concawe

ENVIRONMENTAL SCIENCE FOR THE EUROPEAN REFINING INDUSTRY

review

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Environmental science for the European refining industry

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Foreword

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Clean fuels have made a profound impact on modern society, transporting people, both for work and for leisure activities, and goods that have enabled our living standards to improve with a concomitant increase in life expectancy. However, we cannot rest on the achievements of the past and must move on to new challenges. The petroleum refining industry recognises it has a role to play, in reducing the impact man has on the environment via reduced GHG emissions, improving air quality in cities and using precious natural resources in the most efficient way. The articles in this *Review* report on ongoing work by Concawe to further contribute to the safety of everyone working in our industry, to improve the environmental performance in the manufacture of fuels and other oil products and to develop the fuels for the future, necessary to maintain the position of oil-derived liquid fuels as the most efficient option until fully renewable transport fuels become widely available at an affordable price.

Contents

Abating fugitive VOC emissions more efficiently

Comparing best available techniques for detecting refinery fugitive emissions

This article summarizes the Concawe study, 'Techniques for detecting and quantifying fugitive emissions—results of comparative field studies', that compares the two BAT (best available techniques) detection methods[1] for refinery fugitive emissions (leaks) of non-methane volatile organic compounds (NMVOC): 'sniffing' and 'optical gas imaging' (OGI). The main finding is that the OGI technology is faster and can effectively detect the main leaks. By repairing those leaks, a reduction comparable to that achieved using the sniffing method is achieved, contributing to the total site NMVOC emission reduction.

The petroleum refinery industry has successfully reduced NMVOC emissions—one of the precursors to surface level ozone formation—through leak detection and repair (LDAR) programmes, and technology advances (e.g. improved valve packing). To go further with this reduction, the industry is now focusing its efforts on the control of fugitive emissions which can contribute up to one third of the total site NMVOC emissions. Fugitive emissions are generated at plant components which are supposed to be leak-tight (e.g. pump or compressor seals, valve packings, flanges, sample points, etc.). While a typical site would have more than 50,000 such components, only a few of these contribute to the bulk of fugitive emissions. Identifying these leaks for repair is difficult and time consuming, as they will be spread out over the entire site, and in locations which are difficult to access.

Two methodologies are currently available to detect leaking equipment in LDAR programmes:

1. 'Method 21' (or 'sniffing'), developed by the US-EPA, involves the use of a hydrocarbon ionisation detector; it was historically the first approach and is a widely accepted method.
2. Optical gas imaging, using an infra-red camera, is a newer technique which is gaining increasing acceptance.

Both methods are effective, and each has advantages and limitations (outlined below). However, as they are based on different technologies and applied in the field in different ways, a comparison is not straightforward. The two methods had not previously been compared in large simultaneous, independent field trials in Europe. Such trials were the objective of a project managed by the Concawe OGI Group, and the results obtained are summarized in this article.

Background

Initial methodology: 'Method 21' or 'sniffing'

The monitoring and emissions estimating methodology is described in EPA-453/R95-017 (US) and in EN 15446:2008 (EU) (CEN, 2008), and is commonly referred to as 'sniffing'.

A hand-held hydrocarbon detector (either a flame ionisation detector (FID) or photo ionisation detector (PID)) is used to 'screen' all potential leak points one by one and record, for each of them, the highest hydrocarbon concentration measured (screening value). Above a given concentration threshold (e.g. 10,000 ppmv), the equipment is identified as leaking and must be repaired. A maximum of around 500 components (most of which will not be leaking) can be screened effectively per work day by one person. In EN 15446, factors are provided per equipment type and service, to permit the estimation of NMVOC mass emissions based on the screening value. Those factors were derived by the EPA from a statistical analysis of a significant number of leaks from various components, which were simultaneously both screened and 'bagged' (i.e. the leak flow is captured in an impermeable bag and its concentration and composition are analysed, allowing its emitted mass to be calculated). These data showed a very large spread, e.g. for the same hydrocarbon concentration, the mass emission could vary by as much as four orders of magnitude.

For the lower concentrations, correlations were developed on a log/log scale but can only be statistically representative if applied to a very large number of components. For the higher concentrations (above 50,000 ppmv methane) the FID and PID detectors do

[1] The 'sniffing' method and the optical gas imaging technique are part of BAT6: monitoring of diffuse VOC emissions to air.

not give a linear response. Therefore, the methodology assigns 'pegged values'—fixed mass emission values—to the high concentration readings (e.g. >10,000 ppmv and > 100,000 ppmv).

Newer technology: optical gas imaging (OGI)

In OGI technology, passive mid-wave infrared cameras are equipped with a filter to selectively detect radiation at the specific C-H absorption band (3.2–3.4 μm). The commercial OGI cameras are easy to use and show the hydrocarbon leak as a plume coming from the emitting source. OGI can detect any leak whereas sniffing cannot survey components which are not accessible. A major advantage of OGI is the monitoring speed. The OGI technology provides a qualitative assessment of the size of the leak. The main limitation of OGI is its higher minimum detection limit, i.e. 1–10 g/h, depending on the hydrocarbon, compared to about 0.01 g/h for sniffing.

OGI has proven to be very useful in safety and maintenance applications, and is now commonly used after a unit start-up to verify equipment tightness.

The latest camera models on the market are the FLIR GF320 and the OPGAL EyeCGas. Based on the feedback from several contractors performing OGI surveys, they give comparable results in the field.

Effectiveness of LDAR programmes

Over the years, LDAR programmes based on sniffing have helped to reduce fugitive emissions. Data now available indicate that OGI-based programmes would most likely have achieved similar reductions faster and cheaper, considering that only the largest leakers (less than 2% of the total equipment population) are responsible for more than 90% of the fugitive mass emissions (API, 1997).

Europe promoting the use of OGI-based LDAR

The latest BAT Reference document (BREF) for refining of mineral oil and gas (REF BREF) considers both sniffing and OGI as BAT. In 2013, the Netherlands Standardization Institute (NEN) developed guidelines for performing OGI surveys, aimed at providing a common methodology (National Technical Agreement 8399:2013) (NEN, 2013).

Concawe study objective

In 2012–2013, Concawe carried out several parallel LDAR campaigns. Both OGI and sniffing (EN 15446:2008) were applied by two independent teams. The objective was to compare the NMVOC mass emissions detected by each method. The mass emissions were independently estimated for all detected leaks by 'bagging'[2], when possible. The bagging technique applied uses a combination of two instruments: the High Flow® Sampler (a device developed by manufacturer Bacharach for estimating natural gas leaks) and the 'TVA-B'—a FID/PID detector commonly used in sniffing surveys. The High Flow® Sampler was used to estimate the volumetric flow rate of the leak. The TVA-B was used at the outlet of the High Flow® Sampler to estimate the VOC concentration of the leak. The combination of these two techniques, which is much faster than the original methodologies described in EPA-453/R95-017, will be referred to as 'HFS' throughout this article.

HFS was validated in a controlled experiment and compared to the EPA 'vacuum bagging' method in the field (20 leaks were bagged by both methods). The limit of the validation resulting from the controlled experiment was 200 g/h and this was used as a maximum HFS rate when analysing the results of the field campaign. This approach is similar to the 'pegged values' in Method 21 (see above). For the leak rates between 20–200 g/h, HFS was found to give a larger leak rate by a factor 2 to 5 than vacuum bagging. However, as this results in a conservative estimation of the NMVOC emissions, the HFS results were used for leaks between 20–200 g/h in this study. For the lowest leak rates (1–20 g/h) HFS accuracy was comparable to vacuum bagging.

[2] Bagging techniques are not applicable for regular LDAR surveys as only a maximum of 20 leaks per day can be bagged.

Parallel sniffing and OGI surveys

Units handling gas and light hydrocarbons were surveyed by both methods at two European refineries. Site 1 is a newer facility (built in the 1980s) where LDAR was applied for the first time during this survey. Site 2 is an older facility with an LDAR programme in place for 10 years. A single campaign was done at Site 1 (November 2012) while three consecutive campaigns were done at Site 2 (between June and November 2013). In the first campaign at Site 2 several units were surveyed, totalling 25,000 LDAR points. In the subsequent campaigns, only sub-unit 1 was surveyed (selected as previous surveys had shown this to have a relatively high number of leakers). Site 1 and Site 2 sub-unit 1 have approximately 4500 LDAR points each. The leak definition threshold was 10,000 ppm for Site 1 and 5000 ppm for Site 2 (based on the site permit). Experience with sniffing has shown that the number of components classified as 'leakers' does not increase significantly when the leak threshold definition drops from 10,000 ppm to 5000 ppm, and the two sites can still be compared.

To improve the comparison for site 1 the bagged leaks that were below the Site 1 leak definition but were above or close to the Site 2 leak definition are added to the analysis. In this Concawe work, a leak is defined as either a visible OGI image or a screening value above site leak definition.

