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Foreword

Alain Heilbrunn,
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The implementation process of the REACH legislation is fast approaching the registration phase. CONCAWE is working hard with its members to prepare the registration dossiers, a challenging proposition in view of the tight time schedule and with rules which have not yet been fully clarified. Nevertheless we continue with our normal work and, as usual, report on recent results in this *Review*.

Personal safety remains a major concern for our industry. Our downstream oil industry safety statistics for 2006 were published earlier this year and the findings are summarised in a short article. Of particular note is the significant decrease in the fatality rate over recent years, of which road accidents remain by far the main cause.

Also relevant to safety, but particularly to environmental impact, is our annual survey of spillage incidents in European on-shore oil pipelines. The 2006 survey report has just been published, summarising 36 years of results, and an article in this *Review* gives the highlights.

Over the past three years we have carried out a number of studies to assess the impact of emissions from ships and land-based sources on environment and health, including work to evaluate the impact of ship emissions on climate change, through collaboration with the Massachusetts Institute of Technology. This work is particularly relevant to the new international marine fuels regulation under the International Maritime Organization's MARPOL convention. The first article in this edition of the *Review* supports the view that, to be technically and economically effective, emission controls should be targeted towards the most sensitive areas. It also makes the case that indiscriminate sulphur emission reductions, and particularly the adoption of a stringent global sulphur cap for marine fuels, may in fact have an adverse effect on climate. Indeed, ship emissions contribute both to warming (CO_2 and NO_x emissions) and to cooling of the atmosphere (through the formation of sulphate aerosols), their combined impact being a 'negative forcing', i.e. an overall tendency to cool the atmosphere. Reducing sulphur emissions will turn cooling into warming, while offering minimal improvement in air quality impacts. This is a good demonstration that air quality and climate issues are inextricably linked and that environmental legislation must take account of both. It is not the first time we have seen that setting emission limits in targeted areas offers a far more effective solution than the imposition of a stringent global cap. We hope that this fact will be recognised when the new IPPC Directive enters the adoption process.

The two remaining articles present results from our ongoing research aimed at enhancing our understanding of the complex interactions between advanced vehicles and fuels.

The Euro 5 regulation for light-duty diesel vehicles, coming into force in 2009, will reduce particulate mass (PM) emissions to about 5% of the value stipulated under Euro 2 in 1996. From 2011, a limit on the number of ultra-fine particles will also be introduced. In a test programme involving different fuels in light-duty Euro 3 and 4 vehicles, both diesel and gasoline direct injection, we have shown that the Euro 5 PM limit will almost certainly require the use of a particulate filter in diesel vehicles, a technology which will also reduce emissions of ultra-fine particles. Fuel properties typical of today's fuels, on the other hand, have no significant influence on PM and ultra-fine particle emissions from either diesel or gasoline vehicles.

We have also recently completed an experimental programme on advanced engine combustion concepts and related fuel requirements. The results are encouraging and show that these technologies for light-duty vehicles can be surprisingly tolerant of fuel properties while significantly reducing engine-out emissions. Further research is needed, however, to evaluate their potential impact on fuel quality requirements and, more generally, on the future diesel/gasoline demand.

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The impact of emissions from both land and sea sources needs to be considered when designing cost-effective policies for environmental improvements. In the light of IMO's recently agreed revision of MARPOL annex VI, this article argues that targeted emission reductions in the most sensitive areas, as per the SECA concept, result in optimum impact and cost effectiveness. SO_2 emitted from ships produces sulphate aerosols in the atmosphere, which are known to induce a potentially significant climate cooling effect. In this context, the future stringent global sulphur cap included in the revised Annex VI, and based largely upon a precautionary principle argument, may not in fact be precautionary at all.

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Particle emissions from modern vehicles

Vehicle and fuel effects on particulate mass and ultra-fine particles *page 8*

New procedures and specifications for particulate mass (PM) and particle number (PN) emissions from light-duty diesel and gasoline direct injection vehicles will be introduced through European regulations in 2009 and beyond. In order to anticipate the potential impact of these new limits, CONCAWE has completed a test programme to measure particle emissions from modern vehicles on regulated, transient and steady-state driving cycles.

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Advanced combustion engines for low emissions and high efficiency

CONCAWE test programme on HCCI combustion technologies *page 11*

CONCAWE has completed a test programme to evaluate the practical implementation of advanced combustion concepts, generically called Homogeneous Charge Compression Ignition (HCCI), to meet future emissions and performance targets. A single-cylinder research engine benchmarked for Euro 6 emissions has been used to investigate the relative importance of engine hardware and fuel properties for improving engine-out emissions, engine efficiency, and noise.

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Since 1971 CONCAWE has been collecting data on spillages from cross-country oil pipelines in Europe. The information is collated in an annual report which includes an analysis of the human and environmental consequences and of the underlying causes of such incidents. CONCAWE report 7/08 covers the results for the year 2006 and includes an analysis of the accumulated data for the whole 36-year period from 1971 to 2006.

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The thirteenth yearly assessment of the work incident performance report was issued by CONCAWE (Report No. 2/08). This report presents statistics on work-related personal injuries and fatalities for the European downstream oil industry's own employees and for contractors for the year 2006. Data was received from 20 companies representing more than 80% of European refining capacity. Trends over the past thirteen years are highlighted and the data is also compared to similar statistics from related industries. The total number of fatalities is the lowest ever reported since the start of the data collection by CONCAWE.

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Reducing the sulphur content of marine fuels

Could the cure be worse than the disease?

IMO's MARPOL Annex VI legislation has so far been based on the concept of SECAs, i.e. it seeks targeted sulphur reductions in those specific areas where emission density is high and sulphur impacts from ships are comparable to those from land-based sources. By focusing on emissions where they are the most harmful, rather than setting a global sulphur cap for all marine fuels, IMO has enabled reductions to have maximum benefit for human health and the environment while remaining cost-effective.

As the outcome of the Annex VI review process, IMO's MEPC 58 recently adopted a progressive though dramatic reduction in fuel sulphur levels in SECAs, as well as the future introduction of a stringent global sulphur cap set at one-third of current SECA levels. This, it is argued, would be precautionary with respect to possible effects on human health and the environment.

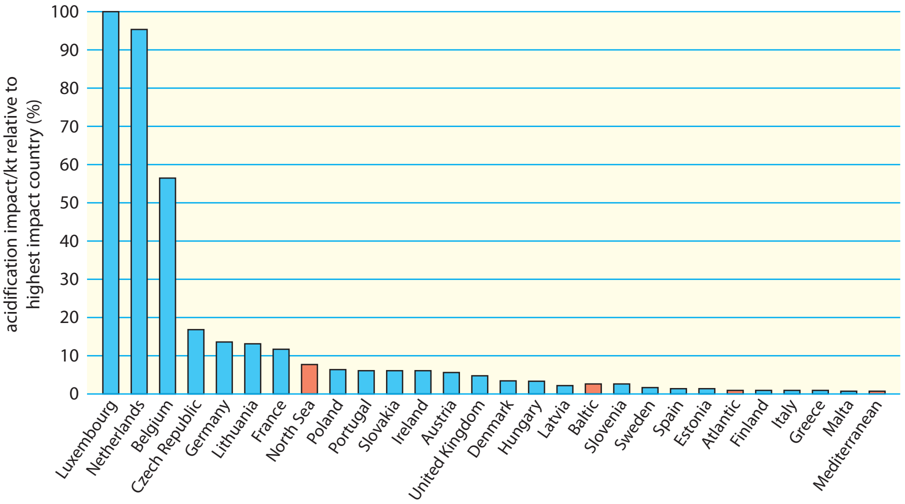
There are of course a number of significant implications of such a move, not least the economic and security of supply issues which have been highlighted by CONCAWE in a recent study[1]. This simplistic view is open to challenge from the point of view of both the air quality benefits of such a global sulphur emission reduction and the undesirable effects that it may have on global warming. This article explores some of the available scientific evidence to challenge the notion that this new regulation is 'precautionary' from an environmental perspective.

