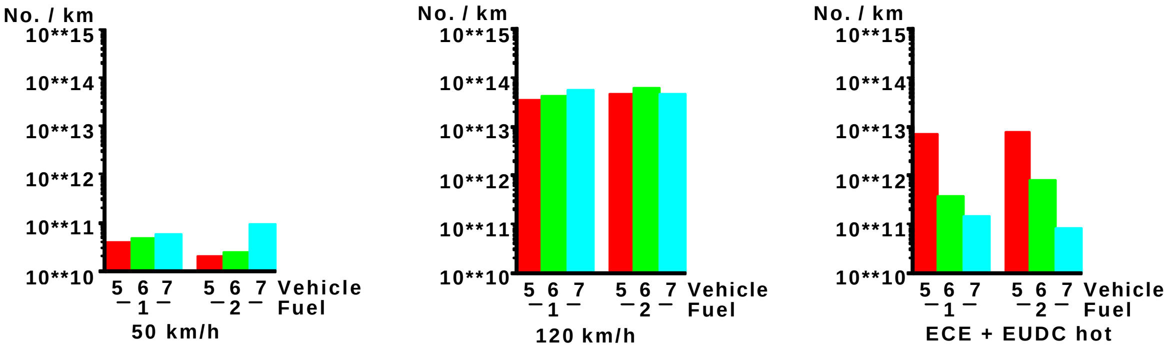


Figure 10 Total Number of Particles Emitted per km for Each Vehicle/Fuel Combination - Diesel



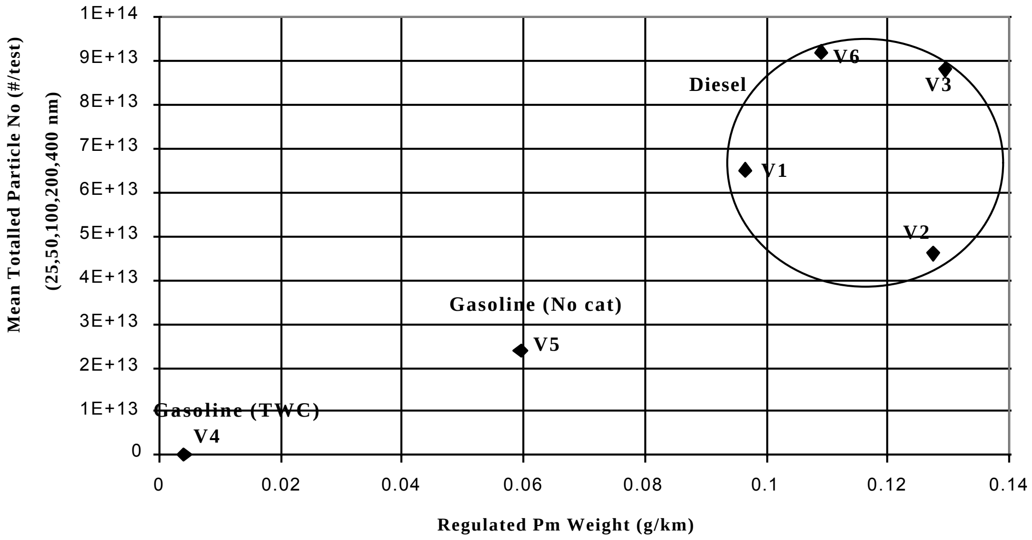
(geometric means normalised to $dN\ /\ d\ \log_{10} d_p$)

Figure 11 Total Number of Particles Emitted per km for Each Vehicle/Fuel Combination - Gasoline



(geometric means normalised to $dN\ /\ d\ \log_{10} d_p$)

Figure 12 Mean Totalled SMPS Pm Number v. Regulated Pm Weight (All Vehicles - Hot ECE+EUDC - Fuel C/UL 95)



Gasoline

The nature of spark-ignition particulate emissions is much less well understood. High numbers of particles have been seen in studies under some test conditions, however the particles are not readily collected on a filter paper and so their composition is difficult to analyse. It is believed that many of these particles may be composed of condensed liquids (hydrocarbon or sulphuric acid), but it is not clear whether they evaporate or persist in the atmosphere. The mechanism by which high numbers of particles are emitted at high speeds is not yet understood.

Heavy Duty Engines

Researchers have observed that modern heavy duty diesel engines which emit low particulate mass could emit higher particle number concentrations than older engines. Concerns on nanoparticle production (<50 nm diameter) have been raised with HD engine operation. Specifically (Bagley et al, 1996) it is reported that a 1991 more advanced HD diesel engine (Cummins LTH) produced 30 to 60 times more particles in the nuclei mode (< 50 nm) than the older 1988 HD engine (Cummins L10) when both engines were run with the same low sulphur fuel under base line conditions. A shift toward more nuclei-mode particles and less accumulation-mode particles (> 50 nm) was noted.

Other researchers (Abdul-Khalek et al, 1998) have identified particles in the nuclei mode in the 7 to 15 nm diameter range and an accumulation mode in the 30 – 40 nm range in a 1995 HD diesel engine. The investigation indicated that the dilution ratio and other conditions applied in testing seems to have a significant effect on the number concentrations and size distributions of particles.

The VERT (Clean diesel engines for tunnel construction) programme (Mayer et al, 1997 and Mayer et al, 1998) showed that a combination of a particulate trap and a metal containing additive provided the most effective reduction in nanoparticles in HD engines tested. It is further reported that these substantial reductions could not be anticipated to result from further developments in either engine combustion, reformulation of fuels and lubricants, or after-treatment devices such as oxidation catalytic converters. Traps were found to be very effective, but especially when a metal containing additive for trap regeneration was used. The test included an extreme fuel (sulphur < 1 mg/kg, aromatics , 0.1 %, cetane index 92). It has to be understood that within the VERT programme the main focus is on the carbonaceous portion of the nanoparticles. Based on the VERT findings the German UBA have no objection to the use of two specified metal containing additives when used in combination with a defined particulate trap (Rodt et al, 1998).

General remarks

More work is required to understand the mechanisms of particle formation and to ensure that the particle distribution equilibrium measured under experimental conditions is representative of particle distributions and concentrations from tailpipe and exhaust plumes when mixing with ambient air. For this reason automotive particles generated at road driving operation have to be further studied as well.

4.3. HYDROCARBON (HC) EMISSIONS

GASOLINE

Hydrocarbon emissions in the EPEFE gasoline fleet ranged from 0.28 g/km to as low as 0.08 g/km, the lowest HC emission being below the Euro 4 standards. This, and the fact that 15% of 1997 vehicle models have the potential to meet the 2005 (Euro 4) standards on current quality gasoline, suggests that changes in gasoline quality over and above those already mandated for 2000 and 2005 are unnecessary.

Fuel hydrocarbons which are compressed into engine crevices (e.g. between piston and the cylinder wall) or dissolved in the lubricant can escape the main combustion process. Under certain conditions, these hydrocarbons can also survive, unreacted or partially combusted, the exhaust system and be emitted into the atmosphere. Changes in base engine design to reduction crevice volumes and lubricant/fuel interactions help to reduce hydrocarbon emissions.

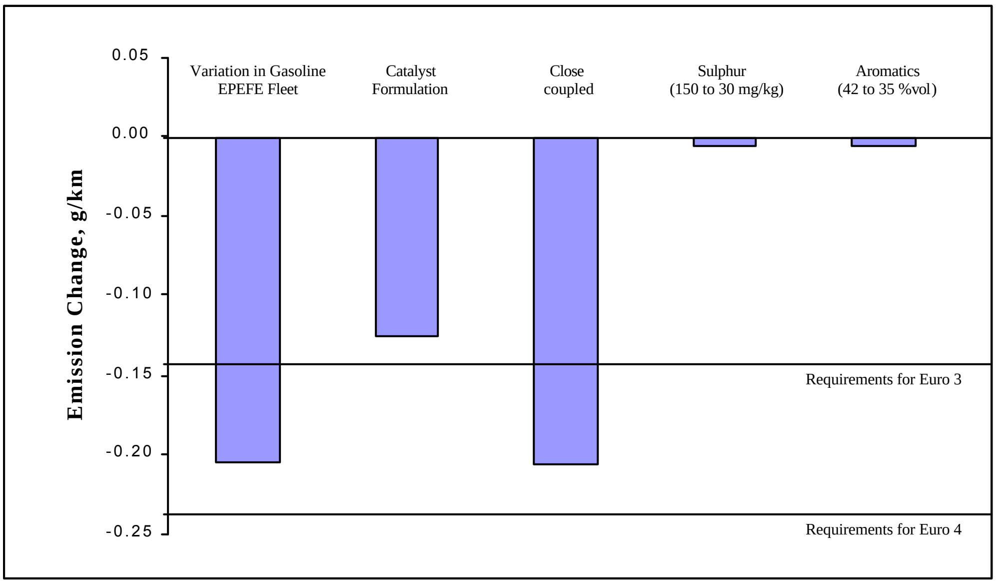
Most of the hydrocarbons that escape the chamber are removed in the catalyst after-treatment system. Changes in catalyst formulation, washcoat formulation and physical design influence hydrocarbon conversion efficiency. For instance, it has been demonstrated that changes in the catalyst formulation can give up to 30% lower hydrocarbons (Bjordal et al, 1996). The increasing use of palladium allows the positioning of catalysts closer to the exhaust manifold (close coupled) and results in faster catalyst light off and therefore up to 60% lower hydrocarbon emissions (EPEFE).

Other after-treatment systems are available that can dramatically reduce hydrocarbon emissions, such as exhaust gas ignition, electrically heated catalysts and hydrocarbon traps. However, hydrocarbon emissions can be adequately and more cheaply controlled with conventional three-way catalysts and therefore the above technologies have not been widely used.

Reductions in gasoline sulphur content from the year 2000 maximum of 150 mg/kg to 30 mg/kg would give a reduction in HC emissions of 0.005 g/km (3%) from the advanced 1996 technology EPEFE fleet. Again, as described in the NOx emissions section, higher sulphur results in some deactivation in the catalysts activity, particularly during fully warmed up operation.

Reductions in gasoline aromatic content from the year 2000 maximum of 42 % vol. to the year 2005 maximum of 35 %vol. would decrease HC emissions by 0.003 g/km. The effects of the above vehicle hardware and fuel formulation changes are compared in **Figure 13** to changes required for future vehicle homologation and with the measured vehicle to vehicle spread in EPEFE. Again, Euro 2 emissions levels (0.34 g/km) are used as a basis to convert percentage effects into absolute changes for the vehicle hardware options.

Figure 13 Change in HC emissions due to changes in gasoline vehicle technologies and fuel qualities.



DIESEL

Hydrocarbon emissions from diesel vehicles and engines are low and are not considered to be a problem for 2005 (Euro 4) diesels. The lowest emitting diesel vehicle in EPEFE emitted only 0.015 g/km. This is well within the diesel emissions limit of 0.06 g/km for HC for 2005 (difference between the NOx and HC+NOx standards) and the 2005 emissions standards of 0.1 g/km for gasoline vehicles. As such, changes in diesel fuel quality is not required to allow light duty diesels to meet the 2005 (Euro 4) emissions levels. Again, it is difficult to assess the impact of fuel quality in future Heavy Duty engines due to the change in test cycles established for 2000 and 2005.

4.4. CARBON MONOXIDE (CO) EMISSIONS

Emissions of CO for catalyst equipped gasoline vehicles and diesel engines/vehicles are not a problem. Currently 44% of the gasoline vehicle models homologated in Germany during 1997 and 43% of the diesel models have the potential to meet the Euro 4 (2005) CO emissions standards. Further improvements in the control of the fuelling process in both gasoline and diesel technologies, to reduce HC, NOx and PM emissions, will also generally reduce CO emissions.