The OGI surveys were performed according to the Dutch guideline (NEN, 2013). The FLIR GF320 camera was used and the equipment was surveyed at no more than two metres distance from multiple angles (for the accessible components). The pace of the survey was 2000 components per person per work day. The sniffing surveys were performed according to EN 15446:2008.

The analyses for comparing the VOC mass emissions estimated by the various methodologies were only done for the bagged accessible leaks. This approach was selected to make the comparison meaningful. Method 21 correlations are only statistically meaningful if applied to a very large number of leaks. The accuracy of the Method 21 estimations for the number of leaks detected in these partial surveys, therefore, is not as high as when full site surveys are undertaken.

The main four observations made during the field LDAR surveys are illustrated and discussed below.

1. The emissions estimated by the EN 15446 factors and correlations are conservative for a facility where no leaks above 200 g/h are present.

Two similar process units were surveyed in two different European refineries (Site 1 and Site 2 sub-unit 1). Figure 1 shows the number of leaks detected by sniffing, and how many of those leaks had a screening value

Figure 1 Total number of leaks found by sniffing (Site 1 and Site 2 sub-unit 1, campaign 3)

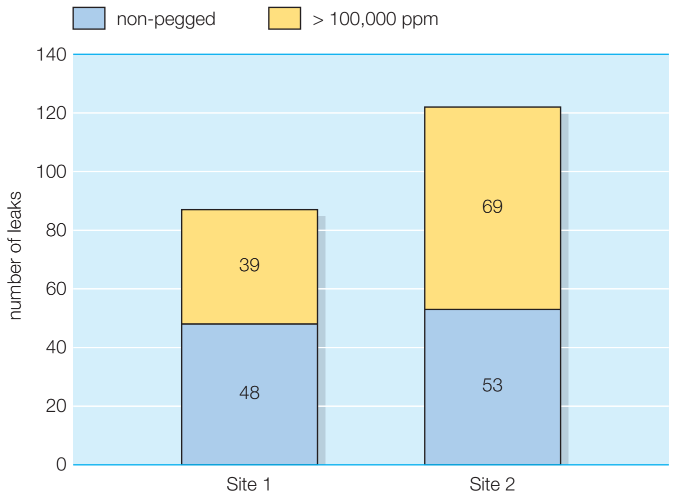
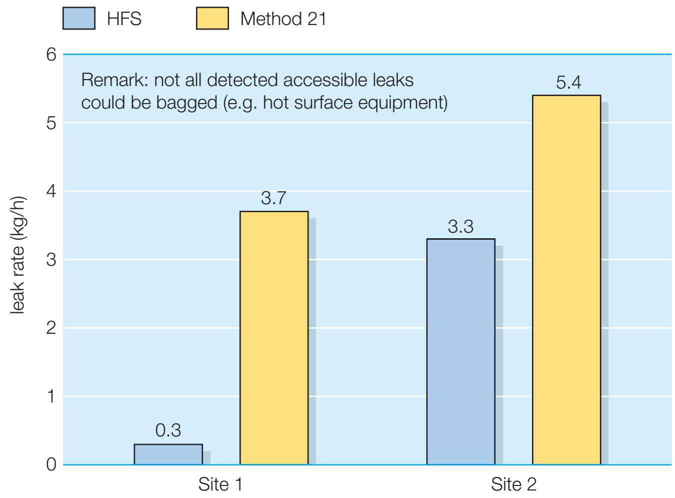


Figure 2 Leak rates estimated by two methods (Site 1: 74 leaks; Site 2: 97 leaks)



above 100,000 ppm (pegged leak) and how many were below 100,000 (non-pegged leak).

In the two facilities, the fraction of 'pegged leaks' was comparable (45% in Site 1 and 57% in Site 2 sub-unit 1).

Figure 2 shows the mass of these leaks estimated with Method 21 and with HFS.

While the number of 'pegged leaks' is comparable, as shown in Figure 1, Site 1 has fewer leaks in total and no single large leak (≥ 200 g/h) based on the bagging results (HFS). Site 2 sub-unit 1 has more leaks in total (but a lower leak threshold) and 8 large leaks.

For Site 2 sub-unit 1, the emissions estimated with Method 21 are close to those estimated with HFS (a factor of 1.6 difference). For Site 1, the emissions estimated with Method 21 are much higher than the HFS estimation (a factor of 12 difference). A possible explanation is that the Method 21 factors and correlations were established many years ago, when the occurrence of large leaks was statistically more frequent. This method has not been revised in 20 years and could misrepresent the current situation, where LDAR programmes and technology advances (e.g. improved valve packing) have resulted in reduced fugitive emissions relative to 20 years ago.

2. OGI and sniffing may not find the exact same leaks. However, the 'common leaks' found represent the largest portion of the total VOC mass emissions.

Figures 3 and 4 show, for Site 1 and Site 2 sub-unit 1, the number of leaks detected by the two methods and the mass of these leaks (calculated with the HFS method). As illustrated above, Site 1 and Site 2 sub-unit 1 are very different in terms of total NMVOC mass leak rate.

In Site 1 (Figure 3), the number of leaks only identified by sniffing was significant (70 out of 104), but the mass of these leaks (0.15 kg/h) is smaller than the mass of the common leaks (0.18 kg/h). One could argue that OGI 'missed' 0.15 kg/h of NMVOC mass on accessible components, but the three 'OGI-only' leaks which could not be quantified (non-accessible) are likely to generate an equivalent mass emission to the 'Method 21-only' leaks.

In Site 2 sub-unit 1 (Figure 4), both the number and the mass of common leaks are the most important. The mass of 'OGI-only' leaks is comparable to the mass of 'Method 21-only' leaks.

Figure 3 Site 1, leaks identified by detection method and mass of bagged leaks (estimated with HFS)

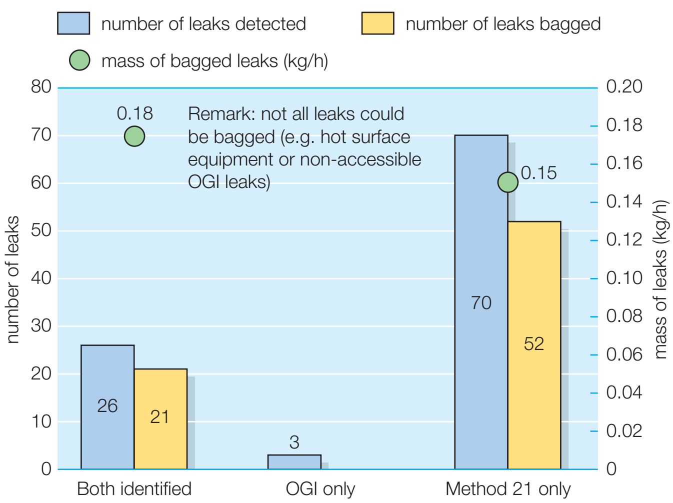
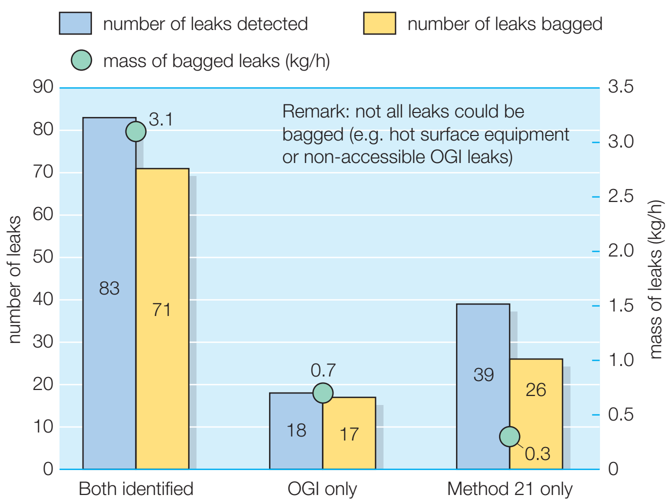


Figure 4 Site 2, sub-unit 1: leaks identified by detection method and mass of bagged leaks (estimated with HFS)

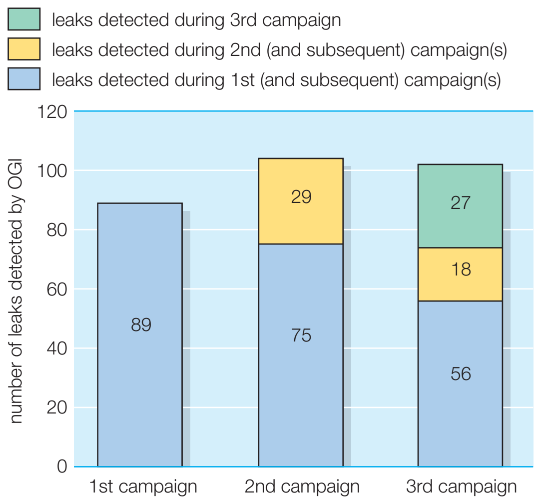


3. OGI was able to detect up to 90% of the total NMVOC mass of accessible leaks in a single campaign. This is comparable to sniffing, where some leaks are missed (e.g. where equipment is not accessible or is missing from the LDAR database).