Air quality impacts

Proximity of emissions to sensitive receptors is an important factor

Figures 1 and 2, abstracted from a recent CONCAWE publication[2], clearly support the current SECA-based approach. Figure 1 shows the relative impact on

Figure 1 Contribution to exceedances of acid critical loads in the EU per unit of SO_2 emissions



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[1] Techno-economic analysis of the impact of the reduction of sulphur content of residual marine fuels in Europe. *CONCAWE Report 2/06.*

[2] Impact on the EU of SO_x, NO_x and primary $PM_{2.5}$ emissions from shipping in the Mediterranean Sea: a summary of the findings of the Euro Delta Project. *CONCAWE Report 1/08.*

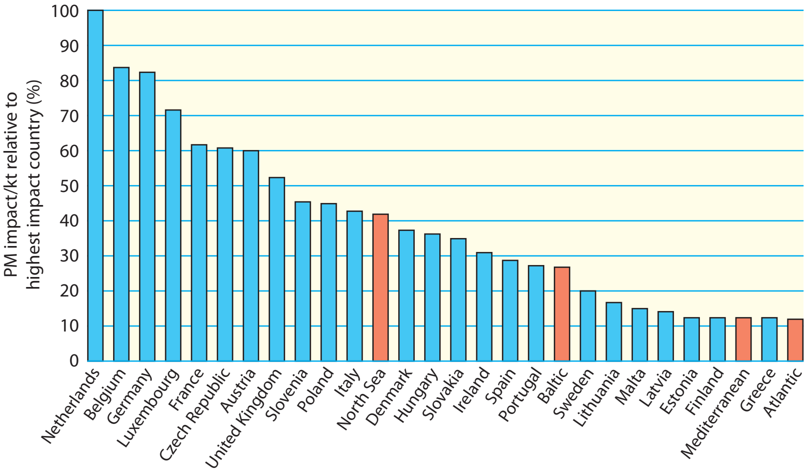
exceedances of critical loads for acidification of a unit of SO_2 emitted in different European countries and sea areas. Geographical location of emissions and emission density both have a significant influence on the relative impact of emissions. For example a unit of SO_2 emitted in the North Sea has more than fifty times the impact of the same unit of SO_2 emitted in the Mediterranean Sea. This is why, as part of its strategy to combat acidification in the second half of the 1990s, the EU successfully applied for the North Sea to be recognised as a SECA, but did not apply for the Mediterranean Sea to be so designated, in spite of the higher quantity of emissions there.

Figure 2 shows the estimated[3] impact on human health of fine particulates derived from a unit of SO_2 emitted in individual European countries and sea areas compared to the highest impact country. Geographical location of emissions and emission density again have a significant influence on their relative impact. Here, it is proximity to heavily populated areas rather than sensitive ecosystems that counts. For example a unit of SO_2 emissions from Germany has about twice the impact of a unit of SO_2 emissions from the North Sea and about seven times that of the Mediterranean Sea.

This SECA-focused approach recognises the need to account for the proximity of emissions to sensitive receptors. It is consistent with the design of cost-effective policies based on Integrated Assessment Modelling, which has underpinned European environmental legislation related to air pollution for more than a decade.

This SECA approach recognises that both land- and sea-based sources should be considered together in order to solve environmental problems.

Figure 2 Impact of fine particulates derived from SO_2 emissions on overall EU population per unit of SO_2 emissions



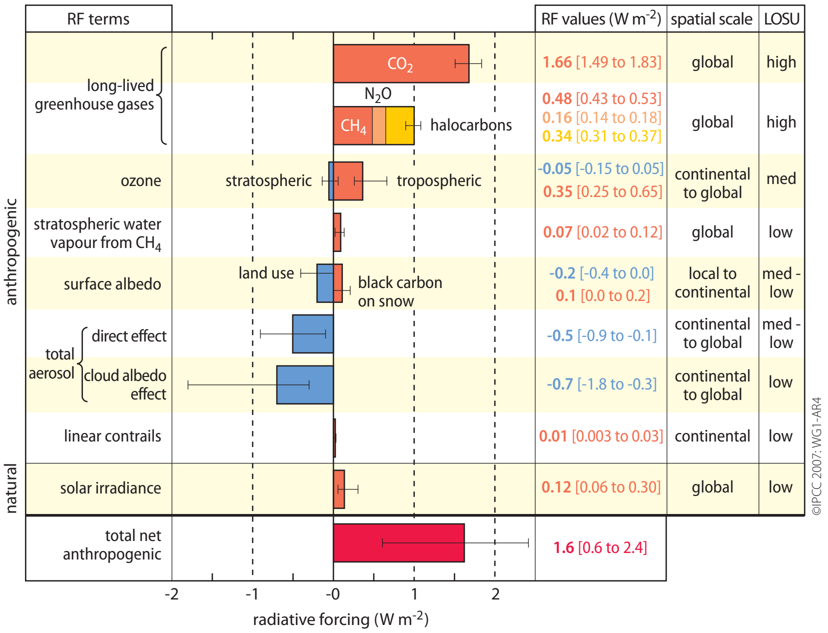
Climate impacts

The role of sulphate aerosols in global cooling

It has long been understood that sulphate aerosols in the atmosphere (e.g. from volcanic eruptions) induce a 'global cooling' signal by modifying the radiation heat balance.

Figure 3, abstracted from the fourth IPCC Assessment Report[4], provides an overall perspective on radiative

Figure 3 Summary of radiation forcing (RF) from all sources



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[3] *Within the framework of the Clean Air For Europe (CAFE) programme and following the advice of WHO pending more data becoming available, it is assumed that all particles, irrespective of composition, pose a risk to human health. The 'health' index used in Europe is the number of life years of the whole population. Work is continuing to establish whether particle composition is important. It is widely believed that directly-emitted combustion particles are more harmful than the secondary sulphate particles controlled by SECA measures.*

[4] *Summary of radiation forcing from all sources. IPCC* Fourth Assessment Report, *Work Package 1, Summary for Policymakers.*

Reducing the sulphur content of marine fuels

Could the cure be worse than the disease?

forcing components in the global atmosphere that contribute to either global warming (positive forcing) or cooling (negative forcing). This figure shows that the largest negative forcing comes from aerosols of anthropogenic origin and has both a direct and indirect forcing component. Direct forcing is due to the aerosol particles (mainly sulphates) themselves, and indirect forcing is due to condensation of water around very fine particles altering cloud cover and cloud properties.

Shipping emissions make a large contribution to both direct and indirect aerosol effects. Ocean areas present a good radiation absorbing surface compared with land and any reduction in cloud cover will increase heat uptake. Because shipping is widely distributed (mostly in the Northern Hemisphere) the direct and indirect aerosol effects due to SO_2 emissions have a potent negative forcing effect readily measured by satellite[5].

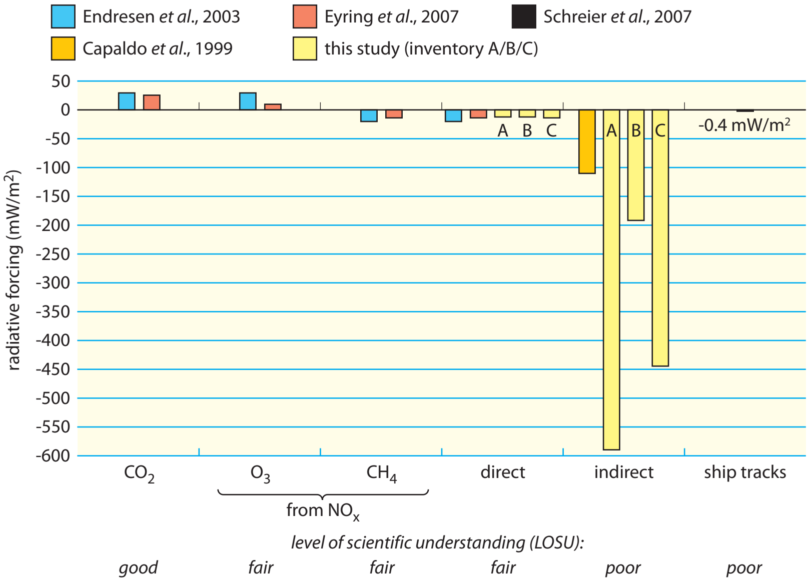
Table 1 Shipping contributions to direct forcing effects

Scenario	Ozone *(mW/m^2)*	Sulphate* *(mW/m^2)*	Methane* *(mW/m^2)*	CO_2 *(mW/m^2)*
2000 base	9.8 ± 2	-14	-14	26
2030 constant ship emissions (2000)	7.9 ± 1.4	-13	-13	24
2030 high growth ships (2.2% per annum)	13.6 ± 2.3	-26	-21	46

* A negative sign means a cooling effect.

After Eyring *et al.*

Figure 4 Indirect forcing from ship emissions



Data estimated by Lauer *et al.*

Nitrogen oxides emissions from ships also play a role. NO_x participates in the formation of ozone which, in the lower part of the atmosphere, acts as a greenhouse gas with positive forcing (Figure 3). However, the chemical reactions involved also destroy some atmospheric methane which is a potent greenhouse gas. These reactions also promote the early oxidation of SO_2 to sulphate, contributing to the cooling effect.