4.5. UNREGULATED EMISSIONS

4.5.1. Benzene

Benzene emissions arise mainly from the exhaust of gasoline engines, though there is some contribution from diesel engines, and from gasoline evaporative losses from vehicles and distribution. Typical exhaust emission levels from passenger cars are (CONCAWE, 1996):

- gasoline non-catalyst cars	70 mg/km	(30 - 160)
- gasoline catalyst cars	10 mg/km	(1.5 - 35)
- diesel cars	2 mg/km	(1 - 5)

Thus fitting catalysts to gasoline cars is the most effective way to reduce benzene emissions, by over 80%. Further measures to reduce exhaust hydrocarbon emissions, such as improved AFR control, catalyst formulation and reduced light-off time, will simultaneously reduce benzene emissions. For example, benzene emissions from the advanced EPEFE fleet on fuel 5 (35% aromatics, 2 % benzene) varied from 4.5 to 13.5 mg/km with a mean of 8.7 mg/km.

Benzene emissions arise mainly from unburned fuel benzene and partially burned heavier aromatics, with some contribution derived from other hydrocarbons. The relative contributions from fuel benzene and aromatics have been studied in some detail (CONCAWE 1998) and can be described by an equation such as:

Benzene (g/km or %HC) = C + A x (% benzene) + B x (% NBA)

Where NBA = Non Benzene Aromatics = (%aromatics - % benzene), to avoid counting benzene twice.

Equations were developed for European catalyst and non-catalyst cars as follows:

For non-catalyst cars:

Benzene (mg/km) = 15.74 + 11.71 (% m/m Benzene) + 0.729 (% m/m NBA)

For catalyst cars

Benzene (mg/km) = 3.04 + 1.07 (% m/m Benzene) + 0.137 (% m/m NBA)

The key feature of these equations is the ratio of coefficients A/B, which is 18.5 for non-catalyst and 7.8 for catalyst cars. This means that between 18% or 8% fuel aromatics gives equivalent benzene emissions as 1% fuel benzene.

Benzene emissions can therefore be controlled by an “Aromatics Index” based on this type of equation, as is done in the US “Simple” and “Complex” models for Air Toxics in their Reformulated Gasoline Legislation.

4.5.2. Aldehydes and 1,3-Butadiene

The EPEFE programme (EPEFE, 1995) has investigated the effects of certain fuels parameters not only on regulated emissions but also provided information on the speciation of hydrocarbon emissions. Among other compounds the effects on emissions of aldehydes and butadiene were reported as follows.

Combined cycle, mg/km	Gasoline cars	Light Duty Diesel cars
1.3-Butadiene	0.36 - 1.8	0.28 - 2.06
Formaldehyde	0.16 - 12.3	3.48 - 22.27
Acetaldehyde	0.06 - 3.48	2.33 - 12.03

NOTE: Also higher aldehydes/ketones were reported. But formaldehyde
and acetaldehyde were the most prevalent species.

Gasoline Engines

Hydrocarbon, aldehyde and ketone speciated emissions were measured for the composite cycle only. There was one measurement per fuel/vehicle combination with no repeats and hence no statistical significance can be assigned to these results.

On average less than 3% of the mass HC emissions were formaldehyde, about 0.8% were acetaldehyde, and 0.6% were 1,3-butadiene. 1,3-butadiene emissions follow the trends observed for all cars tested, which is that those cars with the lowest HC emissions also show the lowest 1,3-butadiene emissions. However, the lowest formaldehyde and acetaldehyde emissions were observed with platinum based catalysts. This suggests a decrease in aldehyde efficiency with palladium based catalysts.

The effects of gasoline sulphur content on the relative distribution of HC species in the exhaust gases was unaffected by the fuel sulphur content. This applied also to the three air toxics, 1,3-butadiene, formaldehyde and acetaldehyde.

No effect of aromatics and E100 on 1,3-butadiene mass emissions in the exhaust gases was found. However, formaldehyde and acetaldehyde showed a slight decrease with increasing aromatic content.

Diesel Engines

Speciated emissions were only determined for light duty diesel vehicles. In mg/km terms formaldehyde and acetaldehyde emissions were greater for light duty diesel vehicles (2 to 3 times) than for gasoline cars, but 1,3-butadiene emissions were of the same order of magnitude.

The limited technical possibilities for measuring air toxics and the fact that particulate composition was determined in duplicate only, mean that a statistical analysis, as in the case of the regulated emissions, was not feasible.

For light duty vehicles a decrease in density reduced 1,3-butadiene emissions in line with the effect of density on total hydrocarbon emissions. Reductions in poly-aromatic levels had no effect on 1,3-butadiene emissions.

Decreases in both density and poly-aromatic levels reduced formaldehyde and acetaldehyde emissions.

Increases in Cetane Number reduced 1,3-butadiene and aldehyde emissions in line with the effect of Cetane on total hydrocarbon emissions.

Reductions in T95 had no effect on 1,3-butadiene emissions, but increased formaldehyde emissions. For acetaldehyde this could not be clearly established.

4.5.3. Polycyclic Aromatic Hydrocarbons

Polycyclic aromatic hydrocarbons (PAH) in the exhaust emissions were not evaluated in the EFEPE programme since it was concluded that no standard analytical methodology was available at that time to properly investigate effects from vehicle technology and fuel quality on PAH in the exhaust emissions.

A recent CONCAWE literature study on "polycyclic aromatic hydrocarbons in automotive exhaust emissions and fuels" (CONCAWE, 1998) shows that there is still no standard analytical methodology available. This might result from the fact that the analytical situation is very complicated (samples taken from the exhaust include a wide range of individual compounds, the range of analytical techniques employed at different laboratories capable of quantifying PAH varies greatly). In addition there is no consensus on the major PAH to be analysed, although the 16 PAH listed by the EPA are the most commonly measured. Due to the wide range of test programme configurations reported (engine/vehicle type, driving cycle, sampling and analytical procedures) it is difficult to define maximum and minimum values of PAH in exhaust. In addition there are few authors who attempt to correlate fuel composition/PAH levels with those measured in the exhaust or even include the measurement of PAH in the test fuels used.

However, one important finding is that total hydrocarbon (HC) emissions (both vapour phase and particulate borne) are very low from modern gasoline and diesel engines.

The generation of exhaust PAH emissions is complex and individual mechanisms can contribute to a greater or lesser extent. The fraction of the fuel PAH which survives combustion is influenced by engine design, test cycle and the compatibility of fuel and engine. Other exhaust PAH can be created from non-PAH fuel components by pyrosynthesis which can be related to the amount of soot in the exhaust and can be a substantial fraction. The lubricating oil may also contribute to the exhaust PAH.

PAH emissions from automotive sources are highly variable and are dependent on a number of factors, including fuel composition. However, published data, though limited in their scope, unequivocally indicates that exhaust after-treatment systems are a highly effective means to substantially decrease PAH emissions with diesel after-treatment devices showing some greater variation. With only a few exceptions these trends hold true for all targeted individual PAH species.

CONCAWE has become involved in practical work to address some of the reported uncertainties. In one part of this work Ricardo and CONCAWE have conducted a co-operative research programme to develop a technique applicable to the simultaneous collection and measurement of both vapour phase and particulate bound PAH in exhaust emissions (Collier et al, 1998).

5. FUEL CONSUMPTION / CO_2

There is a direct link between fuel consumption (l/100km) and exhaust CO_2 emissions (g/km), as CO_2 is proportional to fuel consumption multiplied by a coefficient that contains the volumetric carbon content of the fuel (g/l). Practical conversion factors are 24 g/km of CO_2 per l/100 km for gasoline and 26 g/km of CO_2 per l/100 km for diesel.

In the following discussion only exhaust CO_2 will be considered as a contribution to the global CO_2 emissions. Nevertheless, as stated earlier, CO_2 emissions must be evaluated globally, from "wells to wheels", including emissions due to refinery processing.

Currently refinery energy consumption represents about 6 % of the processed crude oil. However, it can significantly increase if fuel specifications are severely constrained. Moreover, some of these specification constraints may lead to an hydrogen imbalance, i.e. hydrogen has to be specially produced by steam reforming, producing an extensive amount of CO_2 (see **Section 8.1**).

5.1. ENGINE FACTORS

Gasoline engines

Several engine design parameters have been known for a long time as key for improvement of fuel consumption :

- The compression ratio of the engine: the higher it is, the better the thermal efficiency. The compression ratio is limited by combustion knock, which can damage the engine. Knock is fuel and engine dependent and is controlled by the research and motor octane numbers of gasolines.
- The spark advance is also a key parameter, if it is limited by knock and the engine cannot run at optimum timing.
- The combustion speed (controlled by internal aerodynamic or ignition characteristics): the higher it is, the better the thermal efficiency of the engine cycle.
- Reduction of pumping losses: the higher the gravimetric amount of the air/fuel mixture the better the thermodynamic efficiency of the engine. Throttling or pumping losses at light load operation lead to lower engine efficiency.
- The air/fuel ratio: the leaner it is (without engine misfire), the better the thermal efficiency of the engine.

A lot of progress has been made over the last decades to improve the fuel consumption by tuning the first four parameters to optimise for the best compromise between fuel consumption, driveability and emissions. It seems now difficult to obtain substantial improvements in fuel consumption through only these parameters.

New engine designs have been recently introduced on marketed vehicle models, with a greater potential for fuel economy. These are direct injection and lean burn. They must be addressed separately, even if direct injection is the best approach for lean burn.

Direct injection of gasoline in the combustion chamber provides several effects which are beneficial to fuel economy:

- The vaporisation of the fuel results in cooling of the air-fuel charge, which allows increase in compression ratio without reaching the knock limit. The engine runs more efficient, whatever the air-fuel ratio is, stoichiometric or lean.
- EGR ratio can be increased (up to 25 %), resulting in lower intake air throttling and a re-optimised engine tuning. Both help to reduce fuel consumption (see Honda, 1998).

Lean burn is a combustion regime with an excess of air, similar to a diesel engine. This gives a better thermal efficiency of the engine and less intake-air throttling, both contributing to a lower fuel consumption. The lean limit of the air/fuel ratio for a conventional engine is set by combustion quality (ignition, stability, speed). When lean burn is applied in a G-DI engine, stratification of the air-fuel mixture in the combustion chamber is possible, allowing it to run much leaner.

However, even G-DI engines can run lean only at low load / speed conditions. At full load, these engines run rich or stoichiometric to achieve maximum power. Since the engine operates more often in the high load regime during the European test cycles than during the Japanese ones, the lean burn approach provides less beneficial fuel consumption data with the European procedure than with the Japanese.

The fuel economy improvement which can be achieved by lean burn depends on the engine technology, test cycle and emission limits. For example, a multipoint injection lean burn engine meeting the current Japanese emission limits gives an improvement of around 10 % (Honda, 1998) compared to 35% claimed for a G-DI lean burn engine on the Japanese 10.15 test cycle. However, the same G-DI technology gave less than 20 % improvement when adapted to the current European certification requirements (Euro 2) and tested accordingly (Ando et al, 1997). Another G-DI engine, has been reported to give 10 - 15 % fuel economy benefit when running at stoichiometric air/fuel ratio and tested according to the Euro 3 requirements and close to 20 % when running lean (SIA, 1998). Recently a European manufacturer has announced to launch a stoichiometric G-DI engine powered vehicle providing 16% fuel economy when compared to the equivalent MPI engine powered vehicle (SIA, 1998; Renault press release).