Figure 3 shows that, for Site 1, the mass of OGI leaks quantified is 55% of the total mass of accessible leaks. Figure 4 shows that, for Site 2 sub-unit 1, the mass of OGI leaks is 90% of the total mass, which is in line with an analysis done in 1997 (Lev-On *et al.,* 2007) by the American Petroleum Institute (API). OGI effectiveness is highest when the fugitive emissions from a facility are relatively high: total NMVOC mass emission in Site 2 sub-unit 1 is 11 times higher than in Site 1 (3.3 kg/h versus 0.3 kg/h for a comparable process and size, as shown in Figure 2 on page 5). When the facility has relatively low fugitive emissions, e.g. Site 1, the effectiveness of OGI is lower but comparable to Method 21.

Figure 5 shows, for Site 2 sub-unit 1, three successive OGI campaigns performed over six months. A very small number of leaks were repaired between the campaigns (only those with a potential safety issue). Successive campaigns show that some additional leaks were found and some previous leaks were not detected again. An unexpected shut-down took place between campaigns 2 and 3; the opening of some equipment could explain the higher number of new leaks in campaign 3.

Figure 5 Site 2, sub-unit 1: leak trend by campaign for OGI leaks



In the same way, successive sniffing campaigns also point out differences in the leak screening values. But as OGI surveys are faster, it is possible to increase campaign frequency at similar cost and improve leak detection effectiveness.

4. In real conditions, the OGI detection limit cannot be defined by one single number. For the Concawe survey (Site 2 sub-unit 1, Campaign 3), OGI detected all leaks above 43 g/h and 80% of the leaks above 1 g/h (out of all leaks bagged with HFS).

Figure 6 on page 8 shows all the third campaign bagged leaks in the Concawe survey on a log/log scale. The x-axis is the sniffing concentration while the y-axis is the NMVOC mass flow, estimated using HFS. Two horizontal lines can be drawn dividing the data into three zones: all the leaks in the top section were detected by OGI (> 43 g/h); most of the leaks in the middle section were also detected by OGI (between 1 and 43 g/h); leaks in the bottom section (below 1 g/h) were difficult, but not impossible under ideal conditions, to detect with OGI.

In the middle section of Figure 6 (referred to as the 'partial OGI leak detection zone'), there were 90 leaks bagged, with an average emission rate of 13.6 g/h. Twenty-four leaks were missed by OGI and 11 leaks were missed by sniffing.

Estimation of NMVOC mass emissions when using OGI

For OGI, the plume image only gives qualitative information of the leak size. In 2004, the API published leak/no-leak factors to be used in OGI campaigns to report NMVOC mass emissions (see Table 1 on page 8). These factors are based on a model refinery with a statistically relevant leak population, surveyed by OGI. For modelling the leak behaviour, the same bagging data were used as in Method 21. The factors were developed for four different lower detection limits of OGI cameras in the field.

Based on the observed 'average' field detection limit for the new camera model FLIR GF320, when applied according to the Dutch protocol (regarding distance and survey speed), the leak/no-leak factors for 6 g/h (leak definition, Table 1) were chosen for use in the analysis of the field measurement data.

Figure 6 Site 2, sub-unit 1: OGI detection sensitivity

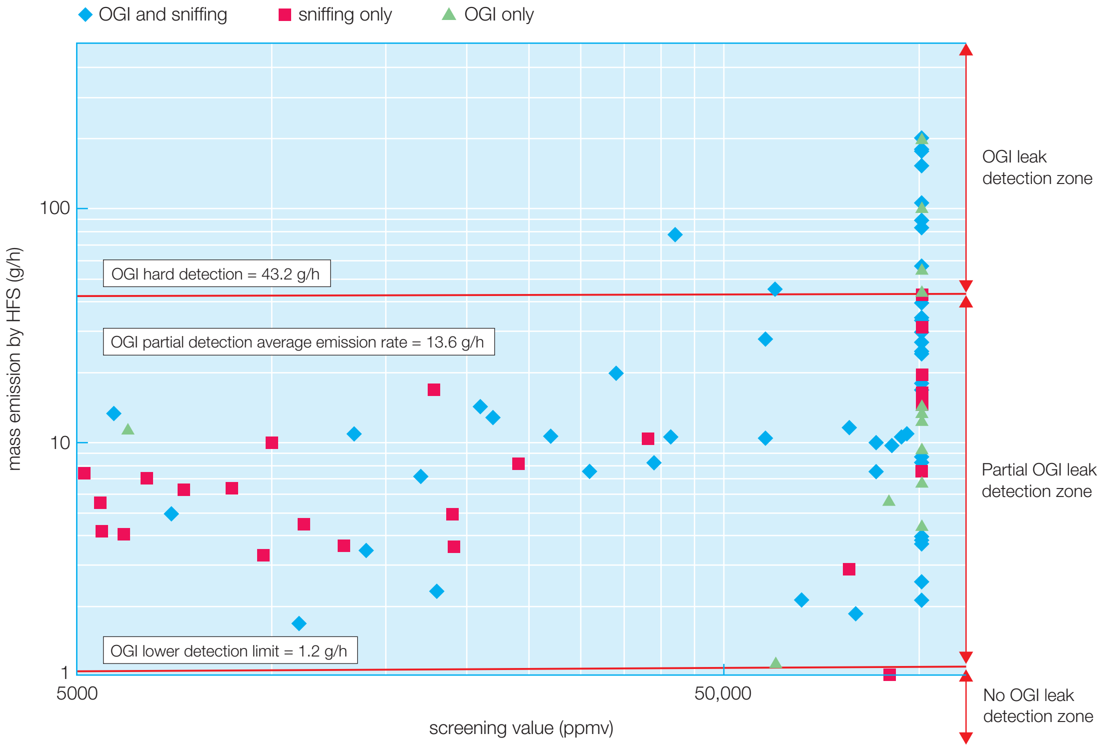
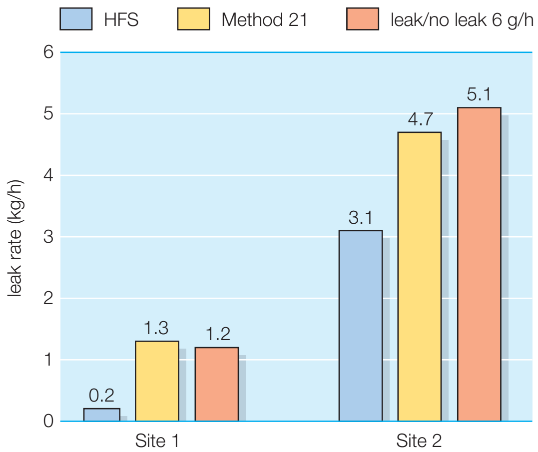


Table 1 Leak/no-leak factors for OGI surveys (API, 2004)

Component type	Emission factors (g/h) for specified leak definitions				
Leak definition—instrument detection limit (g/h)		**3**	**6**	**30**	**60**
Valves	No leak	0.019	0.043	0.17	0.27
	Leak	55	73	140	200
Pumps	No leak	0.096	0.13	0.59	0.75
	Leak	140	160	310	350
Flanges	No leak	0.0026	0.0041	0.01	0.014
	Leak	29	45	88	120
All components	No leak	0.007	0.014	0.051	0.081
	Leak	56	75	150	210

Figure 7 shows, for Site 1 and Site 2 sub-unit 1, a comparison of the NMVOC mass emission (from bagged leaks only) based on the different methodologies: Method 21, HFS and leak/no-leak factors (6 g/h detection limit). The leak/no-leak factors give an overestimate of the emissions for Site 1, as does Method 21. They give a reasonable estimate for Site 2. Knowing that the fugitive NMVOC emissions for Site 1 and Site 2 sub-unit 1 are very different, illustrating the variability that can occur between facilities, the choice of the API leak/no-leak factors for a 6 g/h leak definition seems reasonable.

Figure 7 Comparison of the VOC mass emission based on the different methodologies



Looking ahead

An attempt to improve the existing OGI quantification factors based on new leak bagging and statistical analysis is not justified because the assumptions needed to derive statistical correlations will at best represent an 'average' site situation. The methods for estimating actual NMVOC emissions, e.g. by bagging, are time consuming and/or subject to inaccuracies. Moreover, one should bear in mind that the main objective of LDAR surveys is to reduce fugitive emissions (by identifying leaking components for repair). Only a technology step-out, e.g. an improved OGI camera allowing direct and fast leak mass quantification, has the potential to substantially improve the estimation of fugitive NMVOC emissions in the future.