Climate models have been used to calculate the degree of forcing for each of these different components. Eyring *et al.*[6] looked at direct effects and found that the direct negative forcing due to sulphate aerosols and the removal of methane roughly balanced the positive forcing due to CO_2 emissions from ships (Table 1). They also conjectured that the indirect sulphate effect (influence on clouds) would be at least as large as the direct sulphate contribution, leading to a net cooling effect.

Lauer *et al.*[7] found a huge effect of ship emissions on indirect forcing, an order of magnitude larger than all other effects and amounting to between 17% and 39% of the global radiation budget. Control calculations assuming zero sulphur in marine fuel reduced this effect by 75%, confirming that sulphur emissions from ships are key. The results are shown in Figure 4.

In a study sponsored by CONCAWE, the Massachusetts Institute of Technology (MIT) also ran two ship emission scenarios (a 'base case' and 'a zero sulphur emissions from ships case') to quantify the magnitude of the sulphate cooling signal. They found an averaged direct negative forcing of –12.5 mW/m^2 which is consistent with other studies. To provide a policy perspective, they

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[5] Emissions of International Shipping as Seen by Satellites, *ESA publications (2006), 628, pp 86.*

[6] *Multi Model Simulations of the Impact of International Shipping on Atmospheric Chemistry and Climate in 2000 and 2030.* Atmos. Chem. Phys. *(2007) 7, pp.757–780.*

[7] *Global Model Simulations of the Impact of Ocean-going Ships on Aerosols, Clouds and the Radiation Budget.* Atmos. Chem. Phys. *(2007) 7, pp.5061–5079.*

compared this with the reduction in radiative forcing resulting from a move from the base case scenario to a scenario which assumed the Kyoto protocol CO_2 targets were met. This resulted in a reduction in radiative forcing of 33.2 mW/m^2. Thus the global cooling effect directly generated by the current levels of SO_2 emissions from shipping is equivalent to more than a third of the cooling benefits generated by meeting the Kyoto protocol CO_2 targets. In other words, a global move to very low or zero sulphur levels in ship fuels would substantially negate the benefits of meeting the Kyoto Protocol from direct effects alone. If the magnitude of the additional indirect effects is confirmed, noting that some studies show this can be higher by an order of magnitude, this would become much more significant.

Lifetimes in the atmosphere

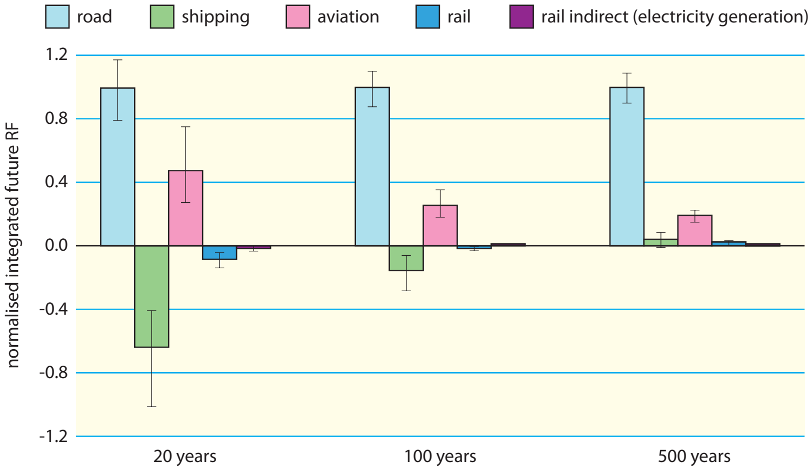
Comparing radiative forcing of different sources and compounds is often criticised as over-simplifying because of the different lifetimes of the agents in the atmosphere. Indeed, aerosol components have a short lifetime and do not accumulate in the atmosphere, so their effect decreases rapidly with time as soon as emissions decrease/cease. By contrast long lifetime agents (such as CO_2 and CH_4) are only slowly removed, thus they accumulate in time and their effects persist long after emissions have ceased.

Fuglestvedt *et al.*[8] examined the integrated impact of radiative forcing for different transport modes using the methodology of the *Fourth Assessment Report*. A pulse of a single year of emissions was simulated and the resulting radiative forcing integrated over a 20-, 100- and 500-year period. Figure 5 shows the cumulative results by mode of transport (normalised against road transport).

The effect of the short lifetime agents such as aerosols that produce negative forcing is seen to be strong over a timescale of 20 years, diminishing to a low level over 100 years and vanishing in less than 500 years. Furthermore, shipping has a 'negative' climate footprint with present fuels.

Figure 5 Integrated radiative forcing of current emissions, by substance and transport sub-sector, over different time horizons

Integrated global mean net RF per sector due to 2000 transport emissions, normalised to the values for road transport for various time horizons (20, 100, 500 years). Uncertainty ranges are given as one standard deviation.



Based on data from Fuglestvedt *et al.*

This means that any reduction or removal of SO_2 emissions has an almost immediate effect. The proposed global sulphur cap for marine fuel would essentially remove the current 'complete offsetting' of the 'warming signal' from CO_2 emissions from shipping, i.e. it would significantly increase the global positive forcing. All models predict this trend. There is disagreement on absolute effect, but even taking the lowest estimates from the MIT studies, effects on the scale of the Kyoto protocol ambitions are indicated.

More work in this important area is clearly needed to contribute to the development of holistic policies aimed at mitigating concerns over ship emissions. However, it is already clear that reducing the present sulphur content of marine fuels in sea areas where such emissions do not contribute significantly to problems of human health or the terrestrial environment (i.e. outside SECAs via a stringent sulphur cap) is certainly not precautionary from a climate change perspective. This may be another 'inconvenient truth' but, given what has been highlighted above, a review of the potential climate implications of the planned 2020 or 2025 imposition of a stringent global sulphur cap appears to be warranted.

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[8] Climate Forcing from the Transport Sectors. *Proceedings of the National Academy of Sciences of the USA, 2008, 105, no 2, pp.454–458.*

Particle emissions from modern vehicles

Vehicle and fuel effects on particulate mass and ultra-fine particles

Ultra-low sulphur fuels have enabled the introduction of modern engine and after-treatment technologies in order to meet increasingly stringent exhaust emissions limits. Through these improvements, substantial reductions in road vehicle emissions have occurred over the past two decades with corresponding improvements in air quality. As one example, light-duty diesel vehicles meeting Euro 5 emissions limits will emit less than 5% of the particulate mass (PM) emitted by similar passenger cars just 15 years ago, with comparable improvements in other exhaust emissions.

While these improvements are being put in place, particle emissions from all sources (transport, manufacturing, farming and others) remain under regulatory scrutiny, due to increasing awareness of their impact on air quality and the potential human health effects of air pollution. Extensive studies have not yet identified exactly how these particles impact upon human health but several hypotheses are being actively investigated.

As total PM emissions from cars have dropped, accurate measurement of the remaining low-level PM emissions has become increasingly difficult. Over the past decade, several research programmes have investigated different procedures for measuring very low particle emissions, driven largely by interest within the regulatory environment. Improved procedures have been developed[1], either by modifying exhaust air filtering procedures for PM or by introducing a new metric for ultra-fine particles, called Particle Number (PN). PN is a measure of ultra-fine exhaust particles that average only about 30 nanometers in diameter, much smaller than the PM emissions that are measured by filter procedures. New European light-duty diesel vehicles entering the market after September 2011 will be required to meet a lower PM limit and a new PN emissions limit of 6x10^{11} particles/km (Euro 5b regulatory limit). These lower particle emissions will be achieved through the use of diesel particulate filters (DPFs) and improvements in combustion performance. The same PM performance will also be expected from gasoline direct injection (GDI) vehicles in 2011 with PN limits to be added in 2014.

Over many years, CONCAWE has studied new engine and after-treatment technologies, including the influence of fuel properties on particle emissions performance. This work has provided an important understanding of particle emissions and measurement techniques, as well as a substantial database on a wide range of vehicles, fuels and driving cycles.

In order to extend this understanding, CONCAWE conducted experiments to measure particle emissions using the new regulatory procedures and to compare the results with data already in hand from previous studies. These experiments have provided both PM and PN emissions results on modern diesel and GDI vehicles tested under the driving conditions of the New European Driving Cycle (NEDC), as well as on various transient and steady-state driving cycles.

Four test vehicles

Two modern diesel cars were tested that represented vehicle technology now available in the European market. These included a medium-sized direct injection (DI) diesel car with an oxidation catalyst (Car E) and a large DI diesel car (Car F) with an additised diesel particulate filter (DPF). Both cars were certified to meet Euro 4 emissions levels.