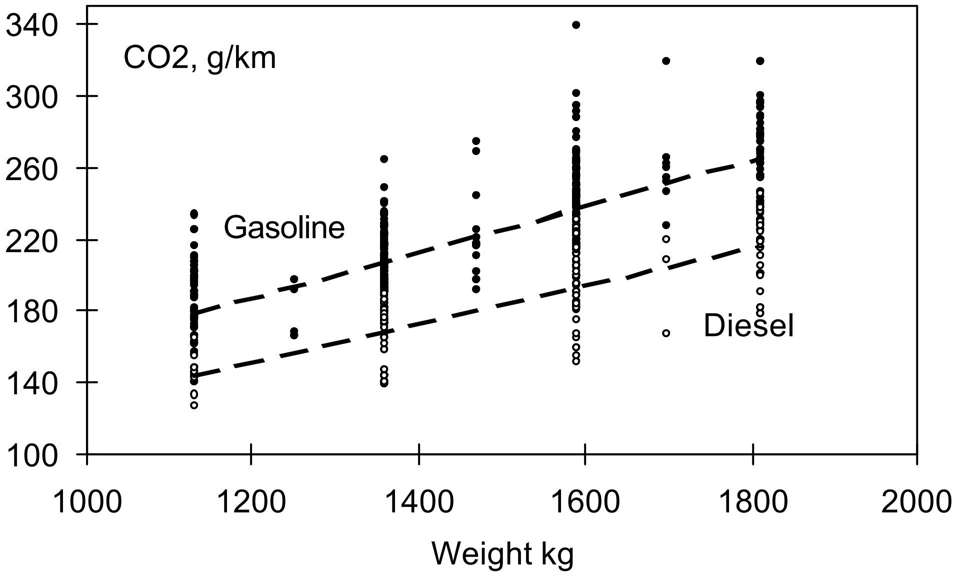
Such numbers must be considered with caution, because they depend on many factors including the approach taken with regard to compliance with emission limit regulations, the vehicle test cycles used, and other parameters, like the efficiency of the catalytic system chosen.

Further improvement in fuel economy has also been made possible by the control of the valve opening/closing timing, known as Variable Valve Timing (VVT). The amount of residual gas fraction can be controlled and adapted to the engine running condition (idle, stoichiometric, lean). This leads to improved fuel economy. Currently marketed systems give 6 to 12 % fuel economy improvement, with no detrimental effect on emissions. More progress, up to 15 % fuel economy, is expected with the electronic control of the valve operation (Rinolfi and Piccone, 1997).

Diesel engines

The thermal efficiency of the diesel engine is better than that of the gasoline engine. This is mainly due to the higher compression ratio, the leaning of the air/fuel mixture and consequent ability to operate without throttling. However, as the volumetric carbon content of diesel fuel is somewhat higher than for gasoline, the fuel economy advantage of the diesel engine is not fully translated into a reduction of exhaust CO_2. The extent of the CO_2 benefit is shown in **Figure 14**, based on the CO_2 emissions of different models which are currently marketed in Germany. This shows that CO_2 emissions from diesel cars are almost 20 % lower than from gasoline cars.

Figure 14 CO_2 emissions range of marketed gasoline and diesel vehicles versus vehicle weight. (generated from data of KBA (Kraftfahrt-Bundesamt) 1997)



The overall CO_2 benefit produced by a switch from gasoline to diesel cars might not necessarily be as great as shown in **Figure 14**. A recent theoretical study (Newsome and Galliard, 1998) of the European diesel market (based on data from the Foremove data from the EU Auto-Oil study) concluded that an increase in proportion of diesel cars would have only a small effect on CO_2. This is due to the fact that diesel cars tend to do higher annual mileage than gasoline cars, and that there is also a greater energy demand at the refinery resulting from further conversion of heavy fractions to middle distillates to increase diesel production. It would have to be established whether the link to higher mileage with diesel cars results from drivers' needs or from their preference.

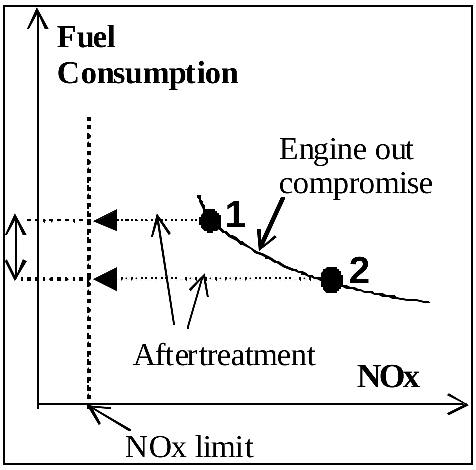
Most recently developed light duty diesel engines are direct injected. Direct injection provides a fuel economy improvement of about 15 % for light duty application versus indirect injection.

Further progress can be expected with a set of different advanced techniques :

- Combustion chamber design
- Variable geometry turbocharger
- Charge air cooling
- High pressure injection using common rail or unit injectors
- Advanced engine control.

The actual CO_2 advantage of these techniques is not known, as no definitive data is yet available. In fact only three Common Rail Light Duty engines have been marketed so far in Europe and further launches have been announced .

Figure 15 Fuel consumption / NOx trade off and possible impact of NOx after-treatment on fuel consumption.



Another way to obtain fuel economy is to use high performance NOx after-treatment. As shown in **Figure 15**, there is a trade-off between engine-out NOx and fuel consumption. Tuning the engine for higher NOx (point 2) instead of lower NOx (point 1) results in a better fuel economy, but this requires exhaust after-treatment with higher de-NOx efficiency. It is understood that some of the options for future high efficiency de-NOx after-treatment devices may lead to some fuel sensitivity issues.

Other vehicle technologies

Continuous variable transmission is a way of maintaining the torque - engine speed at the best compromise at any operating condition, leading to a fuel economy improvement of about 10 - 15 % (Boos and Mozer, 1997). Several marketed models have already been equipped with this technology. Automatically shifted layshaft transmission can be alternatively used with a similar potential (Jackson et al, 1997).

The hybrid powertrain is a combination of the internal combustion engine (compression or spark ignited) with an electrical motor. There are several types of combinations (e.g. parallel or series hybrid). A hybrid model car has been recently launched in Japan and is planned to be available on the US and EU market in year 2000. With Japanese homologation standards, fuel economy improvement is about 50 %, while reducing the pollutants emissions by 90 % below the current regulation limits. Several manufacturers have announced to launch hybrid cars with similar performances in the near future.

It should not be forgotten that there are also non-engine vehicle parameters which can contribute to further improvements in fuel economy (mass reduction (**Figure 14**), aerodynamic drag reduction (Jackson et al, 1997) and low tyre rolling resistance.

5.2. FUEL FACTORS INFLUENCING FUEL CONSUMPTION

The octane number of the gasoline characterises its resistance to auto-ignition and the resulting phenomenon of knock. In principle, with a higher octane number fuel, an engine can operate with a higher compression ratio and therefore greater thermal efficiency. However, it should be noted that producing a gasoline with higher octane implies more use of energy at the refinery. Therefore, a "well to wheels" analysis is appropriate to determine the optimum octane number for minimum energy consumption or global CO_2 emission. Previous studies showed that a pool Research Octane Number (RON) of 95 is the best compromise for globally emitted CO_2 (CONCAWE, 1980).

The faster the combustion, the better is the thermal efficiency of the engine. Combustion speed is little influenced by the fuel chemical structure, but unsaturated molecules such as olefins and aromatics burn faster.

Fuel consumption is expressed in volume per travelled distance, and is therefore influenced by the energy content of the fuel. For a given thermal efficiency of the engine, the fuel consumption is lower when the energy contained in a litre of fuel is higher. As the energy content is generally expressed on a mass basis (heating value in J/kg), both density and heating value are the two relevant fuel properties. However, density and heating value alone have no effect on the thermal efficiency and do not induce energy savings.

Reducing sulphur content may indirectly influence the fuel consumption of the vehicle by enabling different catalytic exhaust after-treatment systems. This would be the case if the after-treatment strategy of a high fuel economy powertrain technology was very sulphur sensitive, requiring very low sulphur content fuel to meet durability targets of the catalyst.

5.3. FUEL FACTORS INFLUENCING EXHAUST CO_2 ONLY

The influence of gasoline aromatic content on exhaust CO_2 emissions is reported in the EPEFE programme which states that this effect is only due to the carbon content of the fuel. There is no improvement of the volumetric fuel consumption when lowering the aromatic content of the fuel.

From an energy point of view, there is therefore no reduction in the amount of crude oil processed. Since all carbon in the crude oil is converted to CO_2, via the different refined products and the refinery's internal energy demand, there is also no reduction in the globally emitted CO_2. However, overly severe processing for low aromatic gasoline could produce additional CO_2 emissions and overcompensate any reduced vehicle CO_2 emissions.

6. CUSTOMER ACCEPTANCE

6.1. GASOLINE VEHICLE DRIVEABILITY

Hot and cold weather driveability has long been regarded as an issue by the oil industry, for their impact on customer acceptance and emissions. In the 1970's, the European oil industry created an Inter-Company Volatility Working Group (ICVWG) to evaluate vehicle driveability and its response to fuel volatility. This has enabled many years of study on the effect of volatility properties on hot and cold weather driveability and has generated an extensive amount of test data. This data has formed the basis of fuel specifications and allows vehicle trend analyses.

Three main factors control gasoline vehicle driveability, during both hot and cold weather:

- vehicle fuel system design
- ambient temperature
- fuel volatility and composition

<u>Vehicle Effects</u>

Fuel system design has the greatest influence on both hot and cold driveability, as some vehicles can exhibit problems while others can operate satisfactorily under the same conditions. Vehicles fitted with carburettors generally have poorer hot and cold driveability performance and are more sensitive to fuel volatility than those with single point injection (SPI), which in turn are more sensitive than multi-point injection (MPI) systems. Thus the move away from carburettors towards SPI and MPI systems has substantially improved vehicle driveability performance and reduced sensitivity to fuel volatility.

Figure 16 Max fuel volatility levels to give customer satisfaction for hot-weather driveability of new vehicle registrations in Germany

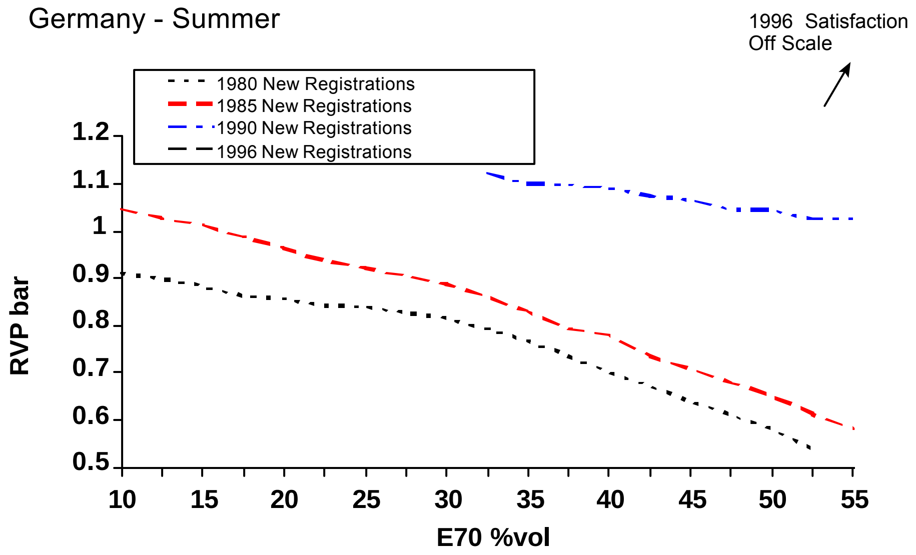
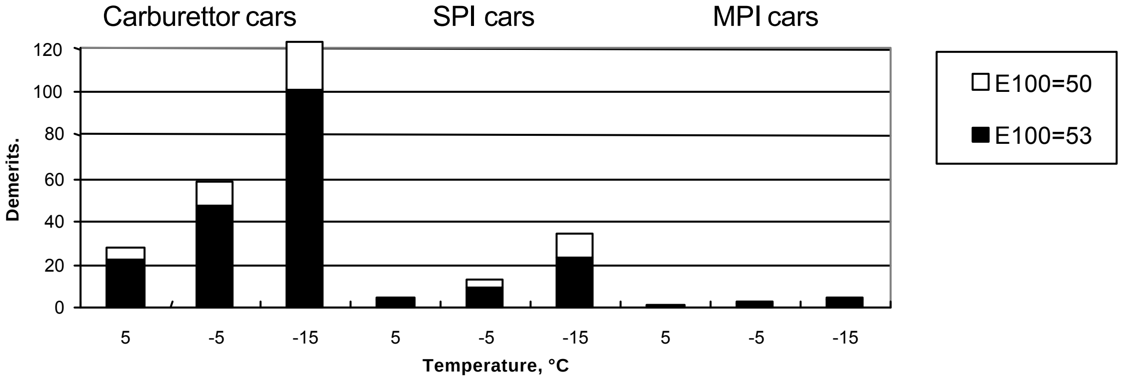


Figure 16 (CONCAWE, 1999) illustrates the improvement of hot weather driveability performance for new vehicles registered in Germany over the period 1980 to 1996 (ICVWG data). The requirements are shown in terms of the maximum gasoline volatility at which customers would be satisfied with their vehicle's performance. The 1990 and 1996 model year vehicles were mainly SPI and MPI technology and clearly gave a dramatic improvement in tolerance of high volatility fuels. In fact, for 1996 the critical fuel volatility level is off scale as very few vehicle malfunctions were found.