Conclusion

The Concawe parallel surveys, based on four large field trials, confirmed that sniffing and OGI are equally able to detect fugitive NMVOC emissions. OGI provides a better identification of the leaks with a high mass emission. The OGI detection limit has improved in the past few years: the new camera models are now able to detect leaks of a few g/h with a high probability. The leaks from accessible components not detected by OGI are all small in size and represent a small fraction of the total NMVOC mass emissions. OGI has the advantage over sniffing of being able to detect any leak above the detection limit present in the surveyed area, and not only the leaks from accessible components listed in the site database. OGI surveys also have the advantage of being much faster, allowing more frequent surveys than sniffing at comparable cost. For the OGI surveys using the new camera models at the surveyed refinery sites, the API leak/no-leak factors for a 6 g/h leak definition provided a reasonable, although conservatively high, estimate of the VOC mass emissions.

In a forthcoming Concawe report detailing this study, an LDAR survey protocol will be proposed using OGI as a standalone technique, comprising both detection and quantification (estimation). This protocol will have a detection efficiency of fugitive emissions similar to the sniffing programmes currently practiced in Europe.

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Spark versus compression ignition in a new energy environment

Could the development of new, more efficient engine technologies also help to address the diesel/gasoline supply imbalance?

Dieselisation of the fuel market is accelerating as commercial transport increases and as the fuel consumption of new passenger cars decreases. At the same time, the recent US revolution in shale gas and tight oil is putting new pressure on worldwide refining as more gasoline molecules are available from light crude extraction and from chemical feedstock substitution. From a renewable fuel perspective, ethanol and its derivatives are available in larger volumes.

As the world considers how to achieve best-in-class 'well to wheels' greenhouse gas reduction from transport, is it time to look at new opportunities to combine the highest efficiency engine technology with the lowest greenhouse gas (GHG)-emitting fuels? Would a low octane, low cetane gasoline or even a current pump gasoline be a better choice for future compression ignition engines?

Introduction

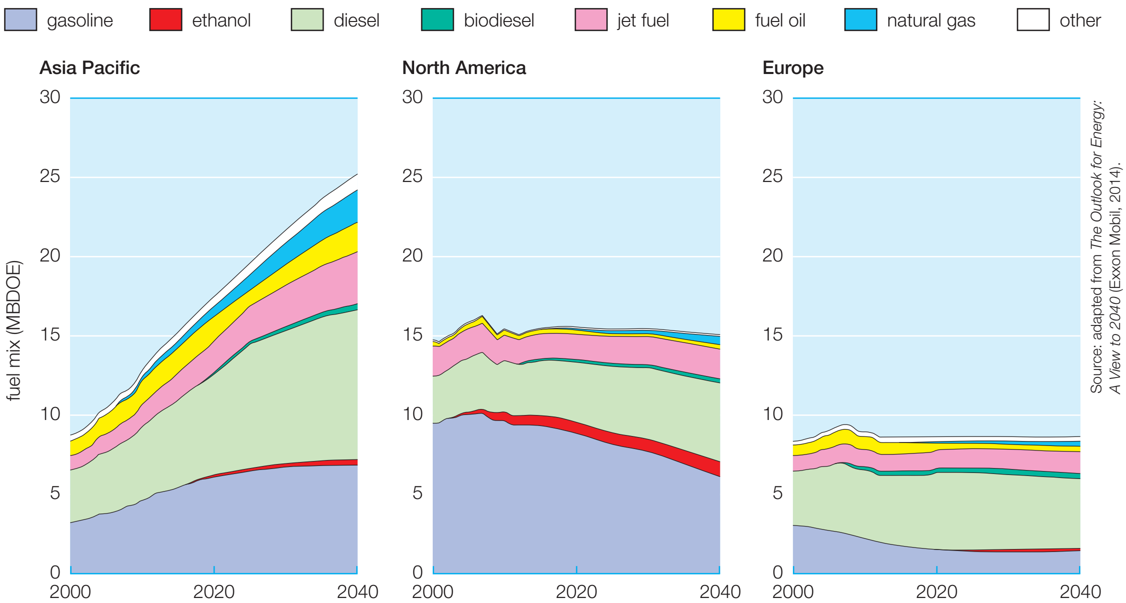
The overall world energy demand is evolving; demand is increasing in developing parts of the world, while in others, such as Europe and North America, it is declining. Looking more closely at transportation, as this is the sector that accounts for about 60% of oil demand today, it is clear that an understanding of the trend in overall fuel demand and the mix of fuel types over time is critical to ensuring that refinery operations and trade opportunities are effective in meeting the changing requirements of people around the world efficiently over time.

It is predicted that, in the period to 2040, the growth in demand for transportation will be led by the Asia Pacific region, and demand in North America and Europe will remain relatively flat while energy demand in Europe for light-duty vehicles is expected to decline by about 40%. Commercial transportation is likely to grow by about 20%, keeping energy demand for transportation stable.

Global diesel demand will increase by more than 75%, led by the Asia Pacific region, where demand for diesel will more than double. The demand for diesel fuel in North America will increase by about 60% even as the overall demand for transportation fuel remains relatively flat. In Europe, diesel volumes grow (+14% by 2025) and then decline (-11% from 2025–2040), remaining stable over the outlook period (+2% until 2040).

Global demand for gasoline will be relatively flat from 2010 to 2040, led by a decline in North America. Gasoline

Figure 1 Transportation fuel mix by region



demand declines due to improved light-duty fuel efficiency as well as increased use of oxygenates. In Europe, the demand for motor gasoline drops significantly (-32% by 2040). It is predicted that oil will remain the fuel of choice for transport in the coming decades, making up 89% of the transport fuel mix for Europe by 2040.

The demand for natural gas used for transportation is expected to grow by nearly 70%, with 60% of the growth in the Asia Pacific region and 15% in North America. Most of this growth comes from commercial transportation, such as liquefied natural gas (LNG) for long-haul trucks and compressed natural gas (CNG) fuelling local delivery fleets and buses.

The past few years has seen a boom in the production of natural gas in the USA, due to both continued production of conventional gas resources, as well as a surge in unconventional gas. In Pennsylvania, for example, the Department of Environmental Protection is reporting a 15x increase in natural gas production. In addition to this there has been an increase in tight oil production in some states, for example North Dakota. These trends are expected to continue.

Challenge to EU competitiveness

As a result, energy prices for US refineries have the advantage relative to those in Western Europe, as well as in the Asia Pacific region. Energy prices in Europe are currently much higher than in the USA, making it difficult for European businesses to compete on the global stage.

EU prices are twice as high for electricity, and three times as high for gas. This regional difference is expected to remain large through to 2035. Energy costs make up around 60% of European refineries' total operating costs, versus 28–30% for Eastern US refineries.

In addition, crude production growth worldwide is focused in the USA, Iran and Canada, with more modest growth in the Middle East and Western Africa, and essentially constant production in Europe. Taken together, Western European refiners are disadvantaged versus other global refiners in terms of energy prices, and crude availability.

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The diesel-gasoline imbalance is expected to increase into the foreseeable future.

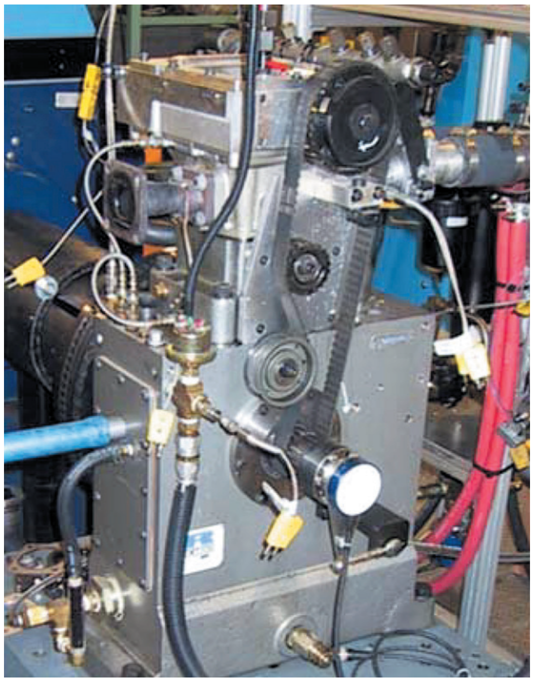
The increasing global diesel demand, the decreasing demand for gasoline and increasing availability of gasoline-type molecules from light crude extraction and chemical feedstock substitution, create a diesel-gasoline imbalance which is expected to increase as time goes on. These factors, as well as pressures to reduce GHG emissions, mean that refiners worldwide, and particularly those in Western Europe, are coming under increasing pressure.

Focus on vehicle efficiency

On the other hand, as pollutant emissions from motor vehicles continue to fall to meet lower regulated emission limits, attention is increasingly focused on vehicle efficiency and on fuel consumption to address future concerns with energy supplies and transport's contribution to GHG emissions. Engine, aftertreatment and vehicle technologies are evolving rapidly to respond to these challenges.