Two gasoline vehicles were also tested, based on GDI engine technology that is expected to represent a significant share of European new car sales in the near future. The first GDI car (Car G) operated under stoichiometric

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[1] *Based on the European Commission's 'Particulates' Consortium Study (2001) and the 'Particulate Measurement Programme' (PMP) on light-duty passenger cars (GRPE-PMP-18-2: 2007) sponsored by the United Nations Economic Commission for Europe (UNECE).*

combustion conditions and was equipped with a three-way oxidation catalyst. The second GDI car (Car H) operated under both lean-burn and stoichiometric conditions depending upon the driving conditions, and was equipped with both a three-way oxidation catalyst and a NO_x trap. These cars were certified to meet Euro 3 and Euro 4 emissions limits, respectively.

Five test fuels

Three diesel fuels were tested in order to investigate the influence of extremes in fuel composition. One fuel (Fuel DB) was the same sulphur-free reference fuel used to develop the PMP regulatory procedure for Euro 5b, while the second was the same fuel doped with a chemical reagent to achieve a higher sulphur level (Fuel DA). Although this fuel is no longer relevant for today's marketplace, it provided a valuable test point for comparing results with data from previous CONCAWE studies. The third diesel fuel (Fuel DC) was a sulphur-free diesel manufactured by the Fischer-Tropsch process[2]. Such fuels are virtually free of aromatics and have a very high cetane number compared to conventional diesel fuels. No bio-components were added to these fuels.

Table 1 Key diesel fuel properties

Diesel properties	Fuel DA	Fuel DB	Fuel DC
Cetane number	53.0	53.0	82.8
Sulphur content (ppm)	306	8	<5
Aromatics content (% m/m)	21.8	21.8	<0.1
Polyaromatics (PAH) content (% m/m)	4.3	4.4	0.0

Two sulphur-free gasolines were tested in the GDI cars, that covered extremes of gasoline qualities within the EN228 specification. This was done to evaluate the influence of gasoline volatility and molecular composition on PM and PN emissions from GDI cars. No oxygenates were added to these fuels.

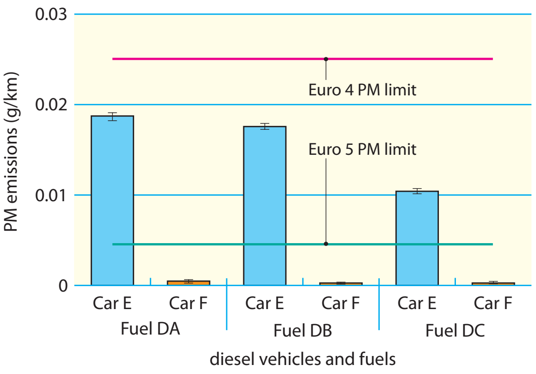
Table 2 Key gasoline fuel properties

Gasoline properties	Fuel GA	Fuel GB
Sulphur content (ppm)	<3	5
Dry vapour pressure equivalent (DVPE) (kPa)	50.2	66.3
Final boiling point (˚C)	204	168
Olefins content (% v/v)	16.3	6.5
Aromatics content (% v/v)	41.5	28.4

Particulate mass (PM) emissions

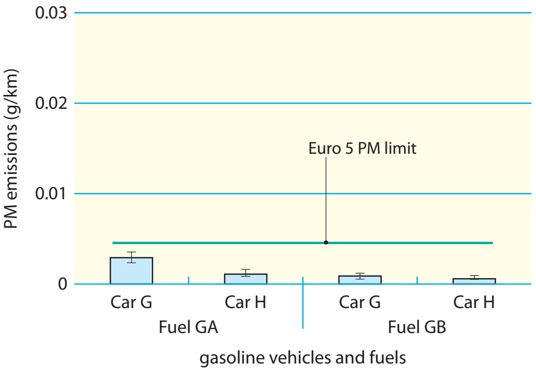
PM emissions from the diesel and gasoline cars are shown in Figures 1 and 2. Car F, equipped with a DPF, emitted very low PM over the NEDC, about 95% below the PM emissions of Car E that did not have a DPF. Although PM emissions from Car E were already below the Euro 4 limit, the high cetane diesel fuel reduced these by about 50%. The diesel fuel composition had no measurable influence, however, on the PM emissions from Car F that was equipped with a DPF.

Figure 1 PM emissions from diesel vehicles (NEDC)



A DPF reduces PM emissions by 95%, to well below the Euro 5 PM limit.

Figure 2 PM emissions from GDI vehicles (NEDC)



On the same scale, two GDI vehicles produce very low PM emissions over the same driving cycle.

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[2] *The Fischer-Tropsch process is a catalysed chemical reaction that converts carbon monoxide and hydrogen into hydrocarbon products. By adjusting the molecular weight and degree of isomerisation in this product, a gas-to-liquids hydrocarbon product can be obtained having the qualities and characteristics of diesel fuel.*

Particle emissions from modern vehicles

Vehicle and fuel effects on particulate mass and ultra-fine particles

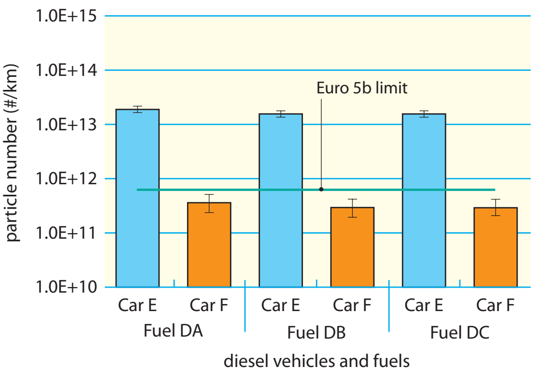
In comparison, the two GDI vehicles emitted a very low level of PM under the same NEDC condition and PM measurement procedure. Although PM emissions are not yet regulated for gasoline vehicles, it is interesting to note that the PM emissions from both GDI vehicles are comparable to those from the DPF-equipped diesel car. The PM emissions also improved between the Euro 3 and Euro 4 gasoline vehicles. The fuel composition had some impact on the total PM emissions, although the absolute PM emissions were very low.

Particle number emissions

In the new Euro 5b regulatory procedure for measuring PN, a portion of the vehicle's exhaust is separated, diluted and heated in order to stabilise the ultra-fine particles in the exhaust for measurement. The resulting stream of 'dry' carbonaceous particles having particle diameters averaging about 30 nm is measured with a particle counter.

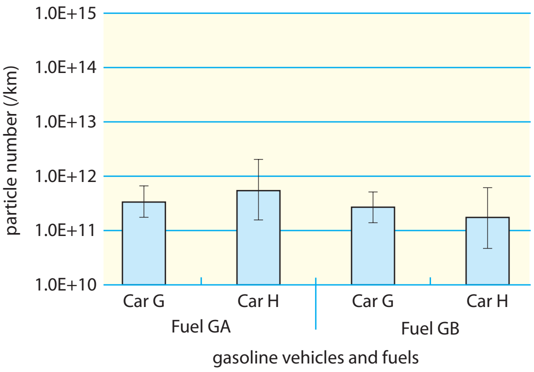
DPFs can be effective in reducing PN emissions, while the fuel properties have no effect.

Figure 3 PN emissions from diesel vehicles (NEDC)



PN emissions from GDI vehicles are comparable to those from DPF-equipped diesel vehicles under the same test conditions.

Figure 4 PN emissions from GDI vehicles (NEDC)



Comparing the results of the diesel vehicles in Figure 3, the DPF in Car F successfully lowered the PN emissions to a level just below the Euro 5b regulated level while reducing the PM emissions at the same time. As seen in Figure 4, the absolute PN emissions for the two GDI vehicles are comparable to those from the DPF-equipped diesel car. Fuel properties had no significant influence on PN emissions in either the diesel or gasoline vehicles.

In summary

Very low PM and PN emissions can be achieved by today's engine and after-treatment technologies operating on ultra-low sulphur fuels. Implementing these technologies is expected to bring continuing improvements in auto emissions as the vehicle fleet is modernised. For diesel vehicles, DPFs substantially reduce PM emissions, by more than 95% in the tests reported here, to levels that are well below the next stage of European PM emissions limits.

DPFs are also effective in reducing the ultra-fine particles, lowering the PN emissions over the NEDC by about two orders of magnitude compared to a vehicle without a DPF. Although gasoline vehicles achieve very low PM emissions already, the PN emissions from GDI vehicles are comparable to those from DPF-equipped diesel vehicles. Additional improvements in the combustion and after-treatment systems are likely to further improve the emissions performance of these vehicles. More testing is needed, however, on vehicles operating on transient and steady-state cycles to ensure that PM and PN emissions are reduced under all operating conditions.

As these new engine and after-treatment technologies are introduced, the potential for additional vehicle emissions improvements through changes in fuel properties appears to be insignificant.