ICVWG tests on cold weather driveability (CWD) have shown that modern, fuel-injected (especially MPI) vehicles also give very good CWD performance. **Figure 17** (CONCAWE, 1997) compares the CWD performance of vehicles equipped with different types of fuel system. It shows that MPI vehicles are less sensitive to fuel volatility and give a much lower level of driveability demerits (about one tenth of those from carburettor vehicles).

Figure 17 Cold weather Driveability Demerits for recent average Carburettor, SPI and MPI vehicles at different temperatures and fuel volatility levels



Traditionally, national and in-house volatility specifications have been based on the prevailing climate and the requirements of the vehicle road population. These have been designed to give adequate performance throughout the year across Europe, based on experience and vehicle test data. The important, controlling volatility properties are summarised below:

Performance Attribute	Controlling fuel properties
Cold start	RVP, E70, E100
Cold Driveability	E100, E150, (DI)
Hot Driveability (Hot Fuel Handling)	$T_{V/L20}$, FVI or VLI = (10 x RVP + 7 x E70)

The current CEN specification has maximum and minimum limits for RVP, E70 and E100; maximum limits for VLI; and a minimum limit for E180. The new EU Directive for 2000 has more severe limits for summer RVP (60 or 70[2] kPa max), E100 (46% v/v min.) and a new limit for E150 (75% v/v min.). The CEN specifications will be amended to bring them into line with these limits.

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[2] "arctic summer" conditions

Hot weather driveability performance of modern fuel-injected cars is now very good. Lower summer RVP levels, introduced to control evaporative emissions (in the USA and soon in Europe) mean that further control via $T_{V/L20}$ or VLI is generally no longer required. VLI limits are not required for summer or winter in the EU, but may be required for transition periods in a few critical markets.

Driveability Indices (DI) are mathematical combinations of distillation properties, developed to describe the influence of fuel volatility on driveability. Thus Vapour Lock Index (VLI = 10 x RVP(kPa) + 7 x E70), could be considered as a form of DI. A debate has been underway for several years in USA over the inclusion of a cold weather DI (USDI) based on a combination of Front-end, Mid-range and Back-end volatility properties in gasoline specifications where:

$$USDI = 1.5 \times T10 + 3.0 \times T50 + T90$$

The DI has recently been accepted for adoption in the ASTM D4814 specification. However, the US CRC has now developed a new driveability test procedure which suggests a step change in the severity of future CWD evaluations.

Cold weather driveability of modern cars is also very good. Analysis of European ICVWG data shows that mid-range volatility (E100 or T50) provides good driveability control for conventional gasolines. Inclusion of additional lower distillation points, such as E70 or T10, add very little control of CWD. Higher distillation points (E150) can be used to form a DI term, which can help to prevent driveability problems with fuels of unconventional distillation curves (confirmed by recent tests, Stephenson and Luebbers 1998). However, the new EU 2000 limits control the distillation curve very well and prevent driveability problems from such “dumb-bell” or “gap” fuels. Therefore a US-style DI specification does not generally give substantive improvement over the conventional control parameters E70, E100 and E150. ICVWG data also shows that oxygenates (especially alcohols) degrade CWD performance of fuels in older, non-catalyst cars, so some compensation for the use of these components may be required. This was also addressed in the WWFC, which proposed an additional term based on fuel oxygen content for inclusion in the USDI equation above.

Another recent test programme (Jorgensen et al, 1996) showed that a DI of the form (E200 + E300 [°F]) or (E93 + E149 [°C]) without a MTBE term gave a better correlation with fuel performance. The latest analysis of CRC driveability data is understood to show that several versions of DI (including E200 + E300) give equally good correlation with driveability of US vehicles, but all need a correction term for oxygenates.

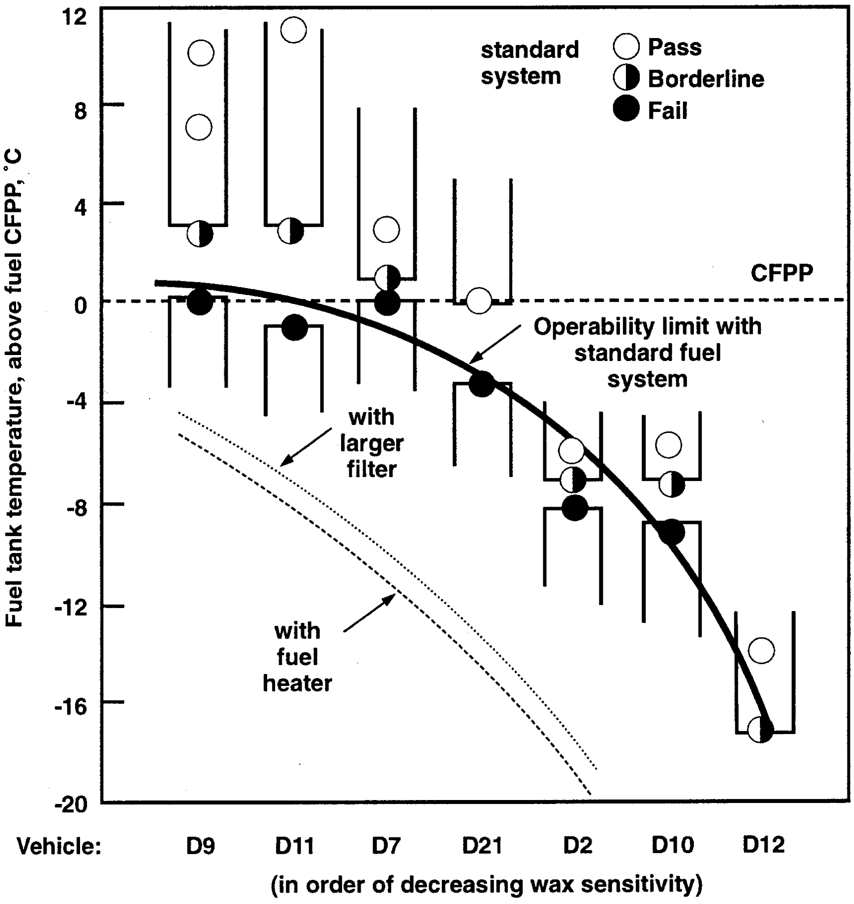
6.2. DIESEL LOW TEMPERATURE PERFORMANCE

Low temperature operability of diesel vehicles is determined by the ability of the vehicle fuel system to cope with the formation of wax crystals formed at low temperatures by the diesel fuel. Normal paraffins are a desirable constituent of diesel fuels, due to their high cetane numbers and superior ignition quality. However, their high melting points lead to their deposition as wax at low ambient temperatures.

If untreated diesel fuel is left in a vehicle tank and filter at sufficiently low ambient temperatures, wax crystals will form and settle to the bottom. On starting the engine, these crystals will reduce fuel flow by accumulation on fuel filter surfaces or by plugging a fuel line. Under these conditions it may be possible to start the vehicle and drive away, only for the engine to stall after a few kilometres when sufficient wax has accumulated to block the filter surface. This particular behaviour has been taken into account in the development of the CEC Code of Practice (M-11-T-89) for low temperature performance tests on diesel fuels and vehicles.

It has been demonstrated that the sensitivity of diesel vehicles can vary considerably. Guidelines have been published for designing fuel systems that are less critical to the formation of wax crystals. Vehicle sensitivity can be reduced by several design features. For example, using larger bore fuel lines without sharp bends; installing the fuel filter in a sheltered location to reduce exposure to the cold air; using larger fuel filters with a wider active surface; and reducing the return flow ratio through the fuel filter. Over the years, car manufacturers have used their experience to improve considerably the low temperature performance of diesel vehicles, incorporating new design features as standard equipment (such as heated fuel filters). The range of fuel system design effects on low temperature operability is illustrated in **Figure 18**.

Figure 18 Fuel system modifications to improve low temperature operability (Source: Owen and Coley, 1995; see also Heinze, 1985)



Low temperature performance of diesel fuels can be described in different ways. Initially with very critical vehicles, Cloud Point was used, being the temperature where wax crystals just start to form. However, the advent of wax crystal modifier additives such as MDFI (Middle Distillate Flow Improvers) and WASA (Wax Anti-Settling Additives) changed the correlation between field performance and lab test results. For diesel fuels containing these additives, Cloud Point is no longer a realistic predictor of low temperature performance. Vehicles could be started and operated without field problems, at ambient temperatures far below the Cloud Point of the fuel. In order to better describe the performance of these fuels and control low temperature performance, the LTFT (low temperature fluidity test) and the CFPP (cold filter plugging point) have been developed for US and European requirements. The CFPP test simulates the flow through a fine mesh (similar to a fuel filter) and, for non-additised diesel fuel, the CFPP is normally one or two degrees below the Cloud Point.

On cooling, normal paraffins precipitate from diesel fuel, forming plates that quickly cover the surface of filters. If undisturbed, these plates lead to gelling of the fuel. MDFI additives improve the cold filterability of diesel fuel by modifying the growth of wax crystals by a combination of nucleation and growth arresting. As the temperature is lowered to the Cloud Point of the fuel, the MDFI provides sites for wax crystal growth and this growth continues until terminated by other additive molecules attaching themselves to the crystal. The result is the formation of very many small crystals, rather than fewer large crystals. However, in sufficient quantities, these small crystals can still cause problems by collecting at the bottom of the tank and restricting flow from the tank outlet. WASA additives are used to retain the wax as a suspension in the fuel for longer, by further reducing the crystal size and so reducing the rate of settling. Because of the intricate relationship between n-paraffin and carbon-number distribution of the fuel and additive structure, good additive response requires careful selection of diesel blending components and additive.

Typically, these additives are used to reduce the CFPP by 10ºC or more. In previous years, a differential of 10ºC between Cloud Point and CFPP had been used to guard against excessive wax formation. In the past, excessive wax formation had led to wax accumulating on the bottom of tanks, separation of fuel and subsequent blocking of lines. However, careful control of the diesel fuel composition and checks against vehicle operability allow larger differentials than 10ºC for safe operation. A specification of Cloud Point in addition to CFPP is not required.

To control low temperature performance in the field, the selection of a control temperature is essential. This should be based for each area on meteorological data and calculated as e.g. the 95-percentile minimum ambient temperature. To select the “lowest expected ambient temperature” would be overly severe and constrain the specification according to the lowest temperature on record, which happens perhaps only once every 50 years.

6.3. NOISE

Noise is primarily a problem for diesel engines due to their high rate of cylinder pressure rise. Engine design is a key factor to control noise. Supercharging, maximum speed rating (1.5 dB par 10 % speed change), bore diameter (the smaller it is, the lower the noise), stiffness of the camshaft and fuel pump capacity all contribute to overall noise levels. Engine shielding also contributes effectively to noise control.

The available information on noise from future engine technology (March and Croker, 1998) suggests a good potential for noise reduction. For example, Common Rail injection with pilot injection substantially contributes to combustion noise reduction.

The use of EGR, and even of knock sensors also help to lower noise levels (March and Croker, 1998).