Considerable research is concentrating on improving the combustion performance of light-duty engines. Compared to spark ignition (SI) engines, compression ignition (CI) engines are already very efficient so the challenge is to maintain or improve CI engine efficiency while further reducing pollutant emissions. Engines using advanced combustion technologies are being developed that combine improved efficiency with lower engine-out emissions, thus reducing the demand on exhaust aftertreatment systems and, potentially, vehicle costs. Because these concepts combine features of both SI and CI combustion, the optimum fuel characteristics could be quite different from those needed by today's conventional gasoline and diesel engines.

In general, these advanced combustion concepts substantially homogenize the fuel-air mixture before combusting the fuel under low-temperature combustion (LTC) conditions without spark initiation. These approaches help to simultaneously reduce soot and NO_x formation. Light-duty diesel engines are well suited for advanced combustion because the higher fuel injection pressures, exhaust gas recirculation (EGR) rates, and boost pressures that aid conventional CI combustion also enable future variations of advanced combustion. In addition, the duty cycle of light-duty diesel engines emphasizes lighter loads where advanced combustion is most easily achieved. Many of the necessary hardware enhancements exist today, although they may be expensive to implement in production engines. Nonetheless, advanced combustion engines are rapidly moving from research into engine development and commercialisation.


Delphi

An early single-cylinder gasoline compression ignition (GCI) test engine developed by Delphi; ongoing development of the GCI concept aims to achieve diesel-like efficiency with low CO_2 emissions under real-world operating conditions.

The gasoline compression ignition concept

From a commercial perspective, it is well understood that there are significant challenges associated with bringing both a new engine concept and a dedicated fuel into the market at the same time. The potential benefits of fuelling advanced CI engines with market gasoline merits further consideration for the following reasons. In general, CI engines have an efficiency advantage over SI engines, and extending their capability to use a broader range of fuels could be advantageous. Second, the ability of CI engine concepts to use an already available market gasoline would allow these concepts to enter the fleet without fuel constraints. Third, more gasoline consumption in passenger cars would help to rebalance Europe's gasoline/diesel fuel demand on refineries and reduce GHG emissions from the fuel supply. Fourth, a successful GCI ('gasoline compression ignition') vehicle could potentially compete in predominantly gasoline markets in other parts of the world.

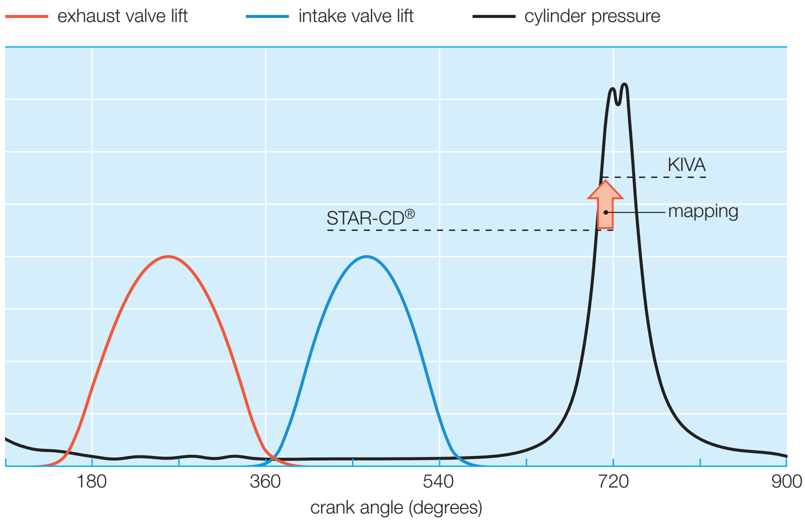
Because of these potential benefits, it was decided to investigate more completely the GCI engine concept, specifically to determine the range of conditions over which an engine could operate successfully in CI mode on a European market gasoline. In addition to an engineering paper study and a bench engine study on the GCI concept (Rose *et al.*, 2013), computational fluid dynamics (CFD) in-flow and combustion simulations were also carried out (Cracknell *et al.*, 2014).

Computational fluid dynamics is a state of the art simulation tool for analysing the flow behaviour in internal combustion engines. To reduce the computation time, only the combustion chamber and port geometries were modelled in this study.

Two main areas which were modelled were gas exchange and turbulent non-reacting flow which was modelled using STAR-CD®, a CFD programme concentrating on the combustion chamber and the port geometries in conjunction with a 1-D GT-Power simulation which was used to define boundary conditions.

The other area was combustion modelling which was done using KIVA software. The KIVA package included other sub-models for looking at spray, turbulence, wall impingement and other aspects. The STAR-CD® fluid flow was mapped to the KIVA simulations and used as boundary conditions (pressure, temperature, gas composition and flow velocity (see Figure 2).

Figure 2 Computational fluid dynamics (CFD) mapping methodology scheme—STAR-CD® to KIVA



Engineering paper study

An engineering paper study was first completed to analyse critical engine and fuel parameters and judge what speed/load range might be feasible for a GCI engine concept. For this engineering study, and for the bench engine work that followed, it was assumed that the GCI engine concept would be fuelled with a typical European market gasoline. The only change that was made was the addition of a lubricity additive.

The paper study identified the autoignition resistance of market gasoline as the single most critical challenge, particularly at low load conditions. Three main approaches were identified to mitigate this challenge:

- Shortening the ignition delay by increasing the charge pressure using two-stage boosting and a higher compression ratio (CR).
- The use of internal EGR to increase the local charge temperature in the combustion chamber when needed via a variable valve timing (VVT) strategy. High levels of EGR would be needed to control engine-out NO_x emissions so that both external and internal EGR would be used with a trade-off in local charge temperature between the competing demands of lowering NO_x emissions and achieving stable combustion.
- The use of combustion assistance (e.g. a glow or spark plug) to stabilise combustion at the lowest load points.

The paper study also recognized the important role of fuel spray and mixing, with higher pressure diesel injector systems being preferred along with an optimized combustion chamber geometry.

Bench engine study

To test the learnings from the engineering paper study, the bench engine study was carried out to provide a proof of principle for the GCI engine concept, and to determine what hardware measures, including ignition combustion assistance, would be most effective for extending the range of acceptable operation. The results from these tests are presented here, based on the background provided in the 'methodology' section. A more detailed account of the engine results is given in Rose *et al.,* 2013.

The success criteria for the bench engine optimization included the following factors: low engine-out NO_x; PM, HC and CO emissions as low as possible and suitable for further reduction by DOC (diesel oxidation catalyst) and GPF (gasoline particulate filter) aftertreatment systems; engine noise in the same range as conventional diesel CI operation; and fuel efficiency at least as good as the base engine configuration.

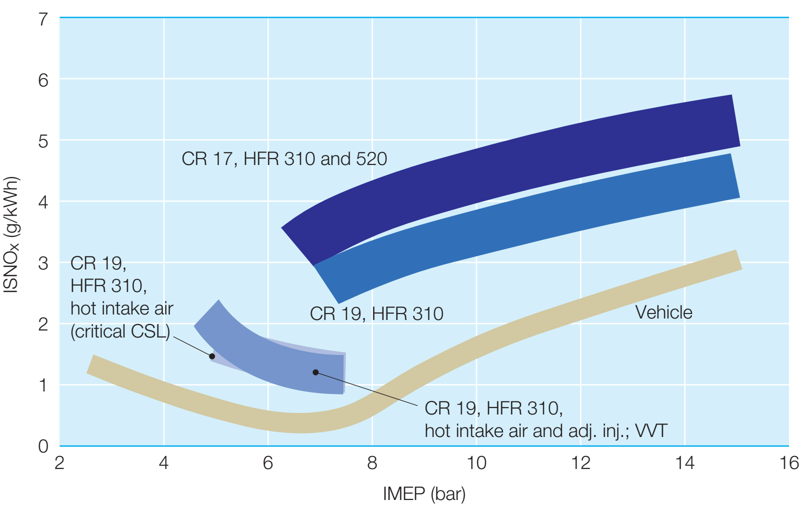
The bench engine included hardware enhancements that enabled it to meet Euro VI emissions limits and beyond. A downsizing concept was employed with a cylinder swept volume of 390 cm^3 that would allow the construction of a 1.6-litre 4-cylinder engine while maintaining the power of today's 2.0-litre engines.

As anticipated by the engineering paper study, it proved difficult to sustain reliable combustion using the market gasoline at lower load operating conditions. Light-load operation could be achieved, but NO_x levels were higher than desired. The combustion was also unstable and would not tolerate additional EGR. For this reason, the engine was fitted with a state-of-the-art glow plug which was capable of a sustained glow temperature of around 1200°C. For these tests, the engine coolant temperature was also reduced to 48°C to simulate the engine warm-up period.

The orientation of the glow plug to the injector spray is known to be critical. The position was adjusted by changing the orientation with respect to one individual injector spray by one-degree increments, while monitoring engine performance. A position close to the spray centre line giving the lowest CO/HC emissions and combustion duration was chosen for testing.

With the glow plug installed, low-load operation was possible at normal boost pressure levels, even at the cooler engine temperature condition. Under hot engine conditions, however, the glow plug did not help to reduce the NO_x emissions. At a 400-bar injection pressure, combustion quality was poor with a higher EGR rate. Reducing the injection pressure further to 260 bars improved combustion, but the increased heat release led to higher NO_x emissions even though the EGR level was already quite high.