Advanced combustion engines for low emissions and high efficiency

CONCAWE test programme on HCCI combustion technologies

Air pollutant emissions from motor vehicles have fallen dramatically over the past two decades as a result of continuing improvements in engine and after-treatment technologies to meet lower regulated emissions limits, and in the quality of fuel used to power these vehicles. As a result, attention is increasingly focused on vehicle efficiency and fuel consumption in order to address concerns over future energy supplies and greenhouse gas emissions while maintaining, and further reducing, exhaust emissions performance. Light-duty vehicle technology is evolving rapidly to respond to these new challenges.

In the search for both improved emissions and even lower fuel consumption, engine research is increasingly directed towards advanced combustion technologies. Highly sophisticated engines using these concepts are being developed which, if commercially successful, could combine improved engine efficiency with lower air pollutant emissions from the engine, thus reducing the demand on exhaust after-treatment systems and, potentially, overall vehicle costs. Because these advanced combustion concepts combine the best features of spark-ignition and compression-ignition combustion, the optimum fuel characteristics could be quite different from those needed by today's conventional gasoline and diesel engines.

These advanced combustion concepts are often called Homogeneous Charge Compression Ignition (HCCI) or Controlled Auto Ignition (CAI)[1]. Broadly speaking, HCCI and CAI describe a wide variety of advanced combustion sequences in which fuel and air are substantially premixed before auto-ignition and the fuel is burned without spark initiation at relatively low combustion temperatures. The temperature of combustion is usually reduced further by using high levels of cooled air and exhaust gas recirculation (EGR) which also reduces the fuel/air ratio. These approaches help to limit both soot and NO_x formation during the combustion event.

The term HCCI can be used, in its most generic sense, to describe these advanced combustion engine concepts that seek to provide:

- low engine-out emissions (especially NO_x and PM);
- low fuel consumption (comparable to, or better than, today's compression-ignition engines); and
- a stable engine operation over a wide load and speed range.

In practice, the HCCI combustion mode is most easily achieved at low engine speeds and loads, and is increasingly difficult to maintain as engine speed and load increase. For this reason, the first production engines are expected to utilise 'part-time' HCCI engines, operating under HCCI combustion conditions at lower loads and reverting to conventional diesel or gasoline operation at higher load conditions. As long as this is the case, fuels used by these engines must be compatible with both operating modes.

These combustion technologies are quite new and it is not yet possible to predict how they will develop in the marketplace. Because of their potential impact upon future fuel needs, however, CONCAWE and the consulting engineers, FEV Motorentechnik GmbH worked together to investigate what advanced combustion benefits can be achieved by practical future engine hardware and how fuel properties could influence the effectiveness of these new technologies.

CONCAWE's test programme

This study began with an assessment of engine hardware options that are likely to be needed to enable future light-duty diesel vehicles to comply with future European and US regulated emissions. A timeline for new emissions

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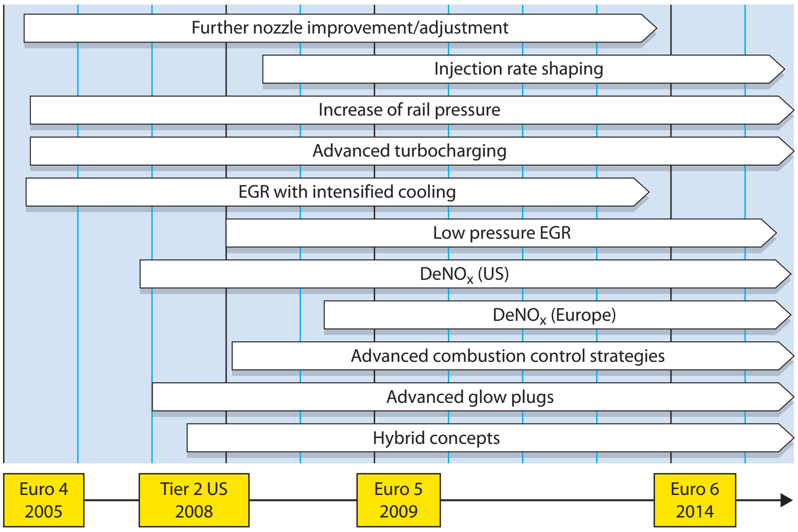
[1] Advanced combustion for low emissions and high efficiency: a literature review of HCCI combustion concepts. *CONCAWE Report 4/08.*

Advanced combustion engines for low emissions and high efficiency

CONCAWE test programme on HCCI combustion technologies

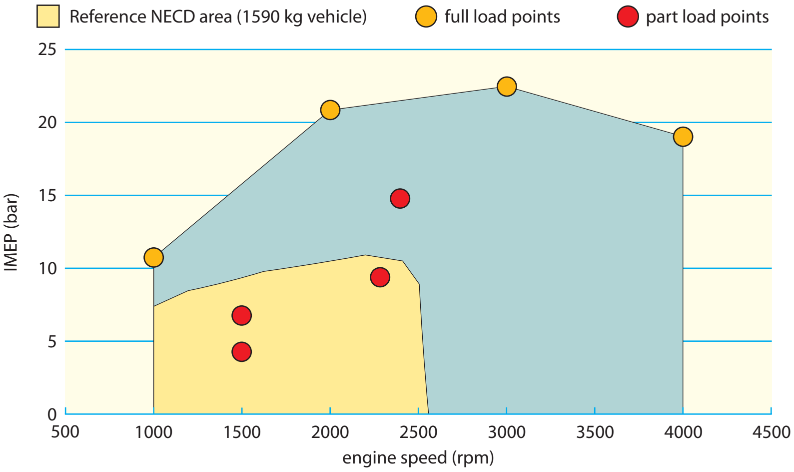
Figure 1 Potential engine hardware improvements to meet future emissions limits for light-duty diesel vehicles



limits and hardware improvements that may be important to achieve these limits is shown in Figure 1.

To explore the potential of these hardware improvements, this test programme was conducted in two parts using an advanced and highly versatile single-cylinder diesel bench engine. In the first part, different combinations of advanced engine hardware were tested in order to see how cumulative engine hardware enhancements could help to reduce engine-out emissions while, at the same time, retaining acceptable fuel efficiency and noise levels.

Figure 2 Engine speed and load points



Because this was a study anticipating engine technology in the next decade and beyond, the diesel engine was benchmarked to achieve at least Euro 6 engine-out NO$_x$ emissions levels without the need for a separate NO$_x$ after-treatment system. It was also assumed that Euro 5 and 6 production engines will be equipped with an HC/CO oxidation catalyst and a diesel particulate filter (DPF) to meet other emissions limits.

In the second part of the study, a broad range of fuels was investigated in the engine optimised in the first part, in order to evaluate the impact of fuel properties on overall engine performance. These fuels included practical and experimental fuels, as well as biofuel blends, and were designed to investigate fully the impact of ignition delay, volatility and molecular composition over a very wide range.

Impact of engine hardware on advanced combustion

It is generally known from the literature that HCCI combustion is facilitated by injecting fuel into the cylinder early enough in the engine cycle so that there is time to achieve thorough fuel-air mixing before combustion starts. For the first part of this study, the concept was to allow as much premixing of fuel and air as possible before combustion began, but the overall success criterion was the performance of the engine (in terms of emissions, efficiency and noise) at all speed and load conditions, not just the nature of the combustion process.

The engine and fuel studies included detailed analyses of the engine performance at eight full- and part-load conditions. The load and speed points tested in this programme are shown in Figure 2 compared to the range that is typical for the New European Driving Cycle (NEDC), the European regulated emissions cycle.

The three lower part-load points are within the range of the regulated cycle (based on a typical engine and vehicle mass) while the fourth and higher part-load point is just outside the NEDC range. This fourth point was added in order to gain information about engine performance and fuel impacts at higher loads, that may be important for real-world driving conditions and for future regulated driving cycles.

Various engine hardware enhancements were cumulatively tested in this programme for their potential to enable optimised combustion behaviour over the broadest range of engine conditions. Low engine-out emissions, fuel efficiency comparable to conventional diesel engines, and acceptable engine noise were the targets for optimised performance. All of these hardware enhancements were intended to enable more HCCI combustion by improving fuel-air mixing and simultaneously lowering the combustion temperature. These approaches included:

- a lower compression ratio;
- a higher maximum cylinder peak pressure;
- a higher maximum fuel rail pressure;
- high levels of EGR, up to 55%;
- intensified charge air cooling;
- enhanced fuel-air swirl inside the cylinder using a novel valve lift design;
- different injection nozzle configurations;
- fuel injection strategies that varied both the timing and duration of the pilot and main fuel injections; and
- adjustment of the fuel injection timing based on an in-cylinder pressure sensor.