On the fuel side, diesel studies have shown cetane number as the main parameter to influence combustion noise. However, the influence of this parameter depends widely on the particular engine and technology. For example :

- a reduction of about 2 dB was observed on a Euro 2 Direct Injection light duty engine when cetane number was increased from 43 to 64 (Gerini and Montagne, 1997).
- a reduction of about 2 to 3 dB was observed for an increase of cetane from 49 to 58 on two Euro 2 Heavy Duty engines with combustion noise levels of about 89 dB(A) (Engine X) and 76 dB(A) (Engine Y) at the 49 cetane level. (Kleinschek et al, 1997).

When assessing fuel effects the overall engine noise, with its major contribution from mechanical noise, has to be considered as well. This is important as indicated by the differences in the absolute combustion noise levels of the above referenced heavy duty engines.

There is no available information on actual fuel effects in engines equipped with future technologies.

6.4. ODOUR AND SMOKE

Odour

Problems of odour are generally associated with diesel vehicles. Visible smoke and exhaust odour are noticed by customers and are a source of complaints related to trucks and buses in city areas. Moreover, unlike most of the other performance parameters considered in this report, odour and smoke are more likely to result in complaints from people other than the customer.

The characteristic odour of diesel exhaust comes from unburned and/or partially burned fuel emitted from the exhaust. This is especially true for diesel engines operating with RME. Measures to reduce emissions of diesel hydrocarbons and the hydrocarbon portion of particulate emissions therefore act to reduce exhaust odour.

As diesel engines have become more widely used in passenger cars and other light duty vehicles, the question of fuel odour itself has become of increasing importance. The oily smell of diesel fuel is unattractive to most drivers, and odour masks and re-odourant additives are used by some suppliers to counteract this.

Although diesel engines are the source of most complaints, gasoline vehicles can also produce unpleasant exhaust odour, especially during warm up, or during transient operation. Vehicle design, vehicle maintenance and high fuel sulphur level can contribute to exhaust odour. Those few vehicles that are worn burn excessive amounts of lubricating oil and contribute disproportionately to both smoke emissions and odour.

Since the introduction of exhaust catalysts to Europe, the characteristic odour of hydrogen sulphide (H_2S) has been detectable occasionally from gasoline vehicle exhausts. This usually happens when traffic stops and then starts again. It is noticeable because sulphur is stored on the catalyst during cruise periods and is purged from the system when the air/fuel ratio becomes rich for acceleration. Therefore, a pocket of H_2S is emitted from the tailpipe, causing the odour. Catalyst formulation and improved control air/fuel ratio help to reduce the problem. Although gasoline sulphur levels are generally higher in the USA (outside California) than in Europe, exhaust odour has never been a problem there: mainly due to the inclusion of Nickel in the catalyst formulation. If mixture control is improved to prevent the over-rich excursions during start-off and acceleration, then the conditions for a “sulphur purge” are avoided.

Clearly reducing the sulphur level will have some impact on reducing the smell. However once fuel sulphur is reduced below about 150 mg/kg level, there is very little detectable odour and by 50 mg/kg, H_2S emissions are undetectable by smell.

Smoke

Black smoke emissions are associated primarily with diesel engines and occur primarily at full load operation. It consists of carbonaceous particles on which partially burnt fuel hydrocarbons have condensed. Although smoke is related to particulate emissions, the relationship is not direct since many of the particles in the exhaust are too small to be seen. Black smoke is related primarily to the larger particles in the exhaust.

Vehicle Effects

Smoke is formed when there is inadequate air in the combustion zone, either because of an over-rich mixture, or because of incomplete fuel-air mixing. Black smoke is emitted from diesel engines at high loads, when the amount of fuel injected exceeds that which can be mixed and burnt effectively. Smoke emissions then become a limit on the maximum power that can be produced by the engine.

In principle, since the current heavy duty engine emissions test procedure includes a full load condition, smoke emissions should reduce as new vehicles come on the road. However, many recent model vehicles still produce visible smoke. For light duty vehicles the legislated emission test does not include a full load condition, but does control particulate mass formation during the transient city and extra urban cycle conditions. For heavy-duty engines smoke and particulate emissions will be controlled by the new ESC/ELR and ETC cycles which will replace the current ECE R49 test. The ESC/ELR cycles include a load response smoke test element (ELR) and the ETC cycle will control smoke and particulate emissions at transient operation. Although a separate ECE regulation is in place to control full load smoke emissions, this is only moderately severe.

White smoke is emitted from diesel engines during start up, especially at low engine temperatures. Smoke emissions arise from unburned or partially burnt fuel passing through the engine, and are associated with long cranking times. Measures that improve starting time will, therefore, reduce cold smoke emissions. Injection retard to achieve low regulated emissions may worsen cold starting, especially on some Euro 2 engines. The use of effective starting aids such as the glow plugs used in IDI engines is the single most important factor influencing cold starting and smoke emissions.

The preceding discussion has focussed on modern, well-maintained vehicles, but poorly adjusted or maintained vehicles can emit a disproportionate amount of smoke. Badly worn engines, be they diesel or gasoline, emit very high levels of smoke resulting from partial combustion of lubricating oil or fuel. Effective Inspection and Maintenance programmes and eventual fleet replacement are the critical factors in removing the gross polluters from the vehicle parc.

Fuel effects

Density

Since black smoke is related to full load performance, i.e. the maximum power output of the engine, fuel properties that increase volumetric energy content can also affect smoke emissions. Density is the most influential parameter. Since fuel is injected volumetrically and fuel energy content relates more closely to fuel mass, higher density fuels produce higher engine power and could produce black smoke at full load, depending on the fuel mass/density to which the engine has been calibrated.

Vehicles and engines are certified to show compliance with emissions standards using the standard reference fuel. Low emission fuels such as Swedish class 1 are effective in the case of black smoke primarily because their lower density relative to the reference fuel produces lower power and hence less smoke. These emission benefits accrue only because the density is lower than that of the reference fuel.

Cetane Number

The fuel property that is most influential for cold start and white smoke emissions is cetane number. However, where effective starting aids are employed even lower cetane fuels produce fast start up and low emissions. Some increase in smoke is generally seen as cetane numbers falls, especially at levels below 45 CN. At cetane numbers above 50, little further improvement in performance is seen. Starting and smoke emissions appear to be related primarily to ignition delay and so cetane improved fuels, generally perform as well as natural fuels of the same cetane number. The effect of other fuel properties is small.

7. DURABILITY

7.1. AFTER-TREATMENT SYSTEMS (CATALYSTS / SENSORS / EMS)

After-treatment devices such as catalysts and traps need complex Engine Management Systems (EMS) to operate properly and reliably over a vehicles lifetime. These systems must be certified to comply with emission standards over 80,000 km (Europe) and 160,000 km (USA) respectively to demonstrate their capability for life-long performance. Consequently durability is a key issue for after-treatment systems.

Changes in automotive after-treatment technology can require significant change in a fuel property. This was the case when catalysts for gasoline engines were introduced which need unleaded gasoline. Lead is a poison to the catalyst making a durable operation impossible. However, while lead is a poison to catalysts, other fuel properties, especially sulfur content, cannot be considered poisons though they may have an effect on conversion efficiency. Findings from a CRC programme (Schleyer et al, 1999) with California Low Emissions Vehicles (LEV) and aged catalysts (100,000 miles) show that while sulphur affects catalyst activity, the effect is largely reversible for the test vehicle fleet when switching between 30 and 630 mg/kg sulphur level using the US06 driving cycle. The paper also concludes that for half of the individual vehicles, no evidence of any irreversibility of sulphur effects was seen.

Long-term catalyst durability is dependent on both physical and chemical routes to deterioration, and it is very difficult to distinguish between the various contributions. Agglomeration of particles leading to loss of active surface area is one important factor, caused by thermal ageing which needs not be dependent on any fuel effect e.g. sulphur. Possible contamination from the lubricant (e.g. phosphorus) can affect long-term catalyst performance as well. In addition it is possible that "artificial ageing" of the catalyst might have some impact on changes in metallurgy / sintering different to those obtained in road operation. This could result in a response to fuel quality (e.g. sulphur) possibly different to that observed in road operation. Work conducted jointly between a catalyst manufacturer and oil companies showed that gasoline sulphur in the range from 50 to 450 mg/kg did not affect the tested catalyst (TWC, Pt/Rd-based) with regard to durability using proper test cycles (Bjordal et al, 1995).

Engine management systems to control air/fuel ratio and hence catalyst conversion efficiency are key for an effective engine / vehicle operation over its life. In Europe such functions will be monitored from year 2000 on for gasoline vehicles with On Board Diagnostic (OBD) Systems. This will generally be done by using a second lambda sensor after the catalyst, and comparing it’s output with that of the main sensor to assess catalyst condition. The second sensor can also be used to “trim” the AFR of the first sensor and improve overall long-term AFR control. This will probably reduce the effect of changes in fuel composition on lambda sensor output and hence on tailpipe emissions.

In the USA where OBD has been applied for some time, the EPA have suggested that fuel sulphur is a potential issue for severely aged catalysts which are at or approaching 1.5 times the emissions standard. However, such sulphur induced deterioration was seen as unlikely under normal conditions up to 100,000 miles. In their 1997 study the EPA concluded that reducing fuel sulphur was not necessary in the short term, but suggested a study to develop a long term solution. CARB has announced that the OBD thresholds are to be relaxed by raising the cut point from current 1.5 to 3 times the emission limit. The view of European car manufacturers seems to be that it is not realistic to expect that close linear relationships may link the OBD thresholds and emission standards for which the vehicle is designed. Complex system interactions lead to high variability limiting the accuracy of the monitoring system. Confirmation of adequate detection capacity and the absence of false failure detection still need further development.

As has been discussed in previous sections, catalysts which reduce NOx under lean conditions will be needed for both G-DI gasoline and diesel engines to reduce CO_2 emissions and fuel consumption. So far Mercedes have shown an advanced passive de-NOx catalyst technology for light duty diesel with durability potential over 70,000 km testing with current sulphur fuel quality (Peters et al, 1998). However the new generation of "NOx storage" catalysts for both G-DI gasoline and diesel engines is still under development, and so far they have not demonstrated adequate durability, even on very low sulphur fuels (Quissek et al 1998).

Catalytic Trap-Oxidisers to reduce diesel particulate emissions are also under development. These will need to be regenerated several times during a vehicles lifetime, requiring a complex control system and raising serious durability problems. One approach to this which is under consideration is to use metallic additives to reduce the ignition temperature of the particulate (Rodt et al, 1998). A number of different metals are under consideration, but it is not yet clear how they would be dosed into the fuel, to prevent this fuel being used by vehicles without traps. An on-board vehicle system appears the most promising solution.

7.2. DEPOSITS (INJECTORS/VALVES/CHAMBER)

7.2.1. Gasoline Engine Deposits

The deposits of concern to the operation of gasoline engines are those in the

- fuel system (carburettor and fuel injector)
- inlet valves (IVD)
- combustion chamber (CCD)

These deposits occur in all engines and are affected by a number of engine design features including:

- fuel injector design, position and temperature profiles during operation
- inlet valve temperatures
- air flow patterns around valves and ports
- oil flow rate down inlet valves
- overlap between intake and exhaust valve opening
- combustion chamber design

Deposit control has been achieved primarily and effectively through the use of fuel additives. The first gasoline detergent additives were developed in the 1950s to control carburettor deposits, followed by so-called "Second Generation Additives" in the 1970s which also controlled inlet system deposits. In the mid 1980s, with the introduction of port fuel injection, there were severe field problems in the USA due to injector deposits. Use of simple carburettor additives controlled port fuel injector (PFI) deposits, but increased IVD. At the same time, evidence emerged that in some fuel injected cars, excessive IVD caused driveability problems. This led to the development of the current generation of improved detergent additives which can control all deposits in the fuel and inlet system to very low levels without giving detrimental side-effects.