Figure 3 Indicated specific NO_x ($ISNO_x$) emissions achievable at 1,500 rpm as a function of indicated mean effective pressure (IMEP)



From the engineering paper study, it was expected that the engine-out NO_x/PM trade-off would be better compared to diesel engines at low engine loads. Figure 3 shows the NO_x levels achieved in this study for the various hardware options tested. The target NO_x levels at 1500 rpm for various loads are shown by the solid band marked 'vehicle'. Even with the optimized injection strategy, higher CR, VVT and hot intake air, the engine was not able to achieve the target NO_x levels without exceeding a reasonable level of HC emissions. With combustion assist in the form of a glow plug, it was possible to achieve loads down to 4.3 bars IMEP as far as the combustion sound limit (CSL) would allow, but not with the EGR levels required to meet the target NO_x levels.

In this study, internal (uncooled) EGR using negative valve overlap was found to be advantageous for reducing HC emissions and improving fuel consumption in the mid-load range.

There are a number of competing effects that occur when more internal EGR is used. For example, higher temperature by itself shortens the ignition delay but also leads to higher NO_x levels which require higher EGR levels to control them. With higher EGR levels, the decrease in local oxygen levels and inhomogeneities associated with the internal EGR concentration led to higher smoke levels and a tendency to lengthen the ignition delay.

Nevertheless, Figure 4 (page 15) shows the brake-specific fuel consumption (BSFC) results, for two different speeds, obtained for the GCI concept compared with the range of state-of-the-art 2012 model-year spark ignition and direct injection compression ignition engines. The GCI concept was found to be well below those of naturally aspirated (NA) and turbo-charged (TC) spark-ignited gasoline engines, and at the bottom end of the range of direct injection diesel engines.

In addition to optimizing the glow plug position and utilising internal EGR to improve gasoline's ignitability under the low load operating conditions, it was concluded that further investigation would be required to find the best configurations of VVT strategy and spray targeting. Thus, three-dimensional CFD simulations were carried out.

Modelling study

Because the engineering study suggested that a glow plug would be required to assist combustion under this low load operating condition, the spray spatial distribution and the local lambda (i.e. air/fuel ratio) were also analysed.

Figure 5 shows the results of the mixture formation analysis performed when the piston is at the top dead centre firing (TDC-F) position for advanced boosted (left) and more realistic boost conditions (right). Here, the spray is visualized inside a 45° mesh sector of the piston bowl, by means of rich lambda iso-volumes coloured by

Figure 4 Brake specific fuel consumption (BSFC) versus engine speed

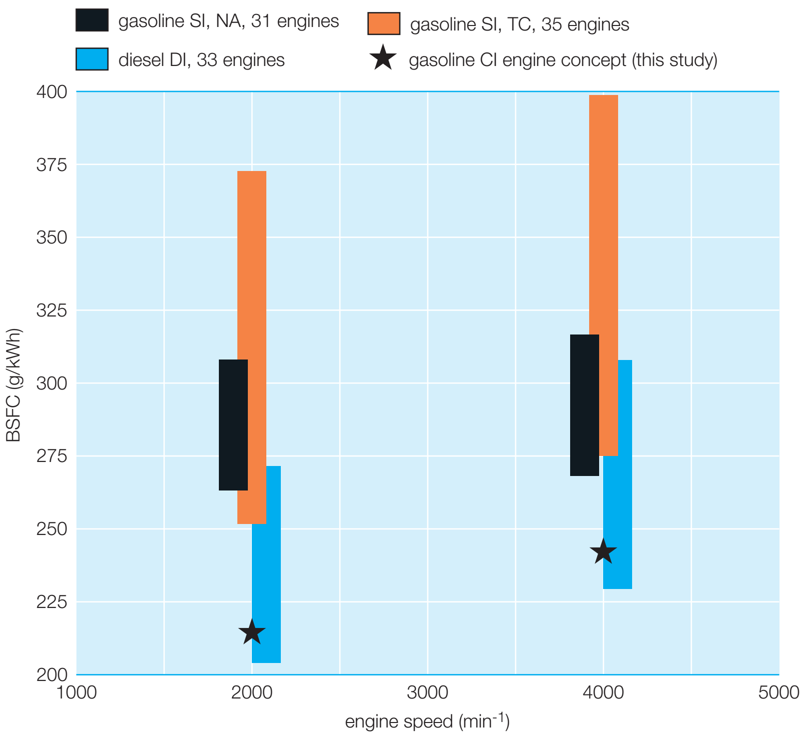
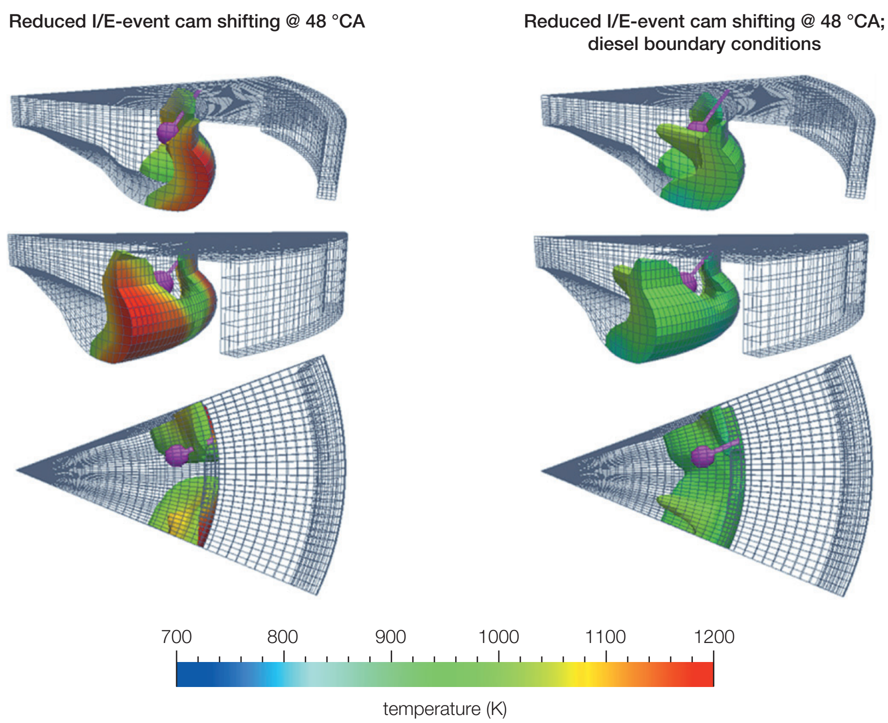


Figure 5 Mixture formation under boosted (left) and more realistic (right) conditions



increasing temperature. Thus, the rich zones, which will probably ignite with the glow plug, are identified. With accurate positioning of the glow plug, a favourable interaction between the fuel spray and glow plug is possible with the chosen nozzle cone angle of 153°. With advanced boosting the glow plug ignites spontaneously. Under more normal boosting conditions the glow plug will need to be heated to ignite the charge.

Further optimization was investigated using simulated spark plug assist instead of a glow plug. Using the optimum nozzle cone angle of 160° and nozzle protrusion of >1.5 mm an ignitable mixture condition around the spark plug is possible.

Apart from the work that Concawe has been doing over a number of years, there is increasing interest in this area of study from others. Delphi is working with Hyundai in collaboration with the University of Wisconsin-Madison's Engine Research Consultants (WERC) and Wayne State University on this topic, with US Department of Energy funding. Argonne National Laboratory and Saudi Aramco are also working on projects in this area of study. With a continuous and increasing trend of gasoline oversupply, an engine that performs at diesel engine fuel efficiency but running on gasoline components seems to be a practical and effective way forward to reduce costs and well-to-wheels (WTW) emissions.

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Downstream oil industry safety statistics for 2013

The 2013 safety statistics report presents data on personal injuries and process safety, highlighting trends over the past 20 years of data collection.

Safety management systems are widely recognized by the oil industry as an essential tool for collecting and analysing safety incident data and continuously improving the safety of employees and contractors. To support this effort, Concawe has, since 1993, been compiling statistical safety data for the European downstream oil industry in order to:

1. provide member companies with a benchmark against which to compare their own company's safety performance; and
2. demonstrate how responsible approaches to safety management can help to ensure that accidents stay at low levels in spite of the hazards that are intrinsic to refinery and distribution operations.

Most importantly, Concawe's annual safety data report enables companies to evaluate the efficacy of their own management systems, identify any shortcomings, and take corrective actions as quickly as possible.

What safety data do we evaluate?

Concawe's 20th report on the European downstream oil industry's safety performance (Concawe Report 8/14) presents statistics on work-related personal injuries sustained by oil industry employees and contractors during 2013. It also highlights trends over the past 20 years of data collection and compares the oil industry's performance to that of other industrial sectors.