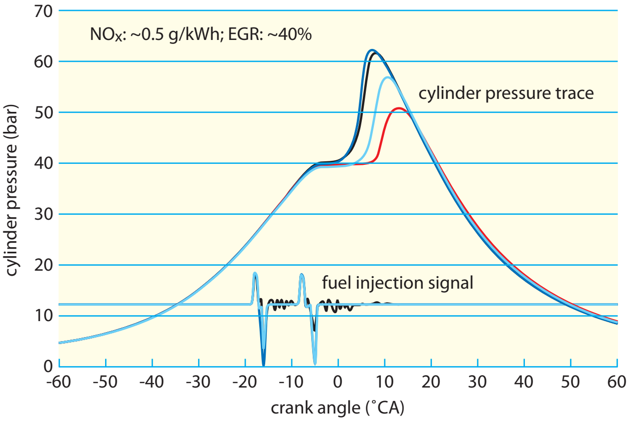
Because there were many different engine parameters to optimise simultaneously, a rigorous 'design of experiments' approach was also used to achieve optimised engine performance at each speed and load condition.

With experience, it was found that a very important optimisation requirement was a constant centre of combustion, that is, ensuring that the combustion peak pressure occurred at the same crank angle in the engine cycle. Typically, the CA50[2] was adjusted to be about 5–11 degrees crank angle (°CA) after top dead centre.

The centre of combustion was brought to the same optimum position by adjusting the fuel injection timing using the readout from an in-cylinder pressure sensor. This approach provided the best and most consistent engine efficiency and simulated the behaviour of a future engine operating with closed loop combustion control (CLCC). Figure 3 shows, for example, the effect that different fuel properties had on the centre of combustion at the same start-of-injection timing (Figure 3a) and at different start-of-injection timing (Figure 3b) for four different fuels.

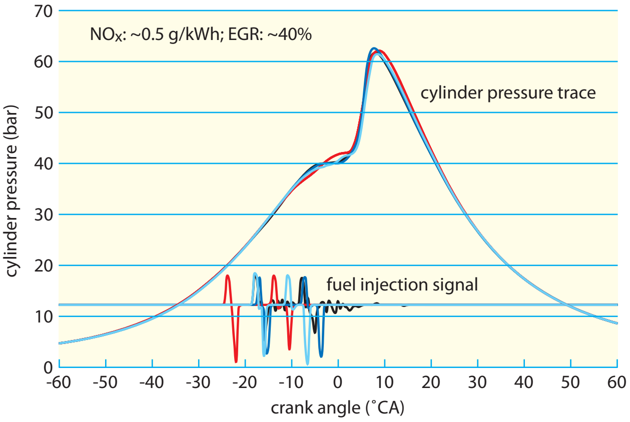
Figure 3 Pressure traces at one speed and load condition for four test fuels

a) Constant start-of-injection timing for all fuels



Lowering the fuel's cetane number delays the peak combustion pressure.

b) Different start-of-injection timing for different fuels



Adjusting the injection timing for each fuel optimises the combustion pressure.

As the cetane number of the fuel was reduced from 53 (typical of European diesel fuel) to 44 (typical of US diesel fuel), the same start-of-injection timing resulted in the combustion peak pressure occurring at a later crank angle (Figure 3a). This is to be expected, since a lower cetane number will lengthen the time between injection and the start of auto-ignition. However, an uncontrolled variation in the combustion peak pressure significantly complicates the analysis of engine versus fuel effects.

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[2] *CA50 is the point where 50% of the injected fuel mass has been converted to heat.*

In order to harmonise the combustion peak pressure for all fuels regardless of the cetane number, the start-of-injection was adjusted (Figure 3b). With this adjustment, the pressure traces now overlap for all four fuels, ensuring that fuel effects are not confounded with engine calibration effects.

Using the constant centre of combustion approach, four diesel and kerosene fuels were tested in order to study the response of the engine hardware enhancements, at optimised combustion conditions, to the fuel's ignition delay (as indicated by cetane number), volatility and molecular composition.

All of the results taken together showed that the various engine hardware enhancements enabled a significant improvement of the emissions behaviour and engine efficiency without deterioration in the engine noise. Compared with these improvements, fuel properties were found to have only a small impact on emissions, efficiency and noise.

What have we learned about engine hardware and advanced combustion?

This part of the study demonstrated that the fully warmed-up single-cylinder diesel engine could be run successfully at all full- and part-load engine operating conditions on a narrow range of four test fuels. When the centre of combustion was harmonised for all fuels, essentially the same indicated efficiency could be achieved at the same speed and load conditions.

This is an important observation because it demonstrates that the engine performance can be robust to a range of market fuel properties. Translating this strategy into future engines seems quite feasible using a CLCC approach.

At higher engine speeds and loads, conventional diesel combustion was observed for all fuels, in which the PM increased rapidly as the NO_x level was reduced. At lower engine speeds and loads, however, this behaviour was not always observed, especially for the lower cetane number and more volatile fuels. In these cases, characteristic HCCI combustion was observed, in which the PM was reduced as the NO_x level was reduced. This observation demonstrated that the hardware configuration used in this study could successfully achieve HCCI combustion, especially at lower speeds and loads. As the speed and load increased, however, all fuels tended to revert to a classic diesel combustion performance.

Using high EGR levels, very low NO_x emission levels were achieved out of the engine. In fact, the NO_x emissions were low enough that a NO_x after-treatment system would not be needed to meet Euro 6 emissions limits. PM, HC and CO were also maintained at levels that could be acceptably treated by a standard oxidation catalyst and diesel particulate filter. Other parameters of interest (noise and efficiency) were also at acceptable levels for all fuels at the full- and part-load operating points.

Impact of fuel properties on advanced combustion

Previous studies have suggested that three fuel properties are especially important to promote HCCI combustion:

- lower cetane number, in order to lengthen the ignition delay and provide time for fuel-air mixing;
- increased volatility, in order to reduce the time needed to achieve fuel-air mixing before auto-ignition occurs; and
- fuel composition, to promote combustion and reduce engine-out emissions.

Although these fuel properties were varied over a narrow range in the first part of this study, the test fuels in the second part of this study were varied over a much wider range. Because fuel parameters tend to be highly correlated, it was not possible to produce a fully orthogonal fuel matrix for all fuel properties of interest. Instead, fuel properties were changed one at a time, keeping the other properties of interest as constant as possible. The effects of fuel property changes could therefore be evaluated by comparing selected pairs of fuels.

The complete fuel matrix is shown in Figure 4 where the derived cetane number (DCN) is plotted versus the total aromatics content. In addition to marketplace fuels, specially blended and reference fuels were also tested to investigate the potential impact of fuel properties.

These fuels included a wide range of both practical and experimental fuels that were designed to investigate the impact of ignition quality (cetane number), volatility, and molecular composition on engine-out emissions and performance. Experimental fuels in the gasoline boiling range were included that are not traditionally associated with diesel engines. Two low-level biofuel blends and a blend of marketplace gasoline and diesel were also tested to look for short-term advantages and disadvantages.

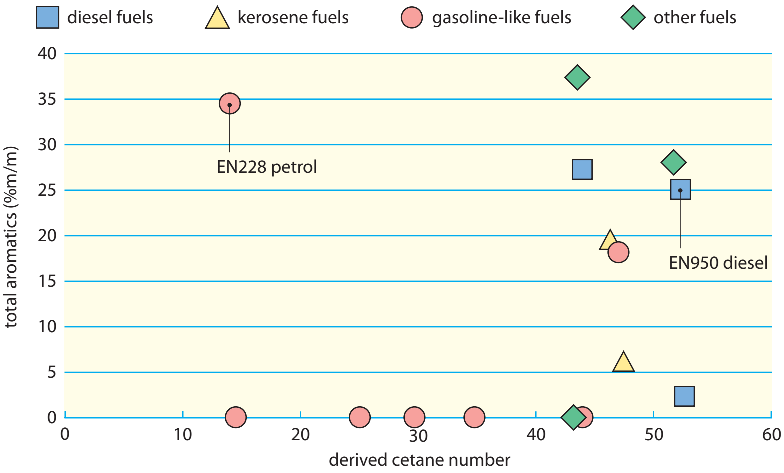
What have we learned about fuel properties and advanced combustion?

All of the results taken together showed that the optimised engine could produce acceptable engine-out emissions, efficiency and noise using a much broader range of fuel properties than tested in the first part of the study. Fuels having DCN values as high as 53 and as low as 25 could be successfully run in the optimised engine at all full- and part-load conditions. Fuel volatility changes from diesel to kerosene to gasoline-like were also accepted without engine modifications.