There is no doubt that engine fuel system and IVD deposits affect emissions, driveability and fuel economy. In fact, fuel marketers have traditionally used these benefits in competitive claims for additivated fuels. The scale of the benefits is relatively small, and was reviewed in the Auto/Oil process in 1994 (van Beckhoven, 1995). The conclusions were that benefits relative to fuels without additives were:

Parameter	**CO**	**HC**	**NOx**	**Fuel economy**
Benefit from additive	10 to15%	3 to 15%	+5 to -5%	2 to 4%

While control of fuel system deposits is clearly desirable, and has been promoted by the oil industry, developing a system to regulate them is difficult. Clearly control of deposit levels should be based on fuel performance, i.e. deposit levels in engines. However, attempts to develop simple laboratory tests that correlate with deposit levels and can be applied to individual fuel batches have been unsuccessful, due to the complex relationship between deposits and fuel composition. In the USA a complex certification system has been developed, whereby fuel/additive combinations must be certified by fuel suppliers on the basis of engine tests. Conformance in the market is by suppliers maintaining inventory records which can be requested by EPA. This is a cumbersome procedure but is similar to the process used for lubricant approvals and appears to be the only feasible way for legislation, if it is necessary. Experience in the USA, however, has shown that such regulation leads to a reduction in additivation to the lowest level required to pass the tests, and provides no incentive to develop new and better additives.

Recently there has been some concern over combustion chamber deposits, and the fact that detergent additives tend to increase CCD. Effects observed are increased NOx emissions and CCD interference where the piston top can strike the cylinder head due to excessive CCD build-up. However, due to reduction in heat loss to the cylinder walls (greater thermal efficiency), CCDs also have some benefits in terms of reduced HC, CO and CO_2 emissions, and improved fuel economy. The effects of CCDs are very variable in different engines and can go in different directions, as summarised in **Table 1** below.

Table 1 Summary of CCD effects on vehicle performance for dirty versus clean combustion chambers (Barnes, 1998)

	CO tailpipe	THC tailpipe	NOx tailpipe	CO_2 tailpipe	Fuel economy	Power	Drive-ability	ORI	CCDI
CCD	Can increase or decrease	Can increase or decrease	Usually increase	Decrease	Improve	Slight decrease	Neutral?	Increase	Occurs in limited number of engines
Typical ranges	-50 to 30%	-30 to 20%	0 to 50%	2 to 10%	2 to 10%	0 to 3%		1 to 10 ON	
Refs	1,4,5,7	1,4,5,7	1,4,5,6,7	1,5,9	1,5,9	1,5,11	1	1	1

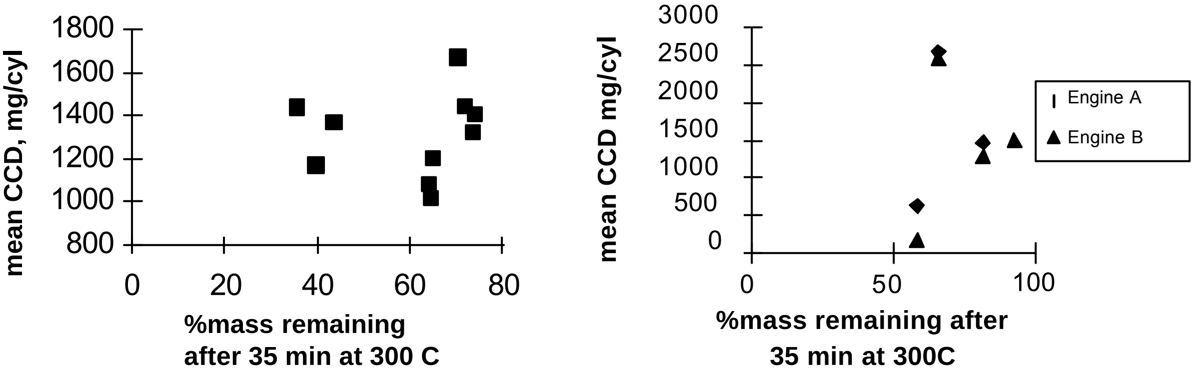
Refs (as numbered in the referenced document):

1	Kalghatgi, 1995	5	Barnes and Stephenson, 1996	7	Harpster et al, 1995	11	Cornetti, 1971
4	Woodyard, 1995	6	Studzinski et al, 1993	9	Yonekawa et al, 1982		

The above table only compares engines in “dirty” (with CCDs) and “clean” (without CCDs) conditions. Effects of intermediate levels of deposits are even less clear, especially on NOx emissions. Some recent work (Barnes, 1998) on a Japanese engine run over the European M102E test cycle showed that a “low CCD fuel” giving CCD 861 mg/cyl. and a “high CCD fuel” giving CCD 1309 mg/cyl. gave very similar increases in NOx emissions of 35% and 37% respectively.

This concern with CCD has led to a wish to specify unwashed gum (UWG) levels, or to develop tests based on Thermo-Gravimetric Analysis (TGA). However, in the same way as for IVD, there is no simple relationship between the results of these tests, fuel properties and CCD levels in engines. No clear relationship with unwashed gum levels has been demonstrated, and control of UWG only restricts levels of detergent additives which appear as gum in the test. While there may be a weak correlation between additive thermal stability and total CCD level, recent work (Clarke and Haddock, 1997) has shown that data scatter is too great to allow CCD performance of additives to be predicted from TGA alone. **Figure 19** shows that for both base fuels and additives there is a very poor correlation between CCD levels and TGA residue of the UWG.

Figure 19 Correlation between CCD mass and TGA residue of UWG for additives and base fuels. (Clarke and Haddock, 1997)



TGA of UWG from 10 additives

TGA of UWG from 4 base fuels without additives

Clearly, as for injector deposits and IVD, any control must be based on engine test results, even though these are not very precise. Such engine test procedures are under development in Europe, USA and Japan. However, the benefits and disadvantages of CCD control need to be more clearly established before considering the need for control.

The latest generation of G-DI engines are likely to pose new challenges in terms of control of both injector tip deposits and CCDs. Fuel injectors will operate under high-temperature conditions similar to a DI diesel, and therefore will be prone to deposit build-up, and coking. As the combustion in these engines is very sensitive to injector spray pattern and fuel/air mixing, such deposits may adversely affect emissions, and new types of detergent additives will be needed. Early investigations also suggest these engines produce relatively high levels of CCDs, and unexpectedly IVDs (Macduff et al, 1999).

Summary remarks

Gasoline engine fuel system deposits (FID and IVD) have small but significant effects on emissions and economy and can be reduced by well formulated detergent additives. Gasoline engine CCDs increase NOx emissions but reduce fuel consumption and CO_2 emissions, effects on CO and HC are variable. Control of fuels to reduce engine deposits is however difficult, as long duration engine tests are needed to show clear effects, and these cannot be applied to refinery batch production. Development of rapid screening tests to predict engine deposit levels has so far been unsuccessful. *If control of engine deposits is considered essential, then an approval mechanism such as used for US Reformulated gasoline is the best approach. However any legislation will have the effect of removing incentives to improve fuel performance and minimising additive treat levels*

7.2.2. Diesel Engine Deposits

The deposits of concern in diesel engines are those which build up in the fuel injector. Such hard carbonaceous deposits build up in the nozzles of fuel injectors of both DI and IDI engines during the first few hours of operation and persist throughout the service lifetime of the injector. This is especially a problem for IDI engines, as the pintle type nozzles employed in these engines are inherently prone to deposit build-up that affects the initial rate of fuel injection. This pilot injection is important to establish smooth and stable combustion and reduce noise, especially under cold engine conditions. This phenomenon is well known, such that a certain deposit level is designed into injectors.

As deposits affect combustion, they have some effects on emissions, although there is no clear direct link. The scale of the effects is again relatively small, and was also reviewed in the Auto/Oil process in 1994 (van Beckhoven, 1995). Based on limited data, benefits relative to fuels without additives for light-duty IDI engines were estimated to be:

LD engines	**CO**	**HC**	**NOx**	**PM**	**Fuel Economy**
Benefits from additives	8 to 10 %	15 to 29 %	1 to 2 %	10 to 22 %	2 to 4%

Developing tests to predict fuel performance is not easy, as susceptibility to deposits varies widely between different engines. A “Fouling Index” has been developed by CEC based on rating reductions in air flow through pintle nozzles tested in the PSA XUD9 engine. However, the engine on which the original test was based is now relatively old, and a revised version of the test on a more modern engine gives very poor repeatability. This highlights the serious issue of maintaining engine test credibility over a long period of time. Some commercial test procedures are also available.

Injectors in DI engines, both light-duty and heavy-duty are generally much less susceptible to deposit build-up. However such deposits do occur, and as for IDI engines do have a limited effect on combustion and hence emissions. However, for LD-DI and HD-DI engines only very limited data were available when the following estimates of benefits from removing deposits for HD-DI engines were reported by van Beckhoven, 1995:

HD engines	**CO**	**HC**	**NOx**	**PM**	**Fuel Economy**
Benefits from additives	10 to 14 %	14 to 15 %	2 %	10 to 15 %	2-5%

Many of the additives reviewed in this work contained ignition improvers which would contribute to these benefits. More recent experience with detergent additives alone suggests that deposit effects on NOx emissions are very small, and generally negative, and that fuel economy benefits of 1-2 % are more typical.

Developing a test method to predict DI diesel engine deposits is even more difficult, as a fouling test is not feasible, and deposit weights are very low. The Cummins L10 test developed in the USA is also applied in Thailand, but this engine has a unique design and is not considered to be representative of other DI engines. Another test based on a Mercedes OM366 engine has been reported (Beck et al, 1999) which will be applied in Brazil. Recent information suggests that common rail diesel engines can suffer from deposits and need study.

Summary remarks

It has been found that diesel fuel system deposits have small but significant effects on emissions and fuel economy. Detergent additive packages have been shown to reduce deposits and so improve slightly emissions and economy. However, more work is needed to develop improved test methods, especially for DI and new Common Rail DI engines to adequately assess additive performance.

7.3. DIESEL PUMP WEAR (LUBRICITY)

An important aspect of the durability for diesel engines is reduction of engine and pump wear. Until recently, fuel properties had little impact in these areas, since the sulphur levels and cleanliness of road fuels have been maintained at levels that maintain good lubricity and avoid damage.

The introduction of very low sulphur diesel fuels in Sweden in 1993 led to problems with certain types of pump. These rotary pumps relied on the natural lubricity of the fuel to prevent wear. It was found that the hydrotreating to remove the sulphur also removed some of the natural lubricity of the fuel. Similar problems were found in other countries with the introduction of 500 mg/kg sulphur fuel in Europe beginning in 1995/96. To counteract this fact, lubricity additives are added to many European diesel fuels, with acceptable performance being assured through the use of the newly developed HFRR test.

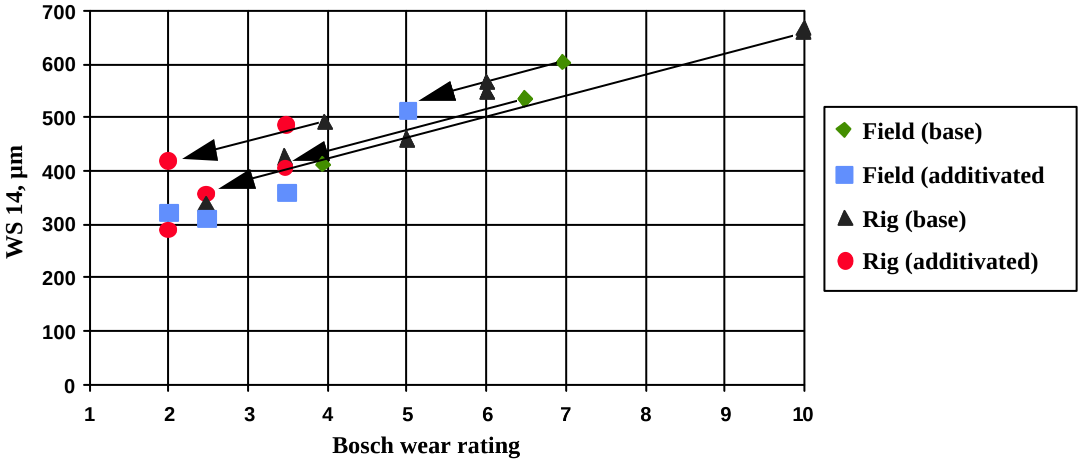
Evaluation of pump rating correlations between various FIE-suppliers (Bosch, Cummins, Lucas, Stanadyne) resulted in the proposed WSD (ISO 1998) with the Bosch-rating being the most severe criterion. The Bosch wear rating is defined by a scaling from 1 to 10, with a wear rate level of less than 4 considered as acceptable by Bosch.