The 2013 report compiles safety data submitted by 34 Concawe member companies, representing about 93% of the refining capacity of the EU-28 plus Norway and Switzerland. The statistics are reported primarily in the form of key performance indicators adopted by the majority of oil companies operating in Europe, as well as by other types of manufacturing industries. These indicators are:

- Number of work-related fatalities;
- Fatal Accident Rate (FAR), expressed as the number of fatalities per 100 million hours worked;
- All Injury Frequency (AIF) expressed as the number of injuries per million hours worked;
- Lost Workday Injuries (LWI) and the Lost Workday Injury Frequency (LWIF) calculated by dividing the LWI by the number of hours worked in millions;
- Lost Work Injury Severity (LWIS): the average number of lost workdays per LWI;
- Road Accident Rate (RAR): the number of road accidents per million km travelled; and
- Process Safety Performance Indicators (PSPIs) that report the number of Process Safety Events (PSEs) expressed as unintended Losses of Primary Containment (LOPCs).


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Process Safety Performance Indicators

Several major industrial incidents, including the Toulouse explosion (2001), the Buncefield fire (2005) and the Texas refinery explosion (2005), have led to increased attention being given to the causation of such events. This has led to several initiatives that focus on the gathering of PSPIs. The lagging indicator for this is the PSEs, mainly Losses of Primary Containment because these have been proven to be the initiating events for the aforementioned disasters.

PSPI data were collected in 2013 for the fifth consecutive year, following the publication of the latest recommended practice of the American Petroleum Institute (API). The additional data provide insights into the types and causes of process safety incidents. PSPIs also enable the refining and distribution industry to compare their European process safety performance with similar data from other regions of the world.

Thirty-two Concawe companies provided PSPI data in 2013. From these responses, a Process Safety Event Rate (PSER) indicator of 1.7 was recorded for all PSEs, which is the lowest result ever. The overall results of the PSPI survey are presented in Table 1 (overleaf).

Table 1 Results of the 2013 PSPI survey

Sector	Manufacturing	Marketing	Both sectors
Companies reporting			
Total	39	23	22
Process safety reporting	32	13	13
Percentage	82%	57%	59%
Hours worked (Mh)			
Total	281	292.5	573.5
Process safety reporting	268.2[a]	223.1	457.7
Percentage	95%[a]	76%	86%
Tier 1 PSE: PSE	115	9	124
Tier 2 PSE: PSE	334	81	415
Tier 1 PSER: PSE/Mh reported	0.43	0.04	0.27
Tier 2 PSER: PSE/Mh reported	1.25	0.36	1.34
Total PSER: PSE/Mh reported	1.67	0.40	1.18

[a] All companies provided both Tier 1 and Tier 2 PSEs for 2013.

Figure 1 PSE data for manufacturing, 2009–2013

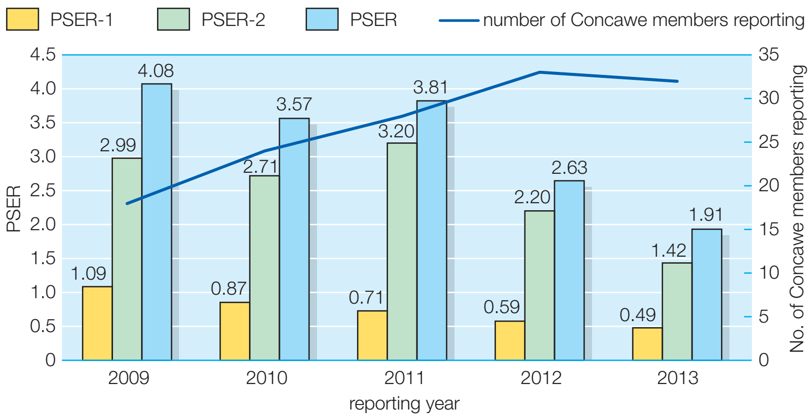
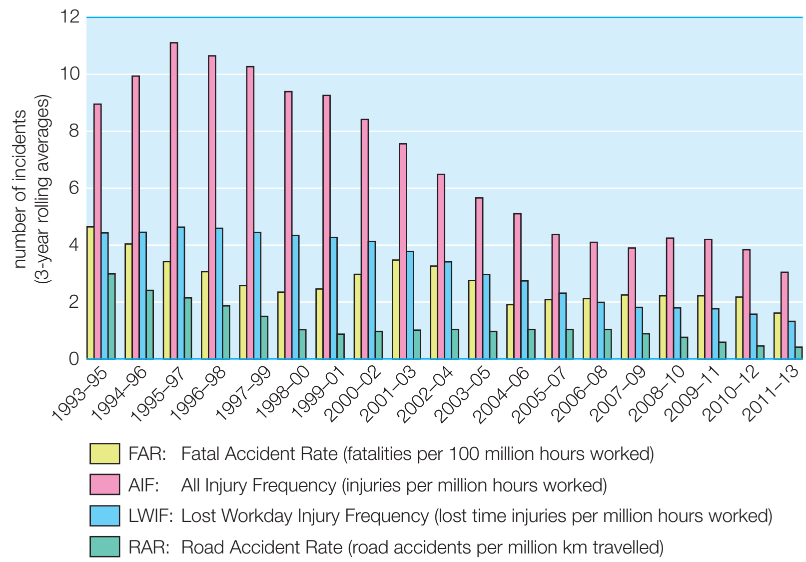


Figure 2 Three-year rolling average personal incident statistics for the European downstream oil industry



Fortunately, none of the reported PSEs resulted in a major incident that the understanding of PSE causation is trying to prevent.

Since the PSI data gathering was started in 2009, there has been a gradual decrease in the PSER, irrespective of the number of reporting companies, as can be seen in Figure 1. This decreasing trend is a good example of the commitment of the Concawe membership to process safety management, and furthermore demonstrates that the systematic gathering of such data enables the membership to actively manage this operational threat.

Personal Safety Indicators

Accident frequencies in the European downstream oil industry have been historically quite low; the 2013 data shows a 1.1 LWIF for 2013, which is the lowest value ever reported in the sector.

In general, performance indicator results are of greatest interest when these can be analysed for historical trends. The evolution of safety performance over a period of time provides indications on how well safety management efforts are working. Figure 2, for example, shows the changes and improving trends in the three-year rolling averages for the four main performance indicators mentioned above.

The trends in these indicators show a steady performance improvement over the past 20 years, with a slow but constant reduction in LWIF which remained below 2.0 for the fifth consecutive year. Although the data suggest that AIF peaked around 1996–97, this could also result from better data reporting as the AIF indicator was not formally used in all companies in the early years of Concawe's data gathering. Since 1997, the trend in AIF has generally been downwards except for a slight increase in 2010.

Regrettably, six fatalities in five separate incidents were reported in 2013:

- one of these fatalities was due to a road accident;
- three were due to two pressure release incidents;
- one was caused by a worker caught in, under or between a moving mass; and
- one was caused by a fall.

The six fatalities in 2013 are again the lowest ever experienced since Concawe started to collect safety data (Figure 3). After a steady downward trend during the 1990s, fatalities began to increase again in 2000 with a very high value of 22 fatalities in 2003. This unfavourable trend was reversed in 2004–06 and the fatality numbers have shown little variation since that time. The three-year rolling average for FAR has also stayed at about 2 for the past four years.

In 2013, contractors in the manufacturing sector of the European oil industry were the most vulnerable work group, experiencing four fatalities. This clearly remains a concern and demonstrates that all companies should ensure that their contractor workforce is fully integrated into their safety awareness and monitoring systems.

The relationships between the AIF, LWIF and FAR are presented in Figure 4.

While the number of fatalities per year has an impact on the two curves that are associated with FAR values, the figure shows relatively stable relationships among these indicators over time. Almost half of safety incidents are LWIs and there was approximately one fatality for every 100 LWIs.

Contrary to the positive trends in the LWIF and AIF indicators, the LWIS indicator, expressing the average number of days lost per LWI, increased in 2013. LWIS data and the three-year rolling average are shown in Figure 5. Although the LWIS results declined after peaking in 2010, the three-year rolling average still remains above the all-time LWIS average of 25. Therefore, the severity of the incidents that occur remains a concern.