Because reducing PM emissions is very important for light-duty diesel engines, however, special attention was given to the impact of fuel properties on PM emissions. The results showed that the relative influence of the fuel's ignition delay, volatility and molecular composition on PM emissions appears to be different at different speed/load points. In general, increasing the ignition delay (by lowering the DCN value) was beneficial at the lower part-load points for diesel fuels but had only a moderate effect for the gasoline-like fuels.

Increasing fuel volatility from the diesel to the kerosene boiling range generally lowered PM emissions as well. Additional volatility increases from kerosene to gasoline-like fuels reduced PM emissions at the low part-load points but gave some increases at the highest part-load point. Reducing aromatics in the fuel consistently lowered the PM emissions. Although the absolute PM emissions were very low for all fuels, sizeable differences were found between the relative PM emissions for different fuels at higher EGR levels.

Figure 4 Test fuels matrix: derived cetane number (DCN) versus total aromatics



Overall conclusions

In this study, the single-cylinder diesel engine optimised with enhanced hardware and operating under simulated CLCC conditions was found to be surprisingly tolerant of fuel properties. This was the case even though the engine operated under HCCI-like conditions at low speeds and loads and under conventional diesel combustion conditions at higher speeds and loads.

This is an important observation because it suggests that a special fuel may not be essential to enable acceptable performance and Euro 6+ emissions performance on advanced combustion technology engines. When combined with the CLCC optimisation approach, engine hardware that is already in use on today's production engines in combination with commercial after-treatment technology may be sufficient. With such an engine configuration, marketplace fuels may be suitable to meet the performance needs of both today's light-duty fleet and future engines.

This study only investigated engine performance and emissions on a fully warmed-up engine and more work will be needed to ensure satisfactory engine performance under cold start and transient conditions. If these observations are validated, however, at least one critical barrier to the broad introduction of advanced combustion technology may be reduced, namely the need for a very special fuel and its associated supply and distribution infrastructure.

Performance of European cross-country oil pipelines

Statistical summary of reported spillages in 2006 and since 1971

Since 1971, CONCAWE has been collecting data on spillages from cross-country oil pipelines in Europe. The information is collated in an annual report which includes an analysis of the human and environmental consequences and of the underlying causes of such incidents. CONCAWE report 7/08 presents the results for the year 2006 and an analysis of the accumulated data for the whole 36–year period from 1971 to 2006.

Pipeline inventory

The ‘CONCAWE inventory’ includes about 35,000 km of cross-country oil pipelines, representing the bulk of such facilities in Europe. This inventory, which originally covered mainly Western Europe, has grown over the years and gradually expanded eastwards. Additionally, the majority of the non-commercial (mostly military) pipelines joined the scheme in the late 1980s, accounting for a big jump in the size of CONCAWE’s survey inventory. These pipelines transport some 800 Mm^3 of material every year, i.e. more than the total EU refinery throughput, about 2/3 of which is crude oil and 1/3 refined products. The majority of these pipelines were laid in the 1960s and ’70s, as a result of which the average age of the inventory has been increasing (Figure 1).

Number of spills and volume spilled

In spite of this ageing, the annual number of spills has slowly decreased over the years, while the spillage frequency shows an even stronger downward trend (Figure 2). Although there are large variations from year to year, the total annual volume spilled has remained broadly constant at around 2000 m^3/a, even though the inventory surveyed has significantly increased over the years. On average, about 60% of the spilled oil is recovered.

Causes of spills

CONCAWE analyses the cause of spillage through five main categories, i.e. mechanical, operational, corrosion, natural events and third-party interference, and a number of sub-categories. The distribution of spills according to main cause is shown in Figure 3, separately for ‘hot’ and ‘cold’ pipelines.

Figure 1 Total length surveyed and age distribution

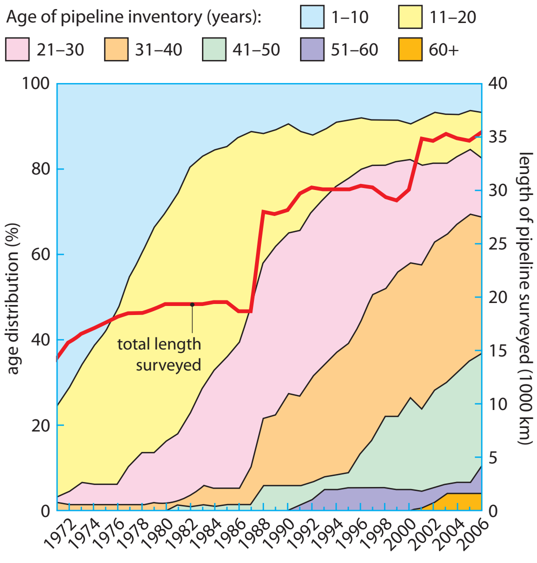


Figure 2 Pipeline spills, 1971–2006

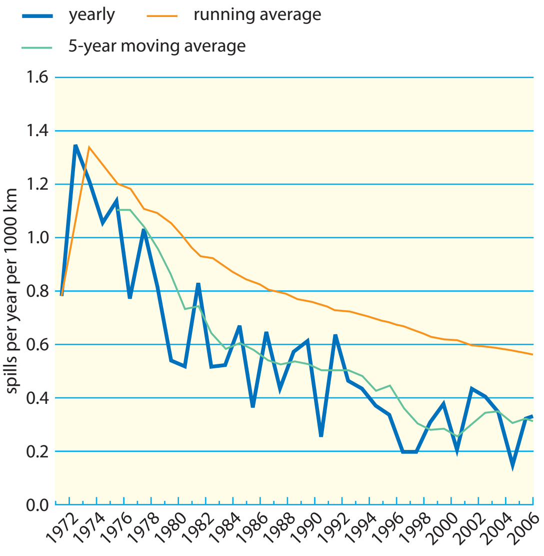
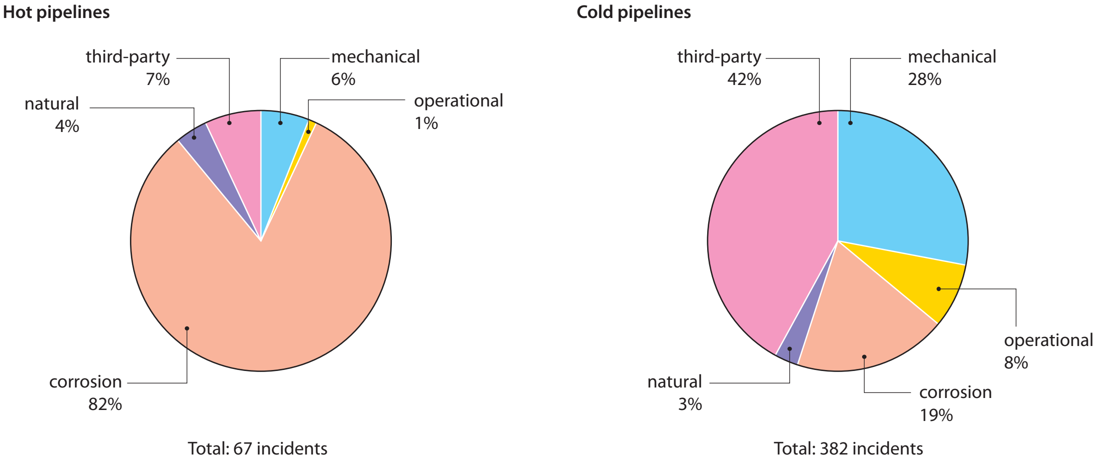


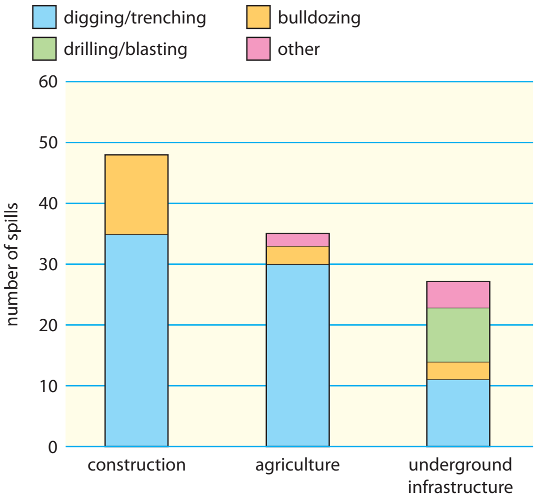
Figure 3 Causes of major spills



'Hot' pipelines form a small and decreasing part of the inventory and consist of insulated pipelines transporting hot products, mainly heavy fuel oil. These pipelines are mostly affected by external corrosion and, partly because of such corrosion problems, the majority have been phased out over the years. Today they represent less than 1% of the total inventory

For the bulk of the inventory ('cold' pipelines), the most common causes of spillage are corrosion, mechanical failure and third-party interference. Although internal and external corrosion failures have occurred in cold pipelines, there is no evidence that these are on the increase, suggesting that corrosion issues are well under control in spite of the general ageing of the inventory. Mechanical failures occur as a result of a range of causes related to design and materials, as well as construction defects.