From available data base a correlation between wear scar diameters, WSD) and the Bosch wear rating was established. These data resulted from several round robin tests (CEC, 1996 and Davenport, 1997).

Pump rig tests would seem to be the most reliable method to predict long term lubricity performance, but as with engine tests, these are long duration and expensive to install. In Europe, the High Frequency Reciprocating Rig (HFRR) has been accepted as the preferred tool for comparison of lubricity performance. This was based on data from several round robin tests (CEC, 1996 and Davenport, 1997), showing a strong linear correlation between Wear Scar Diameter (WSD, WS 14 / HFRR) and the Bosch rating when corrected to constant humidity. The available database resulted in agreement between the FIE suppliers, automobile manufacturers and the oil industry, for a maximum 460µm WSD limit to be included in the revised European diesel specification from 1999, (ISO, 1998). As no problems with Bosch diesel fuel pumps have been reported in the market, this specification should ensure that wear problems will be avoided.

There are no substantial differences between the three types of pump test procedures (100.000 km field trial, Bosch 1000 hour pump rig test, Shell 290 hour rig test). HFRR data (WS 14) obtained with additivated and non-additivated fuels in field and rig tests are shown versus the Bosch wear rating in **Figure 20**. Those HFRR values ranging from 350 to 500 µm WSD all show Bosch wear ratings below 4. The effect of additivation is shown in **Figure 20** as well. The arrows connect four pairs of data points, where a base fuel and the same fuel with additives have been tested. The samples containing a lubricity additive show consistently a lower wear rating than the corresponding base fuel.

Figure 20 HFRR versus Bosch rating and HFRR response to additive treatment (CEC PF-006, 1996)



The results are also supported by tests conducted by ISO TC 22/SC7 W6 in 1998 (Henderson, 1996).

8. IMPLICATIONS

The importance of interactions between fuel quality, vehicle technology, test cycles and their combined effects on emissions and performance aspects has been described in the previous sections. Both adequate emissions and performance of vehicles will effectively contribute to the overall target to meet required air quality standards. The required energy and costs for refining of the specified fuel quality, and therefore the amount of CO_2 generated, are further aspects in a complete assessment. The feasibility of producing a certain fuel quality and refining costs have to be compared with other measures to achieve a cost-effective, and therefore optimum low energy consuming solution. An appreciation of these implications is essential to ensure sustainable conditions.

8.1. REFINING ISSUES

Refinery configuration

Market development in Europe is the result of a complex historical interaction of crude availability, local transport infrastructure, government fiscal policies and climatic conditions. The existing refinery population has evolved to meet local, regional and strategic demands; each refinery has a different configuration, usually tailored to fit a given set of assumptions (valid for a short period). Changes in yield pattern, product demand, crude oil availability/price and product quality all require adaptation of either the operating modes of the hardware, a change of crude diet or investment/dis-investment in equipment.

Historically, investments for conversion projects (e.g. making more distillate from the crude) have been approved and constructed, while investments for changes in product quality have seen no return on the capital invested.

The most significant effect of the current changes in product quality is on the increased demand for hydrogen. Higher levels of desulphurisation, saturation of aromatics and/or olefins and increased conversion requirements to meet limitations in back-end distillation in the diesel pool all require more hydrogen. Hydrogen is typically produced in the catalytic reformer by dehydrogenation of naphthenes to high-octane aromatics used in gasoline. Lowering gasoline aromatics content reduces hydrogen production (from catalytic conversion) while at the same time, sulphur reduction in many products causes an increased demand for hydrogen.

This combined effect leads to a hydrogen imbalance. The shortage of hydrogen will need to be addressed by the addition of new dedicated hydrogen manufacturing capacity. These processes use natural gas and refinery gas or are based on gasification of refinery liquids/coke; all such processing involves a substantial loss of energy content and an associated increase in CO_2.

In this context it is worth noting that the gasoline octane mix (unleaded 91/95/98) needs careful monitoring especially as to important contributors to gasoline octane (aromatics and olefins) are being reduced. Another issue is the balance between gasoline and diesel. This balance when shifted too far to either side, would lead to substantial additional investment and to an energy increase in refining.

Resource

Crudes vary in many respects and can be characterised in terms of high/low sulphur, light/heavy (expressed in distillate yield) and other characteristics such as acidity and density (following from paraffinic or naphthenic nature). After primary distillation and quality upgrading (e.g. octane increase, sulphur reduction) intermediate products are either blended into finished products or used as feed for further conversion processes.

It follows from basic thermodynamics that any processing leads to increased energy usage. Therefore, in principle products should not be modified unless there is a compelling reason:

- A fundamental law of thermodynamics states that any process has an efficiency of less than 100%; therefore any additional processing increases overall energy consumption and increases overall CO_2 emissions.
- Selection of higher quality components - from a fixed pool - in combustion, without an 'intrinsic' improvement in user combustion efficiency is cosmetic. This results from the fact that the CO_2 decrease from combustion of the higher quality product is offset by the increased CO_2 from the remaining other products that have absorbed the higher carbon content.
- CO_2 emissions will be reduced when switching to lower carbon-content fuels (e.g. natural gas instead of liquid fuel - thus changing the pool) and/or by changing the combustion efficiency e.g. G-DI engine. When comparing cases the causal relationships need to be clear.

Some of the necessary quality changes in transport fuel

In today's environment it is required to convert naphtha to high-octane gasoline components, because low octane naphtha does not satisfy the octane requirements of current engines. Future fuel cells on the other hand, when designed to use 'gasoline', would benefit from the use of naphtha as compared to traditional high-octane gasoline.

Sulphur removal from products is either inspired by maintaining conversion of refinery processing catalysts, the direct influence on engine emissions or by their influence on after-treatment technology. In this latter role, there can be an enabling effect on new higher efficiency technology (e.g. new G-DI related de-NOx technology), but further developments have to be waited for.

Effects on CO_2 emissions

Reduction of CO_2 emissions (EU-Kyoto commitments) will lead to fundamental changes in EU economies, with a sustained pressure to improve energy efficiency and lower end-user demand. New technologies will come forward, some with requirements for special fuels. The causal links need to be carefully considered since 'thermodynamics cannot be beaten'; the aspiration for fuel quality change should be: avoid cosmetics and concentrate on fuel quality modifications that do make a contribution.

Thermodynamic and economic logic suggests that a special fuel - linked to a special technology - should only be used in that application. A full-scale fuel quality change would mainly benefit the 'new' technology vehicles and for the existing fleet only involve negative effects in terms of extra CO_2 emissions in fuels production without the benefits shown in new technology vehicles.

Product produceability

The tendency to increase the number of product specifications and to introduce composition-related specifications leads to issues of fuel produceability. The main performance parameter for gasoline is octane. Some of the specifications changes that affect octane are the reductions of benzene, aromatics and olefins content and the summer RVP reduction limiting butane blending. Most of the emissions effects of changing these parameters are small, but the combined effects on gasoline production can be substantial. Reducing aromatics for instance, leads to an increased use of isomerates, with relatively light components replacing the heavier aromatics, causing limitations in E70, one of the volatility parameters in gasoline. In diesel, the reductions in density and distillation (T95) specifications, lead to a reduction in component availability. High density and higher molecular weight components can no longer be used in product blending and now would need further treatment with associated energy use before these can again be used in producing diesel.

Refiners rely on flexibility in product blending and crude selection, allowing climate related adjustments (summer and winter qualities and demand shifts etc.). Generally the emissions effect of fuel changes is relatively small, and the changes in specification bring only small improvements, but at a high price in loss of refinery flexibility and increased energy use.

8.2. COST- EFFECTIVE MEASURES

Previous research studies, including co-operative industry programmes have helped to quantify the relative effects of fuel and hardware changes. To meet future emissions targets, engine and vehicle hardware must improve, as described elsewhere in this document. Changes to base fuel composition are viewed as enabling some of the developing technology. However, the cost implications of both approaches need to be compared as these have to be passed on to the consumer and eventually they can affect the fundamental economy of the region.

Base engine design is known to influence HC emissions through mixture preparation, crevice volumes and piston characteristics. EGR has been used effectively to control NOx in diesel and gasoline lean-burn applications. To compensate for compromises in engine design (e.g. HC/NOx balance), exhaust gas after-treatment must be used to remove unwanted pollutants to acceptably low levels. Limiting factors for this are the composition and temperature of the exhaust gas and the physical and chemical nature of the catalyst. Catalyst manufacturers are continuously striving to improve the performance of their products, but there appear to have been no new technology breakthroughs in the past 2-3 years.

Nevertheless, even with currently available materials, there is still scope for reducing emissions. Perhaps this is illustrated most vividly within the recent CARB activities, where heavy Sport Utility Vehicles (SUV’s) will be subjected to similar emissions requirements to conventional cars through the LEV II programme. This was previously considered to be (almost) an insurmountable technical hurdle for the OEM's, who were claiming that additional (and costly) fuel changes would be required. However, CARB state that their own scientists have adapted existing cars to meet LEV II requirements on existing fuels for on average about $200 each (US$96-304) (New York Times, 6 November 1998). Of course, the cost of this modification is expected to reduce dramatically through economies of scale when applied to full-scale production.

Changes to fuel quality to contribute in meeting the same emissions targets could result in an increase in fuel cost of US$0.05-0.06/gallon (New York Times, 4 April 1999). Assuming average fuel consumption of 29 mpg (8.1 litres /100 km), based on 1997 US CAFE for passenger cars of 28.6 mpg, the customer would pay an additional US$190 over a distance of about 100,000 miles. For the customer, the comparison is remarkable since vehicle modifications will be required anyhow, even if the fuel quality is changed.

Changes to fuel quality and vehicle technology must be compared together in terms of their alignment with the aspiration to meeting required air quality standards, government objectives and policies for:

<u>The environment</u>:

The need to consider CO_2 emissions from the vehicle fleet and refineries. The need to address CO_2 versus specific pollutants (e.g. NOx, PM). The need to develop solutions to local problems versus global issues.

<u>The economy</u>:

Which solutions are most cost-effective and therefore have the least impact on the end customer. In the long-term, which measures also ensure successful industrial operations.

9. CONCLUSIONS

Fuel quality and vehicle technology are intimately linked. Neither fuel nor vehicle can function without the other, and both must work effectively together. This is equally true for the two industries, which have common aims of reducing environmental impact whilst satisfying the same customers in the most cost-effective way. This means that both vehicle technology and fuel quality must evolve in parallel to satisfy society's changing demands. Thus fuel quality levels should be linked to the technology available in any given market, a concept embraced by the WWFC.

Based on this mutual dependency, there are a number of general conclusions which can be drawn from this review of the interactions between vehicle technology and fuel quality.

- The results of EPEFE and other studies show clearly that effects of fuel quality changes ALONE on emissions from fixed technology engines are relatively small compared to reductions achievable from changes to engine technology

- Real benefits from changes to fuel quality arise when they are used to ENABLE new technologies. Good examples are the introduction of Unleaded Gasoline for catalyst cars, low sulphur diesel fuels for Euro 2 diesel engines and development of detergent additives to prevent problems in fuel injected engines. IF lean de-NOx catalysts can be developed with adequate durability and demonstrated to require lower sulphur, further reduction of sulphur can be considered.