Causes of fatalities and LWIs

In the 2013 survey, Concawe also gathered information on the causes of Lost Work Injuries in order to see how closely the LWIs could be related to the causes of fatalities. In 2013 the LWIs were categorised in five main categories also used to report the causes of the fatalities. These five categories were selected after ample analysis of the reporting method for this kind of data by other industrial sectors, and of the previous practice within the Concawe membership. The result is a scheme

Figure 3 Numbers of reported fatalities since 1993

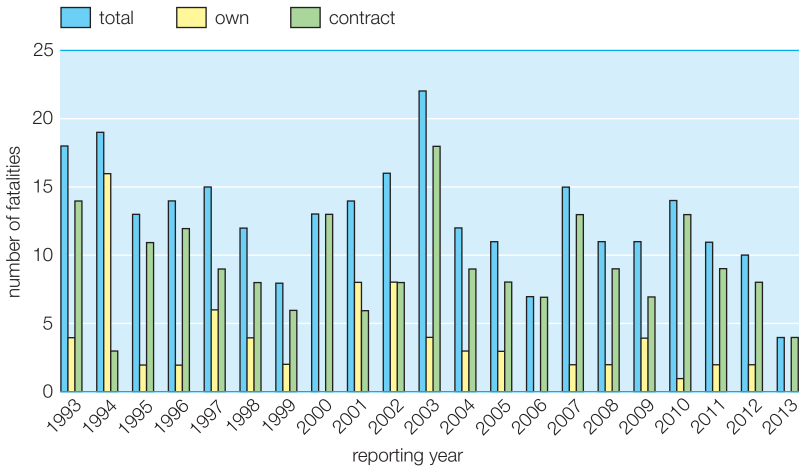


Figure 4 Relationships between incidents and fatalities for the European downstream oil industry

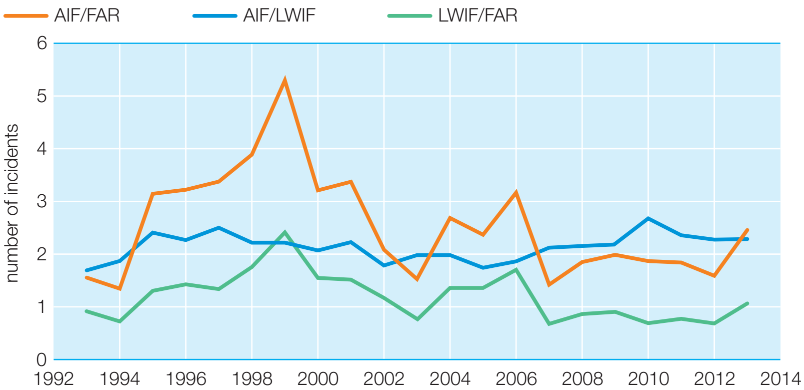


Figure 5 Lost Workday Injury Severity (LWIS) from 1993–2013 and the three-year rolling average for the European downstream oil industry

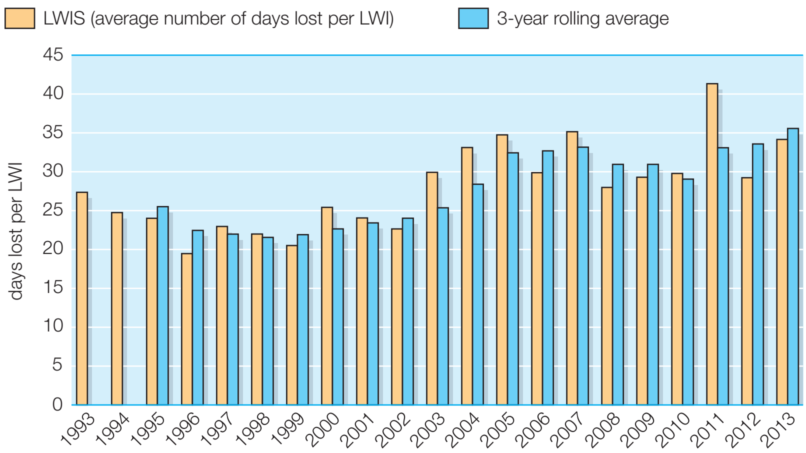
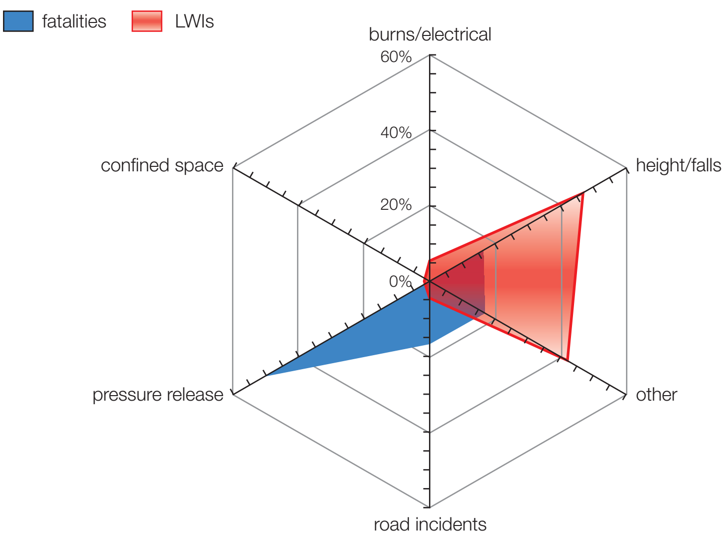


Table 2 LWIs and their causes

Cause		Manufacturing	Marketing	Combined	Percentage
Road accident	Road accidents	6	22	28	4%
Height/falls	Falls from height	24	42	66	10%
	Staff hit by falling objects	10	13	23	4%
	Slips and trips (same height)	89	121	210	33%
Burn/electrical	Explosion or burns	28	3	31	5%
	Exposure (electrical)	1	3	4	1%
Confined space	Confined space	3	2	5	1%
Other causes	Assault or violent act	0	11	11	2%
	Water-related, drowning	1	0	1	0%
	Cut, puncture, scrape	11	21	32	5%
	Struck by	37	25	62	10%
	Exposure, noise, chemical, biological, vibration	16	1	17	3%
	Caught in, under or between	28	19	47	7%
	Overexertion, strain	31	49	80	12%
	Pressure release	6	0	6	1%
	Other	9	11	20	3%
Total		**300**	**343**	**643**	**100%**

Figure 6 Reported causes on a percentage basis for LWIs and fatalities in 2013



very closely related to that of the International Association of Oil & Gas Producers (IOGP), an association comprising many Concawe members and performing scientific advocacy on behalf of their exploration and production activities.

A total of 643 LWIs were reported in 2013, of which only 20 (3%) could not be assigned to one of the 5 agreed categories by the reporting member companies. An overview of the LWI incidents and causes are provided in Table 2.

As can be seen from Figure 6, the percentage data for these LWIs in 2013 show that the distribution of LWI causes is quite different from those that resulted in fatalities.

This data being relatively new, there is no basis yet for a robust analysis of trends. Concawe will continue to collect this data in future years and the results should reveal trends that can be analysed in greater depth, providing valuable data to member companies that can then be used to improve on-the-job safety for employees and contractors.

Abbreviations and terms

AIF	All Injury Frequency
API	American Petroleum Institute
BAT	Best Available Techniques
BAT REF or BREF	BAT Reference document. Full title: ‘Reference Document on Best Available Techniques for ….’ (A series of documents produced by the European Integration Pollution Prevention and Control Bureau (EIPPCB) to assist in the selection of BATs for each activity area listed in Annex 1 of Directive 96/61/EC)
BSFC	Brake-Specific Fuel Consumption
BSI	British Standards Institution
CA	Crank Angle
CFD	Computational Fluid Dynamics
CI	Compression Ignition
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CR	Compression Ratio
CSL	Combustion Sound Limit
DI	Direct Injection
DOC	Diesel Oxidation Catalyst
EGR	Exhaust Gas Recirculation
FAR	Fatal Accident Rate
FID	Flame Ionisation Detector
GCI	Gasoline Compression Ignition
GHG	Greenhouse Gas
GPF	Gasoline Particulate Filter
GT-Power	Part of the ‘GT-Suite’ of engineering software, and the industry standard for engine simulations
HC	Hydrocarbon
HFS	High Flow® Sampler—a device designed for estimating leaks of natural gas
I/E	Intake/Exhaust
IMEP	Indicated Mean Effective Pressure
IOGP	International Association of Oil & Gas Producers
$ISNO_x$	Indicated Specific NO_x
KIVA	A family of Fortran-based CFD software developed by the Los Alamos National Laboratory
LDAR	Leak Detection and Repair
LNG	Liquefied Natural Gas
LOPC	Loss Of Primary Containment
LTC	Low-Temperature Combustion
LWI	Lost Workday Injury
LWIF	Lost Workday Injury Frequency
LWIS	Lost Workday Injury Severity
Method 21	A methodology for identifying leaking equipment by using a hydrocarbon ionisation detector
NA	Naturally Aspirated
NEN	Netherlands Standardization Institute
NMVOC	Non-Methane Volatile Organic Compounds
NO_x	Nitrogen Oxides
OGI	Optical Gas Imaging
PID	Photo Ionisation Detector
PPMV	Parts Per Million by Volume
PSE	Process Safety Event
PSER	Process Safety Event Rate
PSPI	Process Safety Performance Indicator
RAR	Road Accident Rate
SI	Spark Ignition
TDC-F	Top Dead Centre Firing (position)
TC	Turbo-Charged
US-EPA	United States Environmental Protection Agency
VOC	Volatile Organic Compound
VVT	Variable Valve Timing
WTW	Well To Wheels

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