Figure 4 Causes of accidental third-party spills



Third-party interference is seen by pipeline operators as the main threat to the integrity and safety of their operations. A small proportion of the spillages caused by third party activities is the result of malicious or criminal activities (theft attempts), but the majority of these spills are accidental and mostly related to farming and excavating activities (Figure 4). The industry is actively engaged internally, with land owners and contractors, and with national authorities and regulators in order to devise ways to reduce this threat.

Downstream oil industry safety statistics

2006 Report

The collection and analysis of accident data is an essential element of a modern safety management system, and its importance is recognised throughout the oil industry. CONCAWE has been compiling statistical data for the European downstream oil industry for 14 years and the purpose of this activity is twofold:

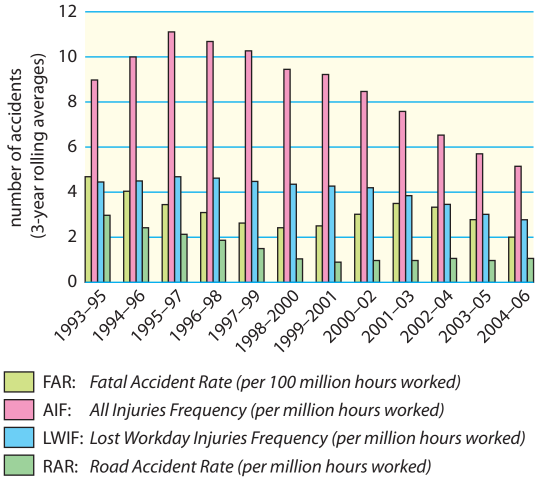
- to provide member companies with a benchmark against which to compare their performance, so that they can determine the efficacy of their management systems, identify shortcomings and take corrective action; and
- to demonstrate that the responsible management of safety in the downstream oil industry results in a low level of accidents, despite the hazards intrinsic to its operations.

The report for the year 2006 was published earlier this year (CONCAWE report 2/08) and is available on CONCAWE's website. Besides the 2006 data, the report also includes a full historical perspective from 1993, as well as comparative figures from other industry sectors. Data was submitted by 20 companies, accounting for more than 80% of the refining capacity of EU-27.

In line with previous reports, the results are reported in the form of key performance indicators that have been adopted by the majority of oil companies operating in Western Europe as well as by other branches of industry. These are: Lost Workday Injury Frequency (LWIF); All Injury Frequency (AIF); Road Accident Rate (RAR); and Fatal Accident Rate (FAR). The statistics include companies' own employees as well as contractors, and are split between 'manufacturing' (i.e. mostly refineries) and 'marketing' (i.e. distribution and retail).

The analytical results are of most interest in the form of historical trends, assisting the safety management efforts for continuous improvement. Figure 1 shows the evolution of the three-year rolling average for the four indicators over the past 14 years.

Figure 1 Personal incident statistics relating to the European downstream oil industry



Overall these indicators show a consistent performance over the years with a slow but steady reduction of LWIF, which is under 3.0 for the second year running. The figures suggest that AIF peaked around 1996–97, but this is also related to incomplete reporting of this indicator in the early years, as it was not formally in use in all companies. The trend is definitely on a downward slope and AIF figures have improved for all categories.

A total of seven fatalities were reported for 2006. Following a steady downward trend during the 1990s, fatality numbers began to increase in the first years of this decade, peaking in 2003. The reverse in this unfavourable trend since 2004 is confirmed by the 2006 figure. The FAR is now below that of 1999, which was the lowest FAR reported since CONCAWE started to compile this information.

Of these fatalities, five were due to road accidents and the two others resulted from hazards directly associated with our industry's maintenance and construction activities. Over the last five-year period road accidents (40%) and incidents during construction/ maintenance activities (40%) remain the principal causes of fatalities.

Abbreviations and terms used in this CONCAWE *Review*

AIF	All Injury Frequency
CA	Crank Angle (degrees)
CA50	Point in the cycle at which 50% of the injected fuel mass has been converted to heat, also called the 'centre of combustion'
CAFE	Clean Air For Europe
CAI	Controlled Auto-Ignition
CLCC	Closed Loop Combustion Control
CN	Cetane Number
CO	Carbon Monoxide (emissions)
DCN	Derived Cetane Number (obtained by calculation for petrol fuels or by measurement in an ignition quality tester for diesel and kerosene fuels)
DI	Direct Injection
DOE	Design of Experiments
DPF	Diesel Particulate Filter
DVPE	Dry Vapour Pressure Equivalent (to RVP)
EGR	Exhaust Gas Recirculation
EN228	European Standard 'Automotive fuels. Unleaded petrol. Requirements and test methods'
EN590	European Standard 'Automotive fuels. Diesel. Requirements and test methods'
FAR	Fatal Accident Rate
GDI	Gasoline Direct Injection
GRPE	Working Party on Pollution and Energy
HC	Hydrocarbon (emissions)
HCCI	Homogeneous Charge Compression Ignition
IMO	International Maritime Organisation
IMEP	Indicated Mean Effective Pressure
IPPC	Integrated Pollution Prevention and Control (EU Council Directive 96/61/EC of 24 September 1996 concerning integrated pollution prevention and control)
LOSU	Level of Scientific Understanding
LWIF	Lost Workday Injury Frequency
MARPOL	1973 International Convention for the Prevention of Pollution from Ships
MEPC	Marine Environment Protection Committee
MIT	Massachusetts Institute of Technology
NEDC	New European Driving Cycle
NO_x	Nitrogen oxides
PM	Particulate Mass, Particulate Matter
PMP	Particulate Measurement Programme
PN	Particle Number
RAR	Road Accident Rate
RF	Radiation Forcing
SECA	SO_x Emissions Control Area
SO_2	Sulphur dioxide
UN-ECE	United Nations Economic Commission for Europe
WHO	World Health Organization

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CONCAWE staff changes

2008 has seen a number of changes in CONCAWE staff. Gary Minsavage became the new Technical Coordinator for Health Issues early this year, replacing Jan Urbanus. Gary was previously working as Senior Toxicologist at ExxonMobil Biomedical Sciences, coordinating internal research and development and providing toxicology support for several business areas.

Klaas den Haan has replaced George Stalter as Technical Coordinator for Water, Waste and Safety. Klaas is a chemist and natural scientist with specialisation in ecotoxicology and environmental risk assessment, and was last working in The Netherlands for Shell Global Solutions. He has been involved in ECETOC (working group on Environmental Exposure Assessment and Modelling), Cefic (working groups on Existing Chemicals) and various Dutch environmental organisations.

CONCAWE’s new Technical Coordinator for Air Quality is Peter (Pete) Roberts, replacing Lourens Post. Pete is an applied mathematician by training, and has been working in Shell in the UK as a technical specialist on air quality issues and major hazards assessment. He has been closely involved in CONCAWE's activities over the past 10 years, as Shell’s representative on several Air Quality Task Forces.

We extend a warm welcome to our new colleagues. To those who have left us, many thanks for all their efforts and achievements during their time with CONCAWE, and best wishes for the future!

CONCAWE publications

Reports published by CONCAWE from 2007 to date

2007	
1/07	Oil refining in the EU in 2015
2/07	Sulphur dioxide emissions from oil refineries and combustion of oil products in Western Europe and Hungary (2002)
3/07	Air pollutant emission estimation methods for E-PRTR reporting by refineries
4/07	Performance of European cross-country oil pipelines—Statistical summary of reported spillages in 2005 and since 1971
5/07	Report of a Workshop on Environment and Health: Air Quality Research Needs in the EU 7th Framework Programme of Research, 15–16 January 2007
6/07	Human exposure information for EU substance risk assessment of kerosine
2008	
1/08	Impact on the EU of SO$_x$, NO$_x$ and primary PM$_{2.5}$ emissions from shipping in the Mediterranean Sea: Summary of the findings of the Euro Delta Project
2/08	European downstream oil industry safety performance. Statistical summary of reported incidents—2006
3/08	Guidelines for blending and handling motor gasoline containing up to 10% v/v ethanol
4/08	Advanced combustion for low emissions and high efficiency: a literature review of HCCI combustion concepts
5/08	Report of a toxicology forum symposium on air quality and cardiovascular health effects: what’s the impact—October 24, 2007
6/08	Optical methods for remote measurement of diffuse VOCs: their role in the quantification of annual refinery emissions
7/08	Performance of European cross-country oil pipelines—Statistical summary of reported spillages in 2006 and since 1971

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