- Thus it is clear that fuels and engines need to be developed together as a common system to meet new challenging emission targets. However while changes to fuels and vehicles are generally aimed at improving local air quality, it is important to consider also their GLOBAL impact. This must be done on an overall “cradle to grave” or “well to wheels” basis.

- It is important also to consider carefully the effect of proposed fuel quality changes on refinery infrastructure and it's ability to produce sufficient quantities of fuels. A good example is demand for very high cetane diesel fuel which cannot be produced in large volumes without major changes to refineries.

- The Oil industry has to manufacture fuels from different crude oils and to meet different demand patterns in different countries. To do this it needs flexibility to vary composition of fuels to meet specifications and demand. Consequently only those fuel properties which have a direct, substantial and proven effect on emissions, performance or customer acceptance should be specified.

- The environmental aspirations of different countries or regions vary according to their:
  - level of economic activity
  - perceived air quality problem
  - climatic and geographical conditions
  - customer priorities (performance, fuel economy, environmental issues).

- A variety of different emissions standards and test cycles exist around the world, which must be met by different combinations of vehicle and fuel technologies. Fuel specifications therefore need only be harmonised in parallel with emissions limits, vehicle technology and test cycles. While these are converging in the USA, Europe and Japan, to achieve full global harmonisation will be a long and complex task.

- Finally, underlying all the above, environmental targets should be developed by rational process involving all stakeholders. Joint industry programmes to develop sound scientific data, such as EPEFE, AQIRP and JCAP are a good basis for such discussions.

10. GLOSSARY

AAMA	American Auto Manufacturers Association
AFR	Air fuel ratio
AQIRP	US “Air Quality Improvement Research Programme” (also known as Auto/Oil)
BSFC	Brake Specific Fuel Consumption
C/H ratio	Carbon / Hydrogen ratio in the fuel
CCDs	Combustion Chamber Deposits
CFPP	Cold Filter Plugging Point
CI	Cetane Index
CN	Cetane Number
CO	Carbon monoxide
CO_2	Carbon dioxide
CP	Cloud Point
CRC	US “Co-ordinating Research Council”
CRT	Continuously Regenerative Trap
de-NOx	NOx reduction
DI	Direct Injection
E70, E100, E150 etc	% gasoline evaporated at 70, 100, 150 °C in ASTM distillation test
EMS	Engine Management System
EPA	US Environmental Protection Agency
EPEFE	“European Programme on Emissions, Fuels and Engine Technologies” Report
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
FBP	Final Boiling Point
FIE	Fuel Injection Equipment
HC	Hydrocarbons
HD	Heavy Duty
HFRR	High Frequency Reciprocating Rig (determines wear scar diameter)
ICVWG	Inter-Company Volatility Working Group
IDI	Indirect Injection
IVD	Inlet Valve Deposits
JCAP	Japan Clean Air Programme
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
PEA	Poly-Ether Amine (gasoline additives)
PFI	Port Fuel Injection

PIBA	Poly Iso-Butene Amine (gasoline additives)
PM	Particulate Matter
RME	Rape Seed Methyl Ester
RON	Research Octane Number
RUFIT	“Rational Use of Fuels in Private Transport” study
RVP	Reid Vapour Pressure
SCR	Selective Catalytic Reduction
SO_2	Sulphur dioxide
SPI	Single Point Injection
T95	Temperature at which 95% v/v fuel has evaporated
TGA	Thermo-Gravimetric Analysis
UWG	UnWashed Gum
VLI	Vapour Lock Index (VLI = 10 x RVP(kPa) + 7 x E70)
VVT	Variable Valve Timing
WSD	Wear Scar Diameter
WWFC	World-Wide Fuel Charter

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APPENDIX

Emission reduction potential of individual automotive technology components and their effect on fuel consumption (based on available information up to September 1998)

Table 1 ***Gasoline Technologies***

Technology	Emissions Reduction Potential	Fuel Consumption	Availability **		
			1998 Market	Technical by 2005	2005 Market
Palladium containing catalysts	HC: ✓✓ CO: ✓✓ NOx: ✓	No effect	Yes	H	H
Catalyst formulation changes	HC, CO NOx: ✓✓✓✓	No effect	Yes	H	H
Close coupled catalysts	HC: ✓✓✓✓ CO & NOx: <10%	No effect	Yes	H	H
Catalyst physical design	HC: ✓ CO: ✓ NOx: ✓	No effect	Yes	H	H
Cold start spark retard and enleanment	Lower emissions, but no data available	No effect	Yes	H	M
Rich start and secondary air injection	Catalyst reaches light-off earlier	Small increase	Yes	H	L
Transient adaptive learning	Lower emissions, no data available	No effect	Yes	H	M
Exhaust gas recirculation	NOx: ✓✓	Small increase	Yes	H	H
Fast light-off lambda sensors	HC: ✓✓✓ CO: ✓✓✓✓ NOx: ✓✓✓	Small reduction	Yes	H	M
On-Board Diagnostics	Improvement mainly due to better I&M of vehicles	Small	Yes	H	H
Electrically Heated Cat	HC, CO: ✓✓✓✓✓	Small increase	Yes	H	L
Gasoline Burner	HC, CO: ✓✓✓✓	Small increase	No	H	L
Exhaust Gas Ignition	HC, CO: ✓✓✓✓✓	Small increase	No	H	L
HC Trapping Systems	HC: ✓✓✓✓✓	No effect ?	No	H	L
Saab "Cold Start" Bags	Can achieve ULEV levels on current cleanest US engines	No effect	No	H	L
Indirect MPI Lean Burn	No effect (w/o cat)	Reduction abt. 10%	Yes	H	M
Gasoline Direct Injection, Lean Burn	HC, CO: ✓✓✓✓✓ NOx: *	Reduction ✓	Yes	H	M
Gasoline Direct Injection Stoichiometric	HC,CO: ✓ (versus conventional) NOx: ✓✓✓ (versus lean-burn G-DI)	Reduction ✓	No	H	L
NOx Storage Catalyst	NOx: ✓✓✓✓✓	No effect	Yes	H	M
Controlled Auto-Ignition	HC, CO & NOx: ✓✓✓	Reduction ✓	No	M	L
Plasma	HC: ✓✓✓✓✓ CO: ✓✓✓ NOx: ✓✓✓✓	Small decrease	No	M	L
Variable Valve Timing	CO_2: ✓ NOx reduction	Reduction ✓	Yes	H	M
Variable Compression Ratio	CO_2: ✓✓	Reduction ✓✓	?	L ?	?

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

** Has been assessed by the Task Force in mid-1998 as:
H = High : likely
M = Medium : limited
L = Low : unlikely

Key: ✓= 10 to 20%; ✓✓ 20 to 35%; ✓✓✓ Up to 50%; ✓✓✓✓ Up to 75% ; ✓✓✓✓✓>75% reduction potential

Table 2 ***LD Diesel Technologies***

Technology	Emissions Reduction Potential	Fuel Consumption	Availability *		
			1998 market	Technical by 2005	2005 Market
Oxidation Catalyst	PM: ✓✓ PM(SOF): ✓✓✓ CO & HC: ✓✓✓✓ NOx: ✓	No effect	Yes	H	H
De-NOx Catalyst SCR (Urea)	NOx: ✓✓✓✓✓ (ECE+EUDC)	No effect	No	H	L
De-NOx Catalyst Passive - FWC (Four Way Catalyst)	NOx: ✓ (ECE+EUDC)	No effect	Yes (very low efficiency)	M	M
De-NOx Catalyst Active - NCR (Non-SCR)	NOx: ✓✓ (ECE+EUDC)	Small increase	Yes	H	M
NOx Storage Catalyst	NOx: > ✓✓✓ (assumed)	Small increase	No	M	L
Continuously Regenerative Trap (CRT)	PM: ✓✓✓✓✓ NOx : <5%	Some increase	No	H	L
Particulate trap (non-CRT)	PM: ✓✓✓✓✓	Some increase	No	H	M
EGR, Non-cooled	NOx: ✓✓ (MVEG) NOx: ✓✓✓✓ (Cruise)	Small increase	Yes	H	M
EGR, Cooled	NOx: ✓✓ (MVEG) NOx: ✓✓✓✓✓ (Cruise) Reduced PM & soot	Small increase	No	H	H
Basic engine design improvements)	See **Table 3** (HD)	Reduced	Yes	H	H
Engine management systems & strategies	PM: ✓✓ NOx: abt. 9% (already demonstrated)	Significant reduction	Yes	H	H
New fuel injection types	PM: ✓✓✓✓ (Cruise) NOx: ✓✓✓✓ (Cruise) (with EGR)	Significant reduction	Yes	H	H
New nozzles/Rate shaped injection	NOx: ✓✓✓ (at constant soot)	Small reduction	No	H	H
Plasma	HC & NOx: ✓✓✓✓ CO: ✓✓✓ "removes soot"	No effect ?	No	M	M
Diesel/water injection and emulsions	All: ✓✓ (with 20% water)	Small increase	No	L	L
Diesel/water injection	PM: ✓ NOx: ✓✓	Small reduction	?	H	M

* Has been assessed by the Task Force in mid-1998 as:

H = High :	likely
M = Medium :	limited
L = Low :	unlikely

Key: ✓= 10 to 20%; ✓✓ 20 to 35%; ✓✓✓ Up to 50%; ✓✓✓✓ Up to 75% ; ✓✓✓✓✓>75% reduction potential

Table 3 ***HD Diesel Technologies***

Technology	Emissions Reduction Potential	Fuel Consumption	Availability *		
			1998 market	Technical by 2005	2005 Market
Oxidation Catalyst	PM: ✓✓ PM (SOF): ✓✓✓ HC & CO: ✓✓✓✓ NOx : ✓	No effect	Yes	H	M
De-NOx Catalyst - SCR (Urea)	NOx: ✓✓✓✓✓ (ECE R49)	No effect	No	H	H
De-NOx Catalyst - Passive FWC (Four Way Catalyst)	NOx: ✓ (ECE R49)	No effect	No	M	L
De-NOx Catalyst - Active NCR (Non-SCR)	NOx: ✓✓ (ECE R49)	Some increase (depends on HC/NOx ratio)	No	H	M
NOx Storage Catalyst	NOx: > ✓✓✓ (assumed, based on LD)	Small increase (depends on regeneration efficiency)	No	M	L
Continuously Regenerative Trap (CRT)	PM: ✓✓✓✓✓ NOx: <5%	Some increase	Yes	H	M
Particulate trap (non-CRT)	PM: ✓✓✓✓✓	Some increase	Yes	H	M
EGR, Non-cooled	NOx: ✓✓ (R49/13-mode)	Small increase	No	H	M
EGR, Cooled	NOx: ✓✓✓ (OICA/13-mode NOx: > ✓✓✓ (R49/13-mode) Reduced PM/soot	Small increase	No	H	H
Basic engine design improvements	Euro 2 to Euro 4 unclear (PM, HC, PM: ✓✓✓✓ shown for Euro 1 to Euro 2)	Reduced	Yes	H	H
Engine management systems & strategies	Unclear for HD (PM: ✓✓ NOx: 9% demonstrated for LD)	Significant reduction	Yes	H	H
New fuel injection types	Significant, but % is unclear	Significant reduction	Yes	H	H
New nozzles/Rate shaped injection	NOx: ✓ (at constant soot)	Small reduction	No	H	H
Plasma	HC, NOx: ✓✓✓✓ CO: ✓✓✓, "removes soot"	No effect ?	No	M	L
Diesel/water injection and emulsions	All: ✓✓ (with 20% water)	Small increase	No	M	L
Diesel/Water injection	PM: ✓✓✓ NOx: ✓✓	Small reduction	?	H	M

* Has been assessed by the Task Force in mid-1998 as:
H = High : likely
M = Medium : limited
L = Low : unlikely

Key: ✓= 10 to 20%; ✓✓ 20 to 35%; ✓✓✓ Up to 50%; ✓✓✓✓ Up to 75% ; ✓✓✓✓✓>75% reduction